

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

# **Meat quality and fat characteristics of lambs finished on different summer forages**

**A thesis presented in partial fulfilment of the  
requirements for the degree of  
Doctor of Philosophy in Animal Science**

At Massey University  
Palmerston North  
New Zealand

**Holly Phillips  
2025**

## Abstract

New Zealand lamb production systems are typically based on grazing perennial ryegrass/white clover pastures; however forage quality and growth tend to be inconsistent over the summer period leading to reduced intakes and animal performance. Summer-active forage crops can be included in the farm system to provide a source of high-quality forage over this crucial finishing period. In addition to this, ensuring consistently high eating quality lamb meat is paramount to maintain and expand export markets, thus any change to production systems need to consider the impact on the meat produced. Whilst alternative forages to perennial ryegrass/white clover have been studied extensively for their agronomic characteristics and animal performance, less is known about the impact of an alternative forage on the value chain from farmer to processor and in particular characteristics that can impact the consumer such as meat quality. This is particularly the case with the relatively new forage brassica species, Raphanobrassica.

This collection of studies conducted a comprehensive assessment of lambs grazing Raphanobrassica, Chicory, Perennial ryegrass/white clover (Chapters 3-7), Leafy Turnip, Red Clover and Perennial ryegrass/white clover + concentrate (Chapters 3-4). Studies utilised a replicated farmlet design and measured lamb growth, carcass production, meat quality, fat characteristics, volatile profile and conducted a consumer sensory evaluation.

Lambs grazing alternative forages had increased lamb growth rates, carcass weights and dressing out percentages (Chapters 3 & 5). Using Raphanobrassica or Chicory resulted in greater per hectare lamb performance (liveweight gain and carcass weight produced per hectare) over the summer and autumn period. The two forage types had different factors driving this increase, with lambs fed Chicory having greater per head performance and Raphanobrassica able to support a larger number of grazing lambs per hectare due to superior forage growth in dry conditions (Chapter 5).

Instrumental measurement of meat quality (pH, meat colour, shear force and water holding capacity) demonstrated small and inconsistent effects of forage diet (Chapters 4 & 6). Grazing alternative forages resulted in greater fat deposition (V-GR and intramuscular fat %) from faster growth and heavier carcasses. Changes in fatty acid composition were small and explained by the differences in IMF deposited (Chapters 4 & 6).

Assessment of different grazing durations over summer and autumn (32, 35 or 67 days) showed that length of time grazing had a greater effect on meat quality and fat deposition than the forages themselves, with longer grazing durations associated with heavier carcasses, greater fat deposition and a fatty acid profile that was more saturated (Chapter 6).

A stepwise analysis was used to assess the volatile profile of lamb meat, with 10 key volatile compounds differentiating the forage grazed and grazing duration. Aldehydes, alcohols and ketones

(derived from lipid oxidation), sulphur compounds and hydrocarbons (non-lipid volatiles) were identified as potential markers for the forage treatments (Chapter 6). A consumer sensory panel identified meat from Chicory fed lamb as being less tender, however this can be explained by the larger carcass weights achieved on this forage type. Scores for overall liking for Raphanobrassica were dichotomous, potentially due to Raphanobrassica having more frequent rankings for greatest flavour intensity, indicating flavour intensity could be a stronger driver of liking for some consumers compared to others (Chapter 7).

This research has shown that alternative forages to perennial ryegrass/white clover can be grazed by lambs over the summer period to improve animal production per head and per hectare without compromising the quality of meat produced for the processor or consumer.

## Acknowledgements

I would first and foremost like to thank my team of Supervisors, Associate Professor Nicola Schreurs, Dr Lydia Cranston, Dr Charlotte Westwood and Emeritus Professor Peter Kemp who retired during the course of my PhD.

I am so grateful to you all for sharing your wealth of knowledge and experience, your guidance and encouragement through the PhD process.

Nicola, you went above and beyond with your time, travelling for the meat sampling across the country.

This research has only been possible thanks to the generosity of my employer, PGG Wrightson Seeds. Thank you for funding this research, and to many of my team members, who spent time helping with farmlot trials, meat quality testing, the sensory panel, or sharing the research with the Farmers, Reps and others in the industry. With your help, this research has already had a huge impact, and I look forward to the next stage of publishing papers.

To my ever-patient husband Jason, thank you for all the support you have provided me over the 6 years I have been on this journey. Your help, especially time spent on weekends and after work on the farmlot trials, is so appreciated. I hope your birthday (Christmas Day) spent shifting lambs in the rain, is remembered as one of your favourites. I could not have done this without you.

To my Mum, even if I haven't always said it at the time, thank you for always encouraging me to keep going when I was struggling with balancing a part time PhD, a full time job, and more recently baby Ruby. I am so grateful for your help looking after Ruby so I could finish writing.

A thank you must also go to Mark Osborne and his team, for the setup of the farmlot trials, in particular the 15 hectare trial in 2020, which was a huge effort! Thank you to Keebles Farm Manager - Steve Bayler, and Massey farm staff for your help managing the lambs.

My summer students, Conor Hopkins and Alisha Harrop, thank you for the countless hours spent over the two summers of my farmlot trials, helping with data collection, shifting and weighing lambs.

Thank you to the FEAST Team for your expertise in planning and executing a 120 person consumer study, this was a great way to complete my studies, and I learnt so much.

A huge thank you to Dr David Baird for help with statistics, Dr Michael Agnew for fatty acid analyses, Fliss Jackson for forage quality and IMF testing, Associate Professor Pat Silcock and Associate Professor Graeme Eyres for volatile compound extraction, Gary Maclennan and the Alliance Staff at Dannevirke and Smithfield plants, for facilitating the meat sample collection. Finally, thank you to everyone else that helped me along the PhD journey, there are too many people to name all of you, but I appreciate each and everyone.

# Table of Contents

Abstract.....	2
Acknowledgements.....	4
List of Tables .....	10
List of Figures .....	12
List of Abbreviations .....	13
Chapter 1.....	14
Introduction .....	14
Thesis aim.....	17
Chapter 2.....	18
Literature Review.....	18
2.1 Sheepmeat production in New Zealand .....	19
2.1.1 Sheep production on grazed pastures .....	19
2.1.2 Contribution of NZ red meat production to the NZ economy .....	19
2.1.3 Markets for NZ sheepmeat .....	20
2.2 The importance of meat quality within the New Zealand red meat industry .....	22
2.3 Carcass classification and characteristics of lamb in New Zealand .....	23
2.3.1 Dressing out percentage .....	23
2.3.2 Intramuscular fat.....	23
2.4 Meat quality characteristics of lamb .....	24
2.4.1 Ultimate pH.....	24
2.4.2 Flavour .....	24
2.4.3 Tenderness.....	25
2.4.4 Meat colour.....	27
2.4.5 Juiciness .....	27
2.5 Fatty acid composition.....	27
2.6 Lamb production on herbage.....	30
2.6.1 Growth rates of lambs on grasses compared to alternative forages .....	31
2.7 Effects of forage finishing diet on carcass and meat quality characteristics .....	32
2.7.1 Carcass characteristics .....	32
2.7.2 Ultimate pH.....	35
2.7.3 Meat colour.....	37
2.7.4 Tenderness.....	40
2.7.5 Water Holding Capacity .....	44
2.7.6 Intramuscular fat.....	44
2.7.7 Fatty acid composition of lamb meat .....	45

2.8 Effects of grazing forages on the fatty acid profile of milk .....	47
2.9 Effects of grazing forages on volatile compounds in lamb meat .....	48
2.10 Sensory characteristics of lamb from different forages .....	51
2.11 Summary and Research objectives .....	53
Research questions .....	54
Chapter 3.....	55
Experiment 1: Lamb performance during summer when grazing six forage treatments.....	55
3.1 Introduction .....	56
3.2 Materials and Methods.....	58
3.2.1 Experimental Design .....	58
3.2.2 Forage Treatments.....	59
3.2.3 Animals and Management.....	61
3.2.4 Grazing Management.....	62
3.2.5 Animal Measurements.....	62
3.2.6 Pasture Measurements.....	63
3.2.7 Weather data .....	63
3.2.8 Statistical analysis .....	64
3.3 Results.....	65
3.4 Discussion.....	70
3.4.1 Forage characteristics .....	70
3.4.2 Lamb Growth Rates.....	71
3.4.3 Carcass measures.....	73
3.4.4 Conclusion.....	74
Chapter 4.....	75
Experiment 1: Meat Quality and Fat Characteristics of Lambs Finished on Six Forage Treatments during Summer .....	75
4.1 Introduction .....	76
4.2 Materials and methods.....	77
4.2.1 Experimental design and treatments.....	77
4.2.2 Slaughter .....	78
4.2.3 Carcass preparation and measurements.....	79
4.2.4 Meat Sampling .....	79
4.2.5 Ultimate pH.....	79
4.2.6 Instrumental colour measurement.....	79
4.2.7 Water holding capacity (WHC).....	81
4.2.8 Shear force and sarcomere length.....	81
4.2.9 Intramuscular Fat (IMF) and fatty acid profile.....	82
4.2.10 Statistical Analysis.....	83

4.3 Results.....	85
4.4 Discussion.....	91
4.4.1 Carcass measures.....	91
4.4.2 Objective meat quality measures.....	92
4.4.3 Fatty acid composition.....	94
4.5 Conclusion.....	97
Chapter 5.....	98
Experiment 2: Lamb Performance Per Hectare on Chicory, Raphanobrassica or Perennial Ryegrass/White Clover during Summer and Autumn.....	98
5.1 Introduction.....	99
5.2 Materials and Methods.....	102
5.2.1 Experimental Design and Animal Management.....	102
5.2.2 Grazing Management.....	105
5.2.3 Animal Measurements.....	105
5.2.4 Pasture Measurements.....	106
5.2.4 Weather data.....	106
5.2.5 Statistical analysis.....	107
5.3 Results.....	109
5.3.1 Forage chemical composition.....	109
5.4 Discussion.....	115
5.4.1 Forage measures.....	115
5.4.2 Lamb performance per head.....	116
5.4.3 Lamb performance per hectare.....	117
5.5 Conclusion.....	120
Chapter 6.....	121
Experiment 2: Influence of Chicory, Raphanobrassica or Perennial Ryegrass/White Clover Diet and Grazing Duration on Meat Quality and Fat Characteristics of Lambs.....	121
6.1 Introduction.....	122
6.2 Materials and Methods.....	124
6.2.1 Experimental design and treatments.....	124
6.2.2 Animals and management.....	125
6.2.3 Slaughter.....	126
6.2.4 Carcass preparation and measurements.....	126
6.2.5 Loin meat quality, intramuscular fat and fatty acid analyses.....	126
6.2.6 Volatile compounds analysis.....	127
6.2.7 Statistical analysis.....	127
6.3 Results.....	130
6.4 Discussion.....	147

6.4.1 Carcass measures .....	147
6.4.2 Objective meat quality measures .....	148
6.4.3 Fatty acid composition .....	150
6.4.4 Volatile compounds .....	152
6.5 Conclusion.....	155
Chapter 7.....	156
Experiment 3: Influence of Chicory, Raphanobrassica or Perennial Ryegrass/White Clover Diet on sensory properties of <i>Longissimus thoracis</i> muscle (loin) of lambs .....	156
7.1 Introduction .....	157
7.2 Materials and Methods.....	158
7.2.1 Experimental design and sample collection .....	158
7.2.2 Loin meat quality, intramuscular fat and fatty acid analyses .....	158
7.2.3 Consumer sensory evaluation.....	159
7.2.4 Statistical analysis .....	160
7.3 Results.....	162
7.3.1 Carcass characteristics .....	162
7.3.2 Objective meat quality tests .....	163
7.3.3 Fatty acid composition.....	164
7.3.4 Consumer sensory study.....	165
7.4 Discussion.....	170
7.4.1 Tenderness.....	170
7.4.2 Flavour Intensity .....	171
7.4.3 Juiciness .....	172
7.4.4 Overall liking.....	172
7.5 Conclusion.....	174
Chapter 8.....	175
General Discussion.....	175
8.1 Introduction and research questions.....	176
8.2 Summary of each research question .....	178
8.2.1 How does the meat quality and fatty acid composition of lamb meat differ between lambs fed alternative forages compared to perennial ryegrass/white clover?.....	178
8.2.2 How does the summer production of alternative forages effect lamb growth and carcass performance? .....	180
8.2.3 How much animal production per hectare can be produced off three forage types over summer? .....	182
8.2.4 Does the length of time on a forage influence the degree of change to meat quality and fat characteristics of lamb meat? .....	184
8.2.5 Does feeding alternative forages to perennial ryegrass/white clover affect the volatile profile and sensory characteristics of lamb meat? .....	186

8.3 Practical implications for lamb finishing .....	189
References .....	192

## List of Tables

Table 2.1: Percentage of total sheepmeat export volume (tonnes) by country and change from Year End (YE) June 2019 .....	21
Table 2.2: Percentage of total sheepmeat export value (NZ \$ millions) by country and change from Year End (YE) June 2019 .....	21
Table 2.3: Hot carcass weight (HCW, kg), dressing out percentage (DO%) and GR depth (mm) of lambs finished on ryegrass based pasture, herbs, brassicas or legume based pastures .....	33
Table 2.4: Ultimate pH of meat from lambs finished on ryegrass-based pasture, herbs, brassicas or legume based pastures .....	36
Table 2.5: Colour (lightness (L*), redness (a*) and yellowness (b*)) of meat from lambs that have grazed ryegrass-based pasture, herbs, brassicas or legumes .....	39
Table 2.6: Shear force of meat from lambs grazing ryegrass-based pasture, herbs, brassicas or legumes.....	42
Table 2.7: Cooking loss and purge loss of meat from lambs finished on ryegrass-based pasture, herbs, brassicas or legumes .....	44
Table 3.1: Forage species, cultivars, sowing rates and number of lambs used in Farmlot study 1 ....	59
Table 4.1: Treatments, cultivars and number of lambs allocated per replicate within treatment ....	77
Table 4.2: Number of lambs from each treatment that were sent for slaughter, and where applicable the number that were below a liveweight of 36kg.....	78
Table 4.3: Mean values for hot carcass weight (kg), final liveweight (kg), dressing out %, intramuscular fat (IMF)% and carcass characteristics of lambs grazed on six forage treatments .....	85
Table 5.1: Area sown per replicate (ha), forage sowing rate (kg/ha), lamb numbers per replicate and forage diet for each of the five treatments over Phase 1 (17 Jan – 20 Feb), Phase 2 (21 Feb – 25 Mar) and Phase 3 (26 Mar – 1 May). Numbers presented here are for all lambs utilised in the study (n=569), both those for meat quality (n=375) and those used to set the stocking rate (n=194). Lambs in Phase 2 are a subset of Phase 1 lambs as they continued on into Phase 2 if they had not reached suitable slaughter weight (39kg). New lambs were introduced for Phase 3. ....	104
Table 5.4: Herbage mass, pre and post (kgDM/ha), lamb numbers (lambs/ha) and calculated disappearance rate (kg/lamb/day) for PRG/WC, Chicory, Raphanobrassica, PRG/Chic or PRG/Raph during Phase 1 (D <sub>1</sub> – D <sub>35</sub> : 17 January 2020 – 20 February 2020) and Phase 2 (D <sub>36</sub> – D <sub>67</sub> : 20 February 2020 – 25 March 2020).....	111
Table 5.5: Start and final live weight (kg), live weight gain (g/day), carcass weight (kg) and dressing out percentage for lambs grazing PRG/WC, Chicory, Raphanobrassica, PRG/Chic or PRG/Raph for Phase 1 (D <sub>1</sub> – D <sub>35</sub> : 17 Jan – 20 Feb) and Phase 2 (D <sub>36</sub> – D <sub>67</sub> : 21 Feb – 25 Mar). Data presented in this table is for lambs selected for meat quality testing (n=300) rather than the complete set of lambs used to set the stocking rate.....	112
Table 5.6: Stocking rate, starting liveweight (kg), liveweight end of phase (kg) live weight gain (g/day), total live weight gained (kg/ha) and total carcass weight (kg/ha) for PRG/WC, Chicory, Raphanobrassica, PRG/Chic or PRG/Raph grazed during Phases 1 (17 Jan – 20 Feb), 2 (21 Feb – 25 Mar) and 3 (26 Mar – 1 May) of study 2. Data presented in this table is for all lambs utilised in the study (n=569).....	114
Table 6.1: Details of area sown, lamb numbers and forage diet for each of the five treatments. Number of lambs per replicate represents the number of meat quality lambs grazing, and does not include additional lambs allocated to set the stocking rate .....	125
Table 6.2: Mean values for hot carcass weight, final liveweight, dressing out percentage, intramuscular fat (IMF) and yield breakdown of lambs grazed on PRG/WC, Chicory or Raphanobrassica for 35 or 67 days.....	132
Table 6.3: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 35 or 67 days.....	133
Table 7.1: Questions asked to participants in sensory study .....	160

<b>Table 7.2: Mean values for hot carcass weight, final liveweight, dressing out percentages, intramuscular fat (IMF) and ViaScan-GR of lambs grazed on PRG/WC, Chicory or Raphanobrassica for 102 days .....</b>	<b>162</b>
<b>Table 7.3: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. ....</b>	<b>163</b>
<b>Table 7.4: Mean vales for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. The means were statistically analysed with pH as a covariate. ....</b>	<b>163</b>
<b>Table 7.5: Fatty acid content (mg/100g raw meat) of the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. ....</b>	<b>164</b>
<b>Table 7.6: Consumer ranking of four attributes for meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. Samples were ranked from 1 - 3, with 1 being the 'least' and 3 the 'most' of each attribute. ....</b>	<b>165</b>

## List of Figures

Figure 2.1: Principal Component Analysis (PCA) overlaying fatty acids and volatiles for samples of meat from lambs that were slaughtered prior to weaning (WEAN) or at 6-8 months of age after grazing chicory (CHIC), perennial ryegrass (GRASS) a pasture mixture (MIX) or red clover (REDC), or were merino labs slaughtered at 12 months of age (MXME). Lambs were also identified by their sex class as either a wether (W), cryptorchid (C) or ewe (E). The PCA identifies distinct fatty acid and volatile patterns for lambs that had grazed different diets (Ye, Eyres et al., 2020). .....	51
Figure 3.1: Farmllet study 1 trial design. 6 forage treatments: PRG/WC (labelled as Pasture in figure), PRG/WC + concentrate (labelled as Pasture + nuts in figure), Chicory, Red Clover, Leafy Turnip (labelled as Turnip in figure) and Raphanobrassica (labelled as Raphno in figure). Figure details the 3 replicates and area of each treatment within a replicate (replicate 1 = yellow (3750 m <sup>2</sup> ), replicate 2 = white (4575 m <sup>2</sup> ) and replicate 3 = blue (4230 m <sup>2</sup> )). .....	60
Figure 3.2: Drone picture of Farmllet study 1 at the end of the experiment after a period of dry weather in February 2019. Photo taken as a side view from Replicate 3 end (Replicate 3 Leafy Turnip bottom left corner, Replicate 1 Chicory top right corner).....	61
Figure 6.1: Drone picture of Experiment 2: Replicates 1 & 2 (12 January 2020) .....	129
Figure 7.1: Consumer responses for Question 1: Overall liking of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least liked, a score of 3 = most liked. ....	166
Figure 7.2: Consumer responses for Question 2: Tenderness of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least tender, a score of 3 = most tender .....	167
Figure 7.3: Consumer responses for Question 3: Flavour intensity of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least flavour intensity, a score of 3 = most flavour intensity .....	168
Figure 7.4: Consumer responses for Question 4: Juiciness of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least juicy, a score of 3 = most juicy .....	169

## List of Abbreviations

<b>Abbreviation</b>	<b>Explanation</b>
PRG/WC	Perennial ryegrass/white clover (Treatment in Chapters 3-7)
PRG/WC + concentrate	Perennial ryegrass/white clover supplemented with concentrate (sheep nut) (Treatment in Chapters 3-4)
PRG/Chic	Crossover treatment: Lambs grazed perennial ryegrass/white clover for first 35 days of study, then transferred to Chicory for the last 32 days of study (Treatment in Chapters 5-6)
PRG/Raph	Crossover treatment: Lambs grazed perennial ryegrass/white clover for first 35 days of study, then transferred to Raphanobrassica for the last 32 days of study (Treatment in Chapters 5-6)
SEM	Standard error of the mean
LWG	Liveweight gain (g/day)
LW	Live weight (kg)
CW	Carcass weight (kg)
DO%	Dressing out percentage
IMF	Intramuscular fat
V-GR	VIAScan estimated GR soft tissue depth
FA	Fatty acids
SFA	Saturated fatty acids
MUFA	Monounsaturated fatty acids
PUFA	Polyunsaturated fatty acids
BCFA	Branched chain fatty acids
LC n-3 PUFA	n-3 long chain polyunsaturated fatty acids
ALA	Alpha linolenic acid
EPA	Eicosapentaenoic acid
DHA	Docosahexaenoic acid
CLA	Conjugated linoleic acid
FAME	Fatty acid methyl ester
LL	Longissimus lumborum muscle
SM	Semimembranosus muscle

# Chapter 1

## Introduction

Producing lamb meat with consistently high eating quality is a key goal of the New Zealand red meat industry in order to maintain and expand markets (Craigie et al., 2017). Eating quality and nutritional characteristics of lamb meat are influenced by fat deposition and composition, whereby intramuscular fat positively influences eating quality and fatty acid composition impacts human health and wellbeing (Kearns et al., 2023; Realini et al., 2021). In turn, meat quality characteristics and fat deposition are affected by production factors (livestock management practices, diet, sex of lamb, age at slaughter), animal genetic factors and processing factors (Diaz et al., 2005; Ponnampalam et al., 2024). Animal diet has been found to play a crucial role in altering the fat deposition and composition and sensorial attributes of meat, and provides a comparatively quicker strategy compared to genetic selection (Mortimer et al., 2014) so has been a key area of research in the last decade. Different finishing diets can act directly on the meat, or indirectly through factors such as animal growth rate or level of fatness (Purchas, 1989).

New Zealand lamb production systems are typically based on perennial ryegrass (*Lolium perenne*)/white clover (*Trifolium repens*) pastures, which provides both a low-cost production system and delivers meat with more beneficial fatty acids than meat from more intensive systems. Meat from pasture fed animals contains more n-3 polyunsaturated fatty acids (PUFA) than meat from concentrate fed animals, due to the naturally high levels of alpha-linolenic acid (ALA) in fresh pasture. Alpha-linolenic acid is an essential fatty acid and is a precursor for production of longer chain PUFA derivatives, including the production of health claimable fatty acids eicosapentaenoic acid and docosahexaenoic acid (EPA + DHA). Climate variation between years and locations makes solely finishing lambs on perennial ryegrass/white clover difficult in New Zealand, particularly over summer when dry conditions and plant development doesn't promote growth of fresh leaf material. This is particularly evident in older, run-out pastures, and rates of regressing on sheep and beef farms are low at approximately 2.3% per year (Stewart et al., 2022). Farmers strategically use summer-active forage crops such as herbs, brassicas and legumes to enable high lamb performance during summer and autumn and as part of a pasture renewal programme. Utilising high quality forages enables increased energy intakes by grazing lambs, with alternative forages having high nutritive values and low fibre content allowing for rapid digestion and greater intakes.

Considerable research has been undertaken on the impact of grazing alternative forages to perennial ryegrass/white clover on animal production measures, particularly liveweight gain and carcass production. It is important to understand the impact of feeding these forages on both animal performance measures and, the physical and chemical properties of the resulting lamb meat produced. Some research has compared the impact of lambs grazing different forages on meat quality characteristics and fat deposition, with some studies finding alternative forage crops increased

deposition of intramuscular fat (IMF%) and increased levels of ALA in the meat compared to perennial ryegrass/white clover pasture (De Brito et al., 2017; Fraser et al., 2004; Lourenco et al., 2007; Ye, Eyres, et al., 2020; Ye, Schreurs, et al., 2020). However, very few studies have utilised a replicated farmlet style design or considered animal performance per hectare. This type of study design minimises the influence of external environmental factors and gives the most robust results. Including stocking rate in combination with lamb growth rates and carcass weights gives an understanding of both live weight gain and carcass weight produced on a per hectare basis which is a better reflection of the impact the forage will have on overall productivity. This has been characterised in herb mixes which has aided with farmer confidence when using these on farm (Kenyon et al., 2017; Somasiri, 2014).

Forage selection for this collection of studies are modern cultivars utilised for lamb finishing in New Zealand. Studying modern cultivars is important as animal performance can differ based on agronomic differences between cultivars, as was previously shown in plantain (Moorehead et al., 2002). Raphanobrassica is a relatively new species of forage brassica utilised for lamb finishing, and minimal research on animal performance or meat quality with this forage is available. Additionally, there is a knowledge gap on the effect of length of time an animal is finished on a particular forage pre-slaughter on fatty acid concentration in lamb meat (Ponnampalam et al., 2024).

Fat composition influences flavour through the production of various volatile compounds generated by oxidation upon cooking and their interaction with Maillard reaction products. A vast number of volatiles have been identified from lamb meat (Resconi et al., 2013; Vasta & Priolo, 2006) and identifying those that contribute to lamb flavour or are influenced by production systems of lamb is a keen area of research interest. Gaining an understanding of any unique volatiles produced in meat from lambs grazing alternative forages could be used as markers, with technologies allowing for identification pre slaughter to differentiate lamb products to unique markets.

Ultimately the consumer drives the value of meat products and so understanding the sensory perceptions is important part of ensuring product quality and consistency. Whilst the effect of feeding certain alternative forages to perennial ryegrass/white clover on fatty acid composition and volatile profile has been characterised, less is known about eating quality. This is important to consider, particularly with Raphanobrassica, given there has been inconsistent impacts of brassica feeding on consumer liking (Frank, Watkins, et al., 2016; Hopkins, Beattie, et al., 1995).

Although laboratory testing can help identify drivers of lamb meat quality, the consumers perspective of lamb meat from different finishing diets is important to consider as it incorporates the complexities associated with an individual's sensitivity, preference and cultural background. For this reason, these studies were concluded with a sensory panel to understand the impact of three finishing diets on

consumers perception of overall liking, flavour intensity, tenderness and juiciness, to ensure no negative perceptions arose from grazing alternative forages.

The production of lamb meat is a value chain involving farmers, processors and consumers. Each of these groups need to be considered when contemplating a change to the production process. This research was designed to be end-to-end and considers the impact on the farmer (lamb growth and carcass performance), processor (carcass characteristics, meat quality and fat deposition) and the consumer (meat quality, volatile profile and sensory characteristics). Having an understanding of the influence of grazing alternative forages at all points of the value chain allows farmers and processors to make better decisions around what production system aspects are useful to achieve consistent eating quality for discerning markets or differentiate products to meet the unique requirements of each of our export markets.

## Thesis aim

The overall aim of this research was to investigate the growth, meat quality and fat characteristics of lambs that had grazed on different summer finishing forages under New Zealand conditions. The goal of the research is to consider if grazing treatments on farm that can influence meat quality and nutritive value of the meat product for discerning consumers. The experimental work included two replicated farmlet studies; Farmlet study 1 (Chapters 3 and 4), Farmlet study 2 (Chapters 5 and 6), and a Sensory study (Chapter 7). The specific objectives were: to evaluate lamb growth and carcass production on a per head (Chapters 3 and 5) and per hectare (Chapter 5) basis; to quantify the effect of grazing different forages on measures of instrumental meat quality and fatty acid composition (Chapters 4 and 6), and to assess the influence of grazing forages on sensory perception of lamb meat utilising volatile compounds and an untrained sensory panel (Chapters 6 and 7).

## Chapter 2

### Literature Review

## 2.1 Sheepmeat production in New Zealand

### 2.1.1 Sheep production on grazed pastures

Globally, sheep meat comes from a wide variety of farming systems utilising outdoor extensive to indoor intensive with animals of various ages at slaughter. In New Zealand the production systems are outdoors, extensive and perennial ryegrass dominant pastures provide the basis of nutrition. The goal for producers of lamb for animals born in spring is to finish (i.e., get sufficient weight and fatness for carcass classification) by 5-6 months of age which then allows for on-farm efficiencies as the feeding period is minimised as the lambs to be off farm before winter when perennial ryegrass pasture growth slows.

In some locations of New Zealand dry conditions in the late summer and into the early autumn can inhibit the ability of lambs to be finished due to slowing the growth of pasture and hence, slowing the growth of the lambs. This is particularly true for unimproved perennial ryegrass pastures. Sheep and beef farms used for lamb finishing systems across New Zealand, on average, have a re-grassing rate of approximately 2.3% of farm area (Stewart et al., 2022) suggesting that much of the lamb finishing farm system is utilising older cultivars of perennial ryegrass or have not had perennial ryegrass pastures refreshed. A solution to this seasonal issue of feed supply with perennial ryegrass dominant pastures has been to implement the use of alternative forages that have stronger growth or resilience under dry conditions. These summer active forages provide the feed quantity and quality that allow lambs to be finished efficiently and to target timeframes (Stewart et al., 2022).

### 2.1.2 Contribution of NZ red meat production to the NZ economy

The New Zealand red meat industry is an integral part of the New Zealand economy, generating \$9.4 billion in export earnings for 2019/2020 (Meat Industry Association, 2020). Despite large increases in dairying, sheep and beef cattle production is still New Zealand's predominant agricultural land use, utilising 63% of the agricultural and forestry area (Beef and Lamb, 2020). New Zealand's climate favours pasture growth throughout the year, and so in combination with forage crops supplies more than 95% of the livestock diet on New Zealand farms (Hodgson et al., 2005). This extensive system is efficient, sustainable and low cost, allowing New Zealand to compete globally as a major exporter of food and fibre (Morris & Kenyon, 2014).

The sheep and beef sector has a strong export focus, with 95 percent of sheep meat and 80 percent of beef being exported (Morris, 2013). In the year ending June 2020, New Zealand exported 386,250 tonnes of sheep meat and 460,170 tonnes of beef, excluding co-products (Meat Industry Association, 2020). Despite its small size, New Zealand is the largest exporter of lamb in the world, accounting for nearly half the world trade in lamb (Stafford, 2017). There has been a large focus on increasing value of exports, with one key shift being the change from exporting whole carcasses to focusing on adding

value by sending primal or sub-primal cuts. Whole carcasses exported dropped from over 90% of the total export mix in 1970/71 to just 3.9% in 2005/2006, and primal and sub-primal cuts grew from less than 10% in 1970/71 to 81.5% in 2005/2006 (McDermott et al., 2008).

2020 saw COVID-19 heavily influence international markets. Food safety, security and reputation have become increasingly important (Beef and Lamb New Zealand, 2020). This is particularly the case in China, where African Swine Fever has damaged both the production volumes and reputation of the pork sector. In addition to this, the nutrition of food is having a resurged importance, as there is demand for food that will support health and immunity in light of a global pandemic. New Zealand is well placed to meet these requirements, and in traditional Chinese medicine, both sheepmeat and beef are considered to provide immune support (Beef and Lamb New Zealand, 2020). Additionally, lockdowns around the world have shifted the channels that consumers purchase food, with less demand in food service channels which utilise the higher value cuts. More food is being prepared in the home, meaning there is more demand for products that are convenient and easy to prepare, such as mince (Beef and Lamb, 2020). Having such a strong export focus means the acceptance of red meat in international markets is an important economic issue (Morris & Kenyon, 2014) and the shifts in the markets in 2020 has highlighted the importance of both product quality and market diversity.

### 2.1.3 Markets for NZ sheepmeat

The volume of sheepmeat exports in 2019/20 was slightly down (by 3%) from the 2018/19 total to 386,250 tonnes (Table 2.1), however due to NZ's value focus and strong global meat prices, the value of these exports increased by 4% to \$4.0 billion (Table 2.2). China is now the largest importer of NZ lamb, importing 54% of the New Zealand export volume for the year ended June 2019 (Table 2.1, Meat Industry Association, 2020). This was largely driven by China's increased demand for meat, due to the impact of African Swine Fever (ASF) on Chinese pork production (Meat Industry Association, 2020). With New Zealand's overall sheepmeat production being down by 3%, and the volume exported to China increasing by 3%, this meant there was less available for other markets, with most markets having a decrease in volume imported for 2019/20 (Table 2.1). The 54% going to China is the highest percentage of sheepmeat exports going to a single market in more than 30 years, however it is still well below the 86% going to the United Kingdom (UK) in the early 1960's (Meat Industry Association, 2020).

Traditionally, the European Union was the biggest importer of NZ lamb, due to favourable market access (McDermott et al., 2008) which has been developed through the counter seasonal supply of lamb, complementing Europe's own production systems. It remains an important market, with the UK being the second highest export destination for sheepmeat in terms of volume and particularly value, with 48% of exports being high-value chilled cuts (Meat Industry Association, 2020). In 2018/19, the

volume exported to the UK dropped 11% (Table 2.1), however the value of these exports remained stable, meaning that the price per kg increased from \$9.72/kg to \$10.83/kg (Meat Industry Association, 2020b).

Taiwan was one of the few markets where both value and volume increased despite significant demand from China. The volume of exports increased by 13% (Table 2.1) and the value increased by 19% to \$93 million (Table 2.2). New Zealand sheepmeat exports to Taiwan have been tariff free since 2017 under the Agreement between New Zealand and the Separate Customs Territory of Taiwan, Pengu, Kinmen and Matsu on Economic Cooperation (Meat Industry Association, 2020).

**Table 2.1: Percentage of total sheepmeat export volume (tonnes) by country and change from Year End (YE) June 2019**

Export Destination	Percentage of total sheepmeat export volume (%)	Annual Volume (tonnes)	Change from YE June 2019
China	54%	209,386	3%
United Kingdom	10%	38,142	-11%
United States	5%	20,252	-21%
Germany	4%	15,709	-2%
Netherlands	3%	12,239	-19%
Taiwan	3%	10,025	13%
Malaysia	3%	9,918	35%
Saudi Arabia	2%	8,607	-1%
France	2%	8,568	-10%
Jordan	2%	7,982	31%
Other markets	12%	45,428	
<b>Total</b>		<b>386,250</b>	<b>-3%</b>

**Table 2.2: Percentage of total sheepmeat export value (NZ \$ millions) by country and change from Year End (YE) June 2019**

Export Destination	Percentage of total sheepmeat export value (%)	Value (NZ \$ millions)	Change from YE June 2019
China	43%	1,695.2	23%
United Kingdom	10%	413.0	-1%
United States	9%	346.7	-24%
Germany	7%	260.6	-2%
Netherlands	5%	206.2	-13%
Japan	3%	107.9	14%
France	3%	103.7	-2%
Taiwan	2%	93.2	19%
Canada	2%	91.3	-20%
Malaysia	2%	88.8	40%
Other markets	14%	567.4	
<b>Total</b>		<b>3,973.9</b>	<b>4%</b>

## 2.2 The importance of meat quality within the New Zealand red meat industry

Meat quality is an integral part of establishing and maintaining meat export markets as it is crucial for consumer satisfaction and to ensure repurchase (Jiang et al., 2015; Troy & Kerry, 2010). Meat quality is defined by those traits that the consumer deems important to acceptability. These include both visual and sensory traits, credence traits of safety and health, and those that relate to the ethical nature of the production system (Becker, 2000; Watkins et al., 2013). Important visual traits include meat colour and texture, amount of fat, fat distribution and colour, and the absence of purge at retail display (Watkins et al., 2013). For cooked meat, consumer satisfaction is primarily driven by the tenderness of the meat, along with its flavour and juiciness (Miller, 2020).

In recent times, factors such as nutritional value, sustainability, animal welfare and traceability have become increasingly important to consumers. Consumers are becoming increasingly aware of how their food choices affect their health. They are looking for food options which are high in omega 3 fatty acids and low in saturated fatty acids (SFA) (Fowler et al., 2019). New Zealand production systems are well placed to meet these expectations; however it is important to note that consumers do not seem to be willing to compromise on taste for other potential benefits (Verbeke, 2006). For this reason, it is a key goal for the New Zealand meat industry to consistently deliver meat with desirable eating quality characteristics (Craigie et al., 2017).

Sheep and beef production systems in New Zealand have traditionally relied on perennial ryegrass dominant pastures. There has been an increase in the use of alternative forage types such as brassicas, legumes and herbs for finishing livestock, as they offer a higher feeding value diet than traditional perennial ryegrass and white clover-based pasture, particularly over summer when the nutritive value of perennial ryegrass declines (White & Hodgson, 1999). These alternative forages allow for faster liveweight gains and greater carcass production per head and per hectare (Kenyon et al., 2017; Lindsay et al., 2007; Somasiri et al., 2015). Understanding the impacts of these alternative forages on carcass and meat quality is essential to be able to deliver meat with attributes that meet or exceed customer expectations in varied and discerning markets. There has been some research done on lambs in New Zealand to investigate this (Campbell et al., 2011; Fraser et al., 1996; Kim et al., 2013; Schreurs et al., 2013; Ye, Schreurs, et al., 2020) however, these studies don't encompass modern varieties used for lamb finishing such as Raphno-brassica. Similarly, there has been considerable work done on the effect of pasture vs grain finishing on beef quality (Muir et al., 1998), but very little work done on alternative forages to perennial ryegrass and white clover-based pastures, particularly under New Zealand conditions.

## 2.3 Carcass classification and characteristics of lamb in New Zealand

Carcass weight (hot carcass weight) and the GR fat (soft tissue) depth form the basis of carcass classification for sheep in New Zealand. Principally, the classification system is designed to identify those carcasses that yield more saleable meat.

It is the carcass classification that provides the basis of the payment schedule for the meat producer. Greater value is placed on those carcasses that are heavier because more meat is yielded. The GR measure is the total soft tissue depth over the 12<sup>th</sup> rib 110mm from the midline of the carcass and is a proxy for the content of fat in the carcass. Increasing the GR depth contributes to saleable meat yield up to the point allowable fat thresholds for meat cuts are obtained (12mm of GR), after which trimming occurs (Kirton, 1989). Increasing carcass fat can also indirectly have positive effects on meat quality because it is associated with improved juiciness and flavour based on increases overall carcass fat also being associated with more intramuscular fat (Liu et al., 2024). However, for lamb carcasses produced and processed in New Zealand there is no carcass classification criteria that incorporates an intramuscular measurement or score (Kirton, 1989).

In parallel to this, meat processors in New Zealand are moving towards technologies such as Video Image Analysis (VIAscan) which allow meat processors to get yield information from leg, middle and shoulder primal cuts and can reward farmers more directly for saleable meat yield.

### 2.3.1 Dressing out percentage

The DO% is the proportion of the live weight which is carcass weight. For most of the calculations of dressing out it uses the final liveweight measured on farm prior to trucking and the hot carcass weight obtained from kill sheet data. Farmers will assume a value for the DO% based on previous kill sheet information and knowledge of how DO% changes as their animals grow, and this will be the likely value of the animal as a carcass.

In research situations measuring the dressing out percentage is important for providing information on the likely proportion of the growth and liveweight that contributes to the carcass with different production or forage practices. It has been shown that chicory-based swards can reduce gut fill and increase dressing out percentage (Somasiri et al., 2016).

### 2.3.2 Intramuscular fat

Within the carcass there are three deposits of fat. Subcutaneous fat lies under the skin of the live animal and covers the carcass and is seen on the outside of the muscles of meat cuts. If a meat cut contains several muscles, there can be seams of fat between the muscles called intermuscular fat.

Fat within the muscle is called intramuscular fat (IMF) and in some animals, it is observed as clusters of adipocytes in the muscle creating a marbled effect. In sheep and lamb meat IMF can be more

dispersed within the muscle and not necessarily observable as marbling (Camacho et al., 2017; Hocquette et al., 2010) as seen in beef.

Although carcass fat is an aspect of composition that influences saleable meat yield, intramuscular fat is more associated as a meat quality characteristic due to its relationship with eating properties in particular tenderness and, for contributing fatty acids that influence nutritive value.

## 2.4 Meat quality characteristics of lamb

Meat quality can be defined as the degree to which a product satisfies the needs and expectations of a consumer (Purchas et al., 1989). The main characteristics of importance to meat quality for the consumer are appearance and palatability, which are influenced by factors such as ultimate pH, lean meat and fat colour, tenderness, juiciness and flavour of the meat (Prache et al., 2022).

Consumers' eating experience and subsequent repurchasing decisions are influenced by meat quality (Purchas, 2003). Therefore, meat quality influences which markets lamb is suitable for, and the price consumers are willing to pay (Prache et al 2022).

### 2.4.1 Ultimate pH

The ultimate pH can affect both palatability and appearance characteristics of the meat product (Purchas et al., 1989). Ultimate pH for red meats under normal conditions is in the range of 5.4-5.6 (Prache et al., 2022; Purchas, 2003; Schreurs & Kenyon, 2017). A quadratic relationship exists between ultimate pH and tenderness, with intermediate pH values of 5.8-6.2 generally producing less tender meat (Purchas, 1990; Purchas & Aungsupakorn, 1993). The pH also has an influence on meat colour, juiciness and flavour. Dark coloured ("dark cutting") meat is associated with an elevated ultimate pH and high pH has also been considered to be dry and have a bland flavour (Prache et al., 2022; Schreurs & Kenyon, 2017).

Because the pH of the meat can influence all other meat quality attributes, and it is an important intrinsic determinant to measure as part of meat quality testing to understand the extent that treatments are influencing meat quality above pH effects (Prache et al., 2022).

### 2.4.2 Flavour

Flavour is an important aspect for the overall acceptability of meat products, which is frequently considered as the most important palatability characteristic of cooked sheep meat (Hopkins et al., 2005; Phelps et al., 2018; Thompson et al., 2005) Just as significant industry efforts have been dedicated to improve meat tenderness, there are studies that report that flavour is becoming a more important driver of overall palatability (O'Quinn et al., 2018). A shift from traditional commodity to

value-based marketing requires optimization of production and processing to guarantee products with favourable meat flavour.

Although the perception of flavour has been defined as integrated sensations of smell, taste and touch (Noble, 1996), the cooked meat flavour is mainly influenced by volatile compounds that reach the receptors in the nasal epithelium through the nose or through the posterior nares at the back of the nose when food is chewed (Farmer, 1994; Mottram, 1998).

Over 1000 volatile compounds have been associated with meat flavour (Mottram, 1998), however, only a few compounds contribute to the baseline aroma of lamb meat according to Watkins et al (2013). Whether a compound has an impact on flavour or odour depend on its concentration and detection threshold and in addition, meat flavour is also affected by consumers' previous experience and cultural background (Font-i-Furnols & Guerrero, 2014). Country of origin of consumers has been reported to exert a significant effect on their preferences for lamb-meat, with consumers preferring forage- or concentrate-fed lamb depending on their nationality (Sañudo et al., 2007).

### 2.4.3 Tenderness

Tenderness is considered an important quality attribute of meat, as it is often the characteristic consumers are most dissatisfied with (Lucero-Borja et al., 2014; Prache et al., 2022; Purchas, 2003; Schreurs & Kenyon, 2017). For lamb, tenderness is often considered secondly after flavour as being meat from a young animal the tenderness is generally not an issue but, still of importance for meat eating consumers (Miller, 2020). Factors affecting tenderness include collagen content and solubility, intramuscular fat and ultimate pH (Prache et al., 2022; Purchas et al., 1989; Schreurs & Kenyon, 2017). Warner-Bratzler shear-force is the most used method to assess tenderness objectively, while subjective tenderness can be measured using sensory panels (Prache et al., 2022; Schreurs & Kenyon, 2017).

#### 2.4.3.1 Role of intramuscular fat in tenderness and palatability

Tenderness and intramuscular fat of sheep are positively correlated (Hopkins et al., 2006). As an animal gets older the proportion of fat in the carcass increases, including intramuscular fat (IMF or marbling) and subcutaneous depots (McPhee et al., 2008). This has been shown to improve tenderness in older animals providing the increase in intramuscular fat can negate the effect of decreased collagen solubility (Ablikim et al., 2016; Dutson et al., 1976; Purchas et al., 1989; Weston et al., 2002; Young & Braggins, 1993). Mashele et al (2017) compared lamb meat from 5 to 14-month-old lambs and noted that the meat from 8-month-old lambs was the most tender due to an increase in intramuscular fat without the reduction in collagen solubility that reduced the tenderness of the meat in meat from the 14-month-old lambs.

Increasing levels of IMF are associated with increasing tenderness, flavour and juiciness (Lambe et al., 2017; Pannier et al., 2014; Phelps et al., 2018). Through an integrated omics approach it has been shown that the composition of flavour compounds differ based on the contents of intramuscular fat and identified major genes associated with this variation (Park & Choi, 2025). IMF also has a role in consumer acceptability of red-meat products, accounting for 11% of the variability in overall liking of lamb as assessed by a trained sensory panel (Lambe et al., 2017). Studies with lamb in Australia indicated that an IMF of 5% or more was required to get a high palatability score and that intramuscular fat explained only 3% of variation in palatability (Hopkins et al., 2006). Pasture-raised lambs in New Zealand slaughtered between 3-8 months of age have an average IMF% of 2.7% and as such do not reach the threshold to have an influence on palatability (Craigie et al., 2017).

Selecting sheep for lean muscle growth traits to meet carcass size and conformation specifications has been associated with a reduction in IMF throughout the carcass, thereby having a negative impact on eating quality attributes (Anderson et al., 2015; Pannier et al., 2014). Additionally, intramuscular fat is considered a late maturing tissue compared to subcutaneous fat and so, IMF at sufficient concentration to influence palatability is usually seen in carcasses from older animals compared to younger animals (Mashele et al., 2017; Pannier et al., 2014).

Although Hopkins et al., (2006) proposed a 5% threshold of IMF for palatability, the optimal level of in lamb meat is variable between studies. Early work from the USA across lamb, pork and beef indicated that some degree of marbling is essential for palatability (Savell & Cross, 1988). Further work indicated that fat levels below 3% are outside the 'window of acceptability', and palatability increases at the highest rate between 1% and 3% (Miller, 2014). More recent consumer studies in Australia, the UK and the USA confirm that increasing levels of IMF improve eating quality and suggest target IMF levels of between 3-5% to optimise palatability (Lambe et al., 2017; Pannier et al., 2014; Phelps et al., 2018). Until recently, there had been no comprehensive consumer studies on New Zealand lamb, which is lower in fat than international lamb. A recent New Zealand consumer study by Realini et al. (2021) compared the impact of IMF on eating quality of lamb meat by testing lamb meat at six levels of IMF (1.65%, 2.12%, 2.65%, 3.20%, 3.58% and 4.40%). They found consumers overall liking of lamb increased significantly from 3% IMF, achieving maximum scores at 4% (Realini et al., 2021). The authors suggested aiming for IMF levels in NZ lamb beyond 3% to maximise eating quality for premium markets.

#### 2.4.4 Meat colour

Lean meat colour is an appearance characteristic that has an important influence on consumers' purchasing decisions as it is one of few characteristics that can be assessed at the point of sale (Young & West, 2001). Bright, light red coloured meat represents freshness to consumers (Faustman, 2014). Meat colour is dependent on the concentration and chemical state of the meat pigments, primarily myoglobin, and on the physical characteristics of meat, such as its light scattering and absorbing properties (Troy & Kerry, 2010). These characteristics are affected by factors such as age, exercise, diet of the animal, as well as genetic and environmental factors (Priolo et al, 2001; Prache et al 2022).

#### 2.4.5 Juiciness

Many studies have reported that consumers prefer juicier meat in pork, beef and lamb (Font-i-Furnols and Guerrero, 2014). Juiciness is related to the water-holding capacity of the meat and its ability to stimulate salivation (Purchas, 1989). Juiciness influences the palatability of meat and is dependent on the amount of water released from the meat or the presence of intramuscular fat which stimulates salivation (Purchas, 1989; Schreurs & Kenyon., 2017; Prache et al., 2022).

Sensory assessment of juiciness of meat (alongside other eating quality attributes) can be undertaken using either trained or untrained consumer panels (Thompson et al., 2005). However, panel analysis is time-consuming, costly and destructive for evaluating juiciness (Van Oeckel et al., 1999) and hence objective measurements of water holding capacity commonly used such as the filter paper press method, driploss of a standardised sample or cooking loss measures (Prache et al 2022).

### 2.5 Fatty acid composition

The major lipid class in lamb adipose tissue (>90%) is triacylglycerol or neutral lipid. The rest of proportions are mainly phospholipid and cholesterol, which have a much higher PUFA percentage in order to perform its function as a constituent of cellular membranes (Wood et al., 2008). Oleic acid (c9-18:1) is the most dominant fatty acid in neutral lipid. This fatty acid is formed from stearic acid (18:0) by the enzyme stearoyl Co-A desaturase, a major lipogenic enzyme. The DHA and EPA are synthesized from the n-3 precursor alpha-linolenic acid (18:3; ALA), whereas long chain n-6 PUFA such as arachidonic acid is synthesized from the n-6 precursor linoleic acid (18:2). The long chain n-3 and n-6 PUFA are mainly found in phospholipid, but also detected in neutral lipid and adipose tissue (Cooper et al., 2004). A major trans fatty acid is conjugated linoleic acid (CLA, c9t11-18:2) formed by the bacterium *Butyrivibrio fibrosolvans* in the rumen (Mir et al., 2000). Human dietary sources of CLA are almost exclusively red meat and dairy products.

Fatty acids play an important role in the overall flavour of lamb meat. Branched-chain fatty acids, mainly 4-methyloctanoic acid, 4-ethyloctanoic acid and 4-methylnonanoic acid, are the main

compounds responsible for the characteristic goaty and sheepy flavour of lamb meat (Prescott et al., 2001). The level of branched-chain fatty acids is in general, negatively associated with sensory scores evaluated by Asian consumers from early studies (Prescott et al., 2001). Alternatively, the total branched-chain fatty acids can play a positive role in defining lamb flavour and acceptance for some consumers up to a certain threshold concentration (Frank et al., 2016).

Fatty acids composition of lamb also effects the mouthfeel of meat. Fat tissue with more saturated fatty acid is firmer and the melting point of fat increases as saturation increases (Wood et al., 2004). Therefore, when the meat is served, with internal temperature cooling down gradually, the intramuscular fat with less saturated profile is more likely to remain molten and provide a smoother mouthfeel. Angood et al., (2008) reported positive correlations between the total fatty acid content of loin meat from lambs and eating quality scores given by a trained sensory panel.

Fatty acids are a key concern for the nutritive value of meat. There are concerns about a high saturated fatty acids (SFA) content, for human health. A high intake of SFA is associated to a number of health concerns such as type II diabetes and cardiovascular disease (Hu et al., 2001). The US Department of Agriculture and Human Health Services (US Department of Agriculture & US Department of Health and Human Services, 2010) have defined cholesterol-raising fatty acids as SFA from C12:0 to C16:0, including the trans-fatty acids, except for those found in products from ruminants. Excessive intakes of n-6 PUFA and high n-6:n-3 ratios are commonly found in modern Western diets and associated with pathogenesis of many diseases, including cardiovascular disease, inflammatory and autoimmune diseases (Simopoulos, 2008). Increasing the intake of long chain n-3 PUFA, without increasing n-6 PUFA intake can decrease the risk of these diseases (Ruxton et al., 2004).

Red meat is an important source of long chain n-3 PUFA (Scollan et al., 2006). The World Health Organization, (2008) recommended that the total PUFA, n-6, and n-3 fatty acids should contribute 6-11%, 2.5-9%, 0.5-2% of the total energy intake for adults, respectively. The World Health Organisation also recommended a combined eicosapentaenoic acid (EPA) plus docosahexaenoic acid (DHA) intake of 250 mg per day for adults (World Health Organisation, 2008). In Australia and New Zealand, health claims can be made with food >22 and 44 mg EPA + DHA/100 g serve for a 'source' and 'good source' of EPA + DHA, respectively (Food Standards Australia New Zealand, 2012); while the European market requires >40 mg and 80 mg EPA+DHA/100 g serve for a 'source' and 'good source', respectively (Commission Regulation of European Union, 2010).

Conjugated linoleic acid (CLA) which has anticarcinogenic, antiatherogenic, antidiabetic, and antiadipogenic properties for humans is commonly found in red meat (Geay et al., 2001). The

mechanism of its benefits, however, is still unclear (Ochoa et al., 2004) and the nutritional recommendations for CLA are not part of any current health guidelines.

## 2.6 Lamb production on herbage

Achieving maximum growth is reliant on ensuring the animal is receiving adequate nutrition and is healthy so that nutrients are partitioned to growth. In the grazing situation for finishing lambs quickly, this means providing sufficient quantity of good quality forage. Optimising growth rates with a pasture diet requires young growing stock to have access to a green, leafy sward. Such pasture will have the highest digestibility and greatest rate of degradation in the rumen which will help ensure feed intake is maximised. For lambs in New Zealand the recommendation for perennial ryegrass dominant pastures is having the grazed pastures no lower than 5cm in height and ensuring pasture height does not exceed 8cm prior to grazing to maintain diet quality (Kenyon & Webby, 2007).

Energy intake or more specifically, metabolisable energy intake is the key impetus of nutrition for growth with forage-grazing ruminant animals. There are times of the year when climatic conditions mean that the growth of pasture is insufficient to meet animal requirements, or the quality of the pasture is reduced, and this can impede metabolizable energy intake. Options to overcome a feed deficit include removing excess animals from the farm to reduce the demand for pasture or using supplementary feeds. Supplementary feeds and alternative forage species that provide sufficient dry matter when pasture is limiting can be used to overcome seasonal quality effects and maintain or improve the energy intake for growing animals.

Forages used for lamb finishing can be categorised into grasses, legumes, herbs and brassicas. Furthermore, forage plants are classified as monocotyledon or dicotyledon which differ in anatomical structure and arrangement of fibres; these create differences in rumen fermentation patterns (Hejcmanová et al., 2020; Merchen & Bourquin, 1994). In general, dicotyledonous species show greater digestibility of dry matter (Ramirez et al., 1997).

Forages alternative to perennial ryegrass such as chicory (*Cichorium intybus*), lucerne (*Medicago sativa*), plantain (*Plantago lanceolata*) and the brassica species (*Brassicaceae*) have all been investigated for improving animal growth and generally result in faster growth rates compared to a ryegrass-based pasture allowing for greater carcass weight production per hectare (Kemp et al., 2010; Kenyon et al., 2017; Somasiri et al., 2015, 2016). The faster growth with alternative forages is a consequence of several interacting factors including greater digestibility, faster rumen degradation, a composition that allows for better nutrient utilisation and an improved grazing capacity for a greater feed intake. The greater feed intake and nutrient density of alternative forages have the potential for achieving energy intakes that exceed the requirements for growth and so, attain a physiological state in the animal that encourages fat deposition, including intramuscular fat (Craigie et al 2017; Ye, Schreurs et al., 2020).

For New Zealand pasture species that are drought resistant or recover more rapidly following dry periods have been recommended to replace the traditional ryegrass/white clover pasture in certain regions (Stewart et al., 2022). These are used as a single species or mixed swards and are now an integral part of sustainable farm management (Young et al., 1994). The development of pastoral systems based on the use of forage species with higher feeding value than ryegrass based pastures has the potential to increase the growth rates and productivity of lamb (Golding et al., 2011).

### 2.6.1 Growth rates of lambs on grasses compared to alternative forages

Perennial ryegrass (*Lolium perenne*) establishes quickly, is highly competitive and is tolerant of treading damage and hard grazing. Perennial ryegrass is winter-active grass (12% of annual DM production) with a flush of production in early spring (40% of annual production). Growth is poor in hot, dry summers but recovery in autumn is rapid (Kemp et al., 2010). Lambs fed perennial ryegrass dominant pasture have growth rates that are generally slower than that of lambs fed other forages because nutrient supply and intake is sub-optimal for maximising growth (Fraser & Rowarth, 1996). In summer the liveweight gains of lambs grazing perennial ryegrass-based pastures are typically 80–150 g/day (Golding et al., 2011) although resown or improved swards of perennial ryegrass that contain clovers are associated with lamb growth rates of 150–250 g/day (Kemp et al., 2010). Kerr (2000) suggested that an ME content of at least 11 MJ/kg DM is required to sustain high lamb growth rates and perennial ryegrass swards drop below this threshold in late summer- early autumn.

Chicory is considered a good quality grazing forage, where lambs achieve growth rates of 150–300 g/day and in general is considered to provide lamb growth rates that are 30% faster than those of perennial ryegrass (Barry, 1998; Golding et al., 2011; Somasiri et al., 2013).

Brassica forage crops are a widely used form of supplementary feed throughout New Zealand. They are used for additional winter feed or as a summer feed in areas which experience drought conditions (Lindsay et al., 2007). Forage rape (*Brassica napus ssp. biennis*) is sown in spring and used in late spring–early summer, when pasture quality is declining markedly (Speijers et al., 2004). Forage rape is highly digestible, but intake of forage, and metabolisable energy (ME) can be constrained by the high water content of the crop (Dove & Milne, 2006). Despite a high concentration of available energy and adequate nitrogen, brassicas have given variable responses in growth rates of sheep (Reid et al., 1994). Hybrid leafy turnips (*Brassica rapa; syn. B. campestris*) have become popular, for lamb finishing over the summer/early autumn months (C. L. Lindsay et al., 2007). They have a higher percentage of leaf than other brassica crops, and have the ability to regrow and be grazed repeatedly within a single season (Lindsay et al., 2007). Campbell et al., (2011) and Lindsay et al., (2007) both found that lamb growth rates on leafy turnips were higher than on new pasture at approximately 320–320 g/day. Some

of the variability in growth rates of animals grazing brassicas can be attributed to the toxic consequences of ingestion of S-methyl cysteine sulphoxide (SMCO) from the forage rape (Dove & Milne, 2006). The presence of these metabolic inhibitors can affect animal health and reduce gains in cattle and sheep (Reid et al., 1994).

## 2.7 Effects of forage finishing diet on carcass and meat quality characteristics

### 2.7.1 Carcass characteristics

Finishing diets can influence the age and weight of an animal at slaughter as well as the composition of fat and muscle (Purchas et al., 1989). The diet can influence meat quality attributes such as tenderness, colour, juiciness and nutritive value. These effects can be directly on the meat or indirectly through factors such as growth rate and carcass fatness (Purchas et al., 1989).

In New Zealand, it is becoming increasingly common to finish lambs on alternative forages over summer when the quality of perennial ryegrass declines (White & Hodgson, 1999). These alternative forages offer superior feeding value due to the dry matter yield and chemical composition providing for higher intakes and greater growth rates (Kemp et al., 2010) Lambs grazed on alternative forages, such as herbs, brassicas and legumes produced heavier and fatter carcasses than lambs grazed on perennial ryegrass based pastures (Table 2.3). Dressing out percentages also increase when lambs graze alternative forages during summer, as rumen fill is reduced due to the increased digestibility and rumen outflow of alternative forages compared to perennial ryegrass based pasture (Waghorn et al., 2007).

**Table 2.3: Hot carcass weight (HCW, kg), dressing out percentage (DO%) and GR depth (mm) of lambs finished on ryegrass based pasture, herbs, brassicas or legume based pastures**

Reference	Origin		Treatment	HCW (kg)	DO %	GR (mm)
<b>Ryegrass based pasture</b>						
Campbell et al. (2011)	NZ	Ewe lamb	Perennial Ryegrass	15.4		
Campbell et al. (2011)	NZ	Ram lamb	Perennial Ryegrass	15.8		
Schreurs et al. (2013)	NZ	Ram lamb	Perennial Ryegrass	15.2		3.9
Hopkins et al. (1995a)	Aus	Cryptorchid lamb	Irrigated pasture, Slaughter 1	21.2	41.6	
Hopkins et al. (1995a)	Aus	Cryptorchid lamb	Irrigated pasture, Slaughter 2	18.5	42.8	
Fraser et al. (1996)	NZ	Year 1	Ryegrass	15.6	45.2	7.2
Fraser et al. (1996)	NZ	Year 2	Ryegrass	14.6		4.7
Fraser et al. (1996)	NZ	Year 3	Ryegrass	18.4		9.9
Kim et al. (2013)	NZ		Ryegrass	18.6		
Elmes (2013) Exp 1	NZ	Ewe lamb	Ryegrass	19.8	44.4	9.0
Elmes (2013) Exp 1	NZ	Ram lamb	Ryegrass	19.83	42.94	4.91
Elmes (2013) Exp 2	NZ	MS <sup>1</sup> lamb	Ryegrass	19.4	43.2	6.1
Ye et al. (2020)	NZ	Ewe lamb	Ryegrass/Clover	16.7		8.1
Ye et al. (2020)	NZ	Wether lamb	Ryegrass/Clover	17.1		7.2
<b>Herbs</b>						
Campbell et al. (2011)	NZ	Ewe lamb	Plantain	15.3		
Campbell et al. (2011)	NZ	Ram lamb	Plantain	15.1		
Schreurs et al. (2013)	NZ	Ram lamb	Chicory herbage mix	18.9		8.8
Schreurs et al. (2013)	NZ	Ram lamb	Plantain herbage mix	18.8		8.1
Hopkins et al. (1995b)	Aus	Cryptorchid lamb	Chicory	22.0		12.4
Fraser et al. (1996)	NZ	Year 1	Chicory	18.3	47.9	9.8
Fraser et al. (1996)	NZ	Year 2	Chicory	20.8		12.4
Fraser et al. (1996)	NZ	Year 3	Chicory	26		17.8
Fraser et al. (1996)	NZ	Year 1	Plantain	16.8	47.9	8.4
Fraser et al. (1996)	NZ	Year 2	Plantain	14.1		5.6
Fraser et al. (1996)	NZ	Year 3	Plantain	17.1		8.3
Kim et al. (2013)	NZ		Chicory	25.4		
Kim et al. (2013)	NZ		Plantain	19.5		
De Brito et al. (2016)	Aus		Chicory/Arrowleaf Clover	25.1	54.7	13.6
Elmes (2013) Exp 1	NZ	Ewe lamb	Chicory	21.7	47.6	10.6
Ye et al. (2020)	NZ	Ewe lamb	Chicory	18.0		7.8
Ye et al. (2020)	NZ	Wether lamb	Chicory	18.1		7.8
<b>Brassicas</b>						
Campbell et al. (2011)	NZ	Ewe lamb	Forage Rape (Goliath)	17.6		
Campbell et al. (2011)	NZ	Ram lamb	Forage Rape (Goliath)	17.3		
Campbell et al. (2011)	NZ	Ewe lamb	Forage Rape (Winfred)	17.0		
Campbell et al. (2011)	NZ	Ram lamb	Forage Rape (Winfred)	17.7		

Campbell et al. (2011)	NZ	Ewe lamb	Turnip	15.8		
Campbell et al. (2011)	NZ	Ram lamb	Turnip	17.8		
Campbell et al. (2011)	NZ	Ewe lamb	Radish	17.1		
Campbell et al. (2011)	NZ	Ram lamb	Radish	13.9		
Hopkins et al. (1995a)	Aus	Cryptorchid lamb	Forage rape, Slaughter 1	25.4	46.8	14.8
Hopkins et al. (1995a)	Aus	Cryptorchid lamb	Forage rape, Slaughter 2	20.7	46.5	12.6
De Brito et al. (2016)	Aus		Forage Rape	23.5	51.5	12.7
Elmes (2013) Exp 1	NZ	Ewe lamb	Forage rape (Spitfire)	22.3	48.1	13.6
Elmes (2013) Exp 1	NZ	Ewe lamb	Forage rape (Titan)	22.7	48.3	14.1
Elmes (2013) Exp 1	NZ	Ram lamb	Forage rape (Spitfire)	23.01	46.34	9.15
Elmes (2013) Exp 1	NZ	Ram lamb	Forage rape (Titan)	22.69	46.73	10.66
Elmes (2013) Exp 2	NZ	MS <sup>3</sup> lamb	Forage rape (Titan)	22.6	47.7	12
<b>Legumes</b>						
Campbell et al. (2011)	NZ	Ewe lamb	Red Clover	15.3		
Campbell et al. (2011)	NZ	Ram lamb	Red Clover	16.8		
Hopkins et al. (1995b)	Aus	Cryptorchid lamb	Lucerne	21.8		12.4
Fraser et al. (1996)	NZ	Year 1	White Clover	20.1	48.3	10.8
Fraser et al. (1996)	NZ	Year 2	White Clover	23.4		16.4
Fraser et al. (1996)	NZ	Year 3	White Clover	25.1		17.5
Fraser et al. (1996)	NZ	Year 2	Lotus	19.3		12.0
Fraser et al. (1996)	NZ	Year 3	Lotus	25.9		17.7
Kim et al. (2013)	NZ		Red Clover	22		
Kim et al. (2013)	NZ		Lucerne	23.4		
De Brito et al. (2016)	Aus		Bladder Clover	21.7	49.2	9.0
De Brito et al. (2016)	Aus		Lucerne/Phalaris	22.1	51.3	9.9
De Brito et al. (2016)	Aus		Lucerne	24.9	54.7	13.5
Elmes (2013) Exp 1	NZ	Ewe lamb	Lucerne	18.4	44.7	6.9
Elmes (2013) Exp 1	NZ	Ram lamb	Lucerne	20.79	44.73	6.69
Elmes (2013) Exp 2	NZ	MS <sup>3</sup> lamb	Lucerne	18.7	44.1	5.3
Ye et al. (2020)	NZ	Ewe lamb	Red Clover	17.7		9.0
Ye et al. (2020)	NZ	Wether lamb	Red Clover	17.9		8.0

<sup>3</sup>Mixed sex

Some Australasian studies investigating forage diets on animal performance have extended their research to include forage effects on meat quality characteristics (Campbell et al., 2011; Fraser et al., 1996; Kim et al., 2013; Schreurs et al., 2013). The meat quality characteristics discussed in this section include ultimate pH, colour, tenderness, water holding capacity and fatty acid composition.

### 2.7.2 Ultimate pH

Alternative finishing diets to perennial ryegrass have resulted in lower pH values in some studies (Fraser et al., 1996; Hopkins, Beattie, et al., 1995; Kim et al., 2013). This effect has not been consistent across all studies, with some showing no difference between forage treatments (Hopkins, Holst, et al., 1995; Schreurs et al., 2013) (Table 2.4).

Contrary to the other studies, Campbell *et al.*, (2011) reported that ram lambs fed radish and red clover had higher pH values than lambs fed perennial ryegrass, forage rape and plantain, but were no different to lambs fed turnips. The radish fed lambs had lower carcass weights and lost weight throughout the study, thus it was suggested that they experienced nutritional stress, leading to a higher pH. Poor quality forages can contribute to nutritional stress which results in lower muscle glycogen stores and a higher pH. De Brito *et al.*, (2016) reported that lucerne and phalaris fed lambs had the highest pH, and this treatment had the lowest levels of metabolisable energy and crude protein, and the highest levels of neutral detergent fibre, indicating poor feed quality.

Although there were statistically significant differences between forage treatments, the biological difference is likely to be negligible as all were within the acceptable pH threshold of below 5.8–6.0. Although the literature suggests some differences in ultimate pH for lambs on different forage diets, but when all factors are considered the forage diet is not a strong driver of ultimate pH and it is likely to be other factors such as transport or yarding stress that are likely to be more influential.

**Table 2.4: Ultimate pH of meat from lambs finished on ryegrass-based pasture, herbs, brassicas or legume based pastures**

Reference	Origin		Treatment	Ultimate pH
<b>Ryegrass based pasture</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Perennial Ryegrass	5.62
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Perennial Ryegrass	5.61
Schreurs <i>et al.</i> (2013)	NZ	Ram lamb	Perennial Ryegrass	5.83
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, LL <sup>1</sup>	Irrigated pasture	5.58
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, SM <sup>2</sup>	Irrigated pasture	5.51
Fraser <i>et al.</i> (1996)	NZ		Ryegrass	5.97
Kim <i>et al.</i> (2013)	NZ		Ryegrass	5.8
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Ryegrass/Clover	5.47
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Ryegrass/Clover	5.43
<b>Herbs</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Plantain	5.61
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Plantain	5.57
Schreurs <i>et al.</i> (2013)	NZ	Ram lamb	Chicory herbage mix	5.84
Schreurs <i>et al.</i> (2013)	NZ	Ram lamb	Plantain herbage mix	5.82
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid lamb	Chicory	5.56
Fraser <i>et al.</i> (1996)	NZ		Chicory	5.75
Fraser <i>et al.</i> (1996)	NZ		Plantain	5.89
Kim <i>et al.</i> (2013)	NZ		Chicory	5.68
Kim <i>et al.</i> (2013)	NZ		Plantain	5.71
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, LL <sup>1</sup>	Chicory/Arrowleaf Clover	5.57
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, SM <sup>2</sup>	Chicory/Arrowleaf Clover	5.71
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Chicory	5.40
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Chicory	5.41
<b>Brassicas</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Forage Rape (Goliath)	5.58
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Forage Rape (Goliath)	5.61
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Forage Rape (Winfred)	5.59
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Turnip	5.64
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Turnip	5.64
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Radish	5.64
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Radish	5.68
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, LL <sup>1</sup>	Forage rape	5.49
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, SM <sup>2</sup>	Forage rape	5.45
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, LL <sup>1</sup>	Forage Rape	5.61
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, SM <sup>2</sup>	Forage Rape	5.76
<b>Legumes</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Red Clover	5.58
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Red Clover	5.66
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid lamb	Lucerne	5.56

Fraser <i>et al.</i> (1996)	NZ		White Clover	5.66
Fraser <i>et al.</i> (1996)	NZ		Lotus	5.72
Kim <i>et al.</i> (2013)	NZ		Red Clover	5.74
Kim <i>et al.</i> (2013)	NZ		Lucerne	5.73
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, LL <sup>1</sup>	Bladder Clover	5.62
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, LL <sup>1</sup>	Lucerne/Phalaris	5.63
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, LL <sup>1</sup>	Lucerne	5.59
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, SM <sup>2</sup>	Bladder Clover	5.70
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, SM <sup>2</sup>	Lucerne + Phalaris	5.72
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb, SM <sup>2</sup>	Lucerne	5.71
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Red Clover	5.39
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Red Clover	5.43

<sup>1</sup>Longissimus lumborum muscle, <sup>2</sup>Semimembranosus muscle, <sup>3</sup>Mixed sex

### 2.7.3 Meat colour

Different forage diets have been shown to have minimal impact on meat colour measures (De Brito *et al.*, 2016; Hopkins, Holst, *et al.*, 1995; Schreurs *et al.*, 2013) (Table 2.5), but can have an effect on colour stability over time (Campbell *et al.*, 2011; Kim *et al.*, 2013). Generally, forage treatment has shown to have little effect on the lightness (L\*) of meat, with diet related differences in the L\* being found between concentrate fed and pasture fed lambs, with concentrate fed lambs having lighter and redder meat (Priolo *et al.*, 2001; Zhang *et al.*, 2022).

In Elmes (2013) first experiment, ram lambs on forage rape (Spitfire) had redder (a\*) meat than other treatments. Ewe lambs showed small objective differences in lightness, having darker meat on lucerne and chicory than other treatments. Ram lambs had darker meat on lucerne and pasture compared to rape. This difference was also reported by Elmes (2013) second experiment and by Hopkins, Beattie *et al.*, (1995), where lambs fed rape had lighter meat than those fed irrigated ryegrass. As with the pH difference, Hopkins, Beattie *et al.*, (1995) suggested that the lighter meat from lambs grazed on rape was due to the heavier and fatter carcasses chilling more slowly. Additionally, an increase in carcass fat has been attributed to an increase in intramuscular fat in the loin (McPhee *et al.*, 2008). This intramuscular fat dilutes muscle fibres, therefore diluting myoglobin (Priolo *et al.*, 2001). Despite being statistically significant, these differences in chroma meter values would not be large enough for a visually observable colour difference.

Kim *et al.*, (2013) and Campbell *et al.*, (2011) carried out colour stability experiments over a 7 day period to establish whether a lambs finishing diet would impact the meat colour degradation over time. Both found that there were significant differences in redness values by the end of the display

period, with lucerne and red clover showing greater colour instability and had browner meat as a result. Ryegrass and plantain, on the other hand, showed the greatest stability over time. Kim *et al.*, (2013) also measured hue angle and chroma values, and found the loins from the lambs grazed on lucerne had the most rapid surface deterioration and least colour intensity, followed closely by chicory. Lambs finished on ryegrass had the lowest hue angle value indicating the least discolouration and superior colour stability. Sensory colour data supported these results, with ryegrass and plantain having the lowest discolouration score at Day 4.

The greater instability of the meat from lambs grazing red clover and lucerne could possibly be attributed to both forages being legumes. Lambs grazed on forage legumes have previously been reported to have a higher proportion of unsaturated to saturated fatty acids (Fraser *et al.*, 2004). This may contribute to oxidative instability by inducing oxymyoglobin to form metmyoglobin, causing an undesirable brown colour (Kim *et al.*, 2013).

**Table 2.5: Colour (lightness (L\*), redness (a\*) and yellowness (b\*)) of meat from lambs that have grazed ryegrass-based pasture, herbs, brassicas or legumes**

Reference	Origin		Treatment	Lightness (L*)	Redness (a*)	Yellowness (b*)
<b>Ryegrass based pasture</b>						
Campbell <i>et al.</i> (2011)	NZ	Day 1	Perennial Ryegrass	41.4	21.1	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Perennial Ryegrass		20.2	
Campbell <i>et al.</i> (2011)	NZ	Day 4	Perennial Ryegrass		19	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Perennial Ryegrass		15.3	
Kim <i>et al.</i> (2013)	NZ	Day 1	Ryegrass	39.2	25.7	
Kim <i>et al.</i> (2013)	NZ	Day 4	Ryegrass	38.2	17.1	
Kim <i>et al.</i> (2013)	NZ	Day 7	Ryegrass	39	9.5	
Schreurs <i>et al.</i> (2013)	NZ	Ram Lamb	Perennial Ryegrass	40.9	14.8	
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid Lamb, LL <sup>1</sup>	Irrigated pasture	35.14	15.03	8.13
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid Lamb, SM <sup>2</sup>	Irrigated pasture	31.03	15.72	8.8
Elmes (2013) Exp 1	NZ	Ewe Lamb	Ryegrass	41.53	16.04	
Elmes (2013) Exp 1	NZ	Ram Lamb	Ryegrass	39.39	13.8	10.37
Elmes (2013) Exp 2	NZ	MS <sup>3</sup> lamb	Ryegrass	41.42	15.25	11.7
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Ryegrass/clover	41.6	13.5	3.1
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Ryegrass/clover	42.1	13.3	3.8
<b>Herbs</b>						
Campbell <i>et al.</i> (2011)	NZ	Day 1	Plantain	41.6	22.2	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Plantain		21.3	
Campbell <i>et al.</i> (2011)	NZ	Day 4	Plantain		19.7	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Plantain		16.4	
Kim <i>et al.</i> (2013)	NZ	Day 1	Chicory	39.6	25.4	
Kim <i>et al.</i> (2013)	NZ	Day 4	Chicory	38.7	12.8	
Kim <i>et al.</i> (2013)	NZ	Day 7	Chicory	41.6	6.5	
Kim <i>et al.</i> (2013)	NZ	Day 1	Plantain	39.5	25.5	
Kim <i>et al.</i> (2013)	NZ	Day 4	Plantain	39	17.5	
Kim <i>et al.</i> (2013)	NZ	Day 7	Plantain	41	8.6	
Schreurs <i>et al.</i> (2013)	NZ	Ram Lamb	Chicory herbage mix	40.9	14.7	
Schreurs <i>et al.</i> (2013)	NZ	Ram Lamb	Plantain herbage mix	41.6	15.3	
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid Lamb	Chicory	36.2	14.2	7.0
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid Lamb	Chicory/Arrowleaf Clover	38.9	15.8	1.5
Elmes (2013) Exp 1	NZ	Ewe Lamb	Chicory	40.89	14.85	
Ye <i>et al.</i> (2020)	NZ	Ewe Lamb	Chicory	41.2	14.0	3.2
Ye <i>et al.</i> (2020)	NZ	Wether Lamb	Chicory	42.1	13.4	3.0
<b>Brassicas</b>						
Campbell <i>et al.</i> (2011)	NZ	Day 1	Forage Rape (Goliath)	41.0	20.9	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Forage Rape (Goliath)		20.3	
Campbell <i>et al.</i> (2011)	NZ	Day 4	Forage Rape (Goliath)		19.1	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Forage Rape (Goliath)		16	
Campbell <i>et al.</i> (2011)	NZ	Day 1	Forage Rape (Winfred)	41.1	21.1	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Forage Rape (Winfred)		20.2	
Campbell <i>et al.</i> (2011)	NZ	Day 4	Forage Rape (Winfred)		18.8	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Forage Rape (Winfred)		15.5	
Campbell <i>et al.</i> (2011)	NZ	Day 1	Turnip	40.8	21.2	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Turnip		20.5	
Campbell <i>et al.</i> (2011)	NZ	Day 4	Turnip		19.1	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Turnip		15.9	
Campbell <i>et al.</i> (2011)	NZ	Day 1	Radish	41.5	20.7	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Radish		20.7	

Campbell <i>et al.</i> (2011)	NZ	Day 4	Radish		19.3	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Radish		15.8	
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid Lamb, LL <sup>1</sup>	Forage rape	37.08	15.19	8.87
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid Lamb, SM <sup>2</sup>	Forage rape	33.39	14.86	8.79
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid Lambs	Forage Rape	37.2	16.0	1.1
Elmes (2013) Exp 1	NZ	Ewe Lambs	Forage rape (Spitfire)	41.36	15.34	
Elmes (2013) Exp 1	NZ	Ewe Lambs	Forage rape (Titan)	41.87	15.27	
Elmes (2013) Exp 1	NZ	Ram Lambs	Forage rape (Spitfire)	42.54	15.02	12.17
Elmes (2013) Exp 1	NZ	Ram Lambs	Forage rape (Titan)	41.16	14.19	11.39
Elmes (2013) Exp 2	NZ	Mixed	Forage rape (Titan)	42.02	14.69	11.78
<b>Legumes</b>						
Campbell <i>et al.</i> (2011)	NZ	Day 1	Red Clover	40.8	21.3	
Campbell <i>et al.</i> (2011)	NZ	Day 2	Red Clover		20.5	
Campbell <i>et al.</i> (2011)	NZ	Day 4	Red Clover		19	
Campbell <i>et al.</i> (2011)	NZ	Day 7	Red Clover		13.2	
Kim <i>et al.</i> (2013)	NZ	Day 1	Red Clover	41.4	27.0	
Kim <i>et al.</i> (2013)	NZ	Day 4	Red Clover	40.4	14.0	
Kim <i>et al.</i> (2013)	NZ	Day 7	Red Clover	41.6	7.4	
Kim <i>et al.</i> (2013)	NZ	Day 1	Lucerne	39.8	24.8	
Kim <i>et al.</i> (2013)	NZ	Day 4	Lucerne	39.8	10.9	
Kim <i>et al.</i> (2013)	NZ	Day 7	Lucerne	41.9	6.3	
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid	Lucerne	36.8	14.1	6.9
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid	Bladder Clover	38.0	15.5	1.2
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid	Lucerne/Phalaris	38.0	15.9	1.6
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid	Lucerne	38.5	15.2	1.2
Elmes (2013) Exp 1	NZ	Ewe lamb	Lucerne	40.96	15.28	
Elmes (2013) Exp 1	NZ	Ram lamb	Lucerne	38.93	14.05	10.09
Elmes (2013) Exp 2	NZ	MS lamb	Lucerne	40.93	15.14	11.46
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Red Clover	41.8	14.1	3.5
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Red Clover	42.7	14.6	4.1

<sup>1</sup>Longissimus lumborum muscle, <sup>2</sup>Semimembranosus muscle, <sup>3</sup>Mixed sex

#### 2.7.4 Tenderness

Forage effects on meat tenderness are usually minimal (Table 2.6) and are exerted through altering growth rates and thus animal age or weight at slaughter (Purchas *et al.*, 1989). Most studies found no significant differences between forage treatments for shear force values (Campbell *et al.*, 2011; De Brito *et al.*, 2016; Hopkins, Beattie, *et al.*, 1995; Hopkins, Holst, *et al.*, 1995). Campbell *et al.*, (2011) extended their research to include sensory testing and reported no significant effects of forage treatment on any of the eating quality measurements. Schreurs *et al.*, (2013) reported more tender meat from lambs grazing a plantain herbage mix and a chicory herbage mix compared to perennial ryegrass. Similarly, Elmes (2013) reported more tender meat from lambs grazed on forage rape and lucerne compared to ryegrass. The lambs grazing these alternative forages had heavier carcasses and higher levels of fatness (via GR). Higher carcass fatness is attributed to higher levels of IMF (McPhee *et al.*, 2008), which could have explained the increased tenderness of the meat from these lambs.

However, both studies still found differences between some treatments despite adjusting for intrinsic factors than can affect tenderness such as pH and GR. Other drivers that may impact shear force values are diet induced differences in collagen concentration and solubility (Mashele et al., 2017) however these were not measured in these studies. Elmes (2013) included sensory panel testing and no difference in tenderness was reported by the consumers. In beef cattle, including summer bulb turnips as 50% or 70% of the diet during summer, reduced shear force values compared to the control diet of pasture plus concentrate. However, like the lamb studies no differences in tenderness were detected by a sensory panel (Rodríguez-Pereira et al., 2025)

Despite reported differences in measured shear force in some studies (Table 2.8), with the exception of Campbell *et al.*, (2011) all values were all low (<7kgF) suggesting that the differences are unlikely to be detected as a difference in tenderness by consumers.

Young *et al.*, (1994) carried out a sensory study with lambs grazing 7 forage types. Lambs grazing phalaris (*Phalaris aquatics*) had more tender meat than the other forages tested. However, panellists also reported marked foreign flavours, which resulted in the phalaris treatment having the lowest acceptability. This indicated that the foreign flavour dominated perceptions, rather than tenderness, and suggests it's important to include sensory testing of all novel forage types. When comparing pasture finished lambs to those finished on concentrate, meat from concentrate finished lambs was found to have lower shear force values (Zhang et al., 2022).

**Table 2.6: Shear force of meat from lambs grazing ryegrass-based pasture, herbs, brassicas or legumes**

Reference	Origin	Sex	Treatment	Shear Force (kgF)
<b>Ryegrass based pasture</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Perennial Ryegrass	5.8
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Perennial Ryegrass	9.5
Schreurs <i>et al.</i> (2013)	NZ	Ram lamb	Perennial Ryegrass	3.77
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, LL <sup>1</sup>	Irrigated pasture	3.11
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, SM <sup>2</sup>	Irrigated pasture	4.2
Elmes (2013) Exp 1	NZ	Ewe lamb	Ryegrass	5.25
Elmes (2013) Exp 1	NZ	Ram lamb	Ryegrass	6.31
Elmes (2013) Exp 2	NZ	MS <sup>3</sup> lamb	Ryegrass	5.75
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Ryegrass/clover	2.50
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Ryegrass/clover	2.65
<b>Herbs</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Plantain	7.4
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Plantain	8.1
Schreurs <i>et al.</i> (2013)	NZ	Ram lamb	Chicory herbage mix	3.18
Schreurs <i>et al.</i> (2013)	NZ	Ram lamb	Plantain herbage mix	2.98
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid lamb	Chicory	4.4
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid lamb	Chicory/Arrowleaf Clover	3.50
Elmes (2013) Exp 1	NZ	Ewe lamb	Chicory	4.57
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Chicory	2.69
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Chicory	2.69
<b>Brassicas</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Forage Rape (Goliath)	7.9
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Forage Rape (Goliath)	7.1
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Forage Rape (Winfred)	7.7
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Forage Rape (Winfred)	6.9
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Turnip	6.7
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Turnip	8.2
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Radish	7.3
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Radish	7.3
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, LL <sup>1</sup>	Forage rape	2.47
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, SM <sup>2</sup>	Forage rape	3.73
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid lamb	Forage Rape	3.69
Elmes (2013) Exp 1	NZ	Ewe lamb	Forage rape (Spitfire)	4.47
Elmes (2013) Exp 1	NZ	Ewe lamb	Forage rape (Titan)	4.27
Elmes (2013) Exp 1	NZ	Ram lamb	Forage rape (Spitfire)	5.89
Elmes (2013) Exp 1	NZ	Ram lamb	Forage rape (Titan)	6.03
Elmes (2013) Exp 2	NZ	MS <sup>3</sup> lamb	Forage rape (Titan)	4.57
<b>Legumes</b>				
Campbell <i>et al.</i> (2011)	NZ	Ewe lamb	Red Clover	6.8
Campbell <i>et al.</i> (2011)	NZ	Ram lamb	Red Clover	8.0
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid lamb	Lucerne	4.2
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid lamb	Bladder Clover	3.53
De Brito <i>et al.</i> (2016)	Aus	Cryptorchid lamb	Lucerne/Phalaris	3.70

De Brito <i>et al.</i> (2016)	Aus	Cryptorchid lamb	Lucerne	3.81
Elmes (2013) Exp 1	NZ	Ewe lamb	Lucerne	4.9
Elmes (2013) Exp 1	NZ	Ram lamb	Lucerne	4.37
Elmes (2013) Exp 2	NZ	MS <sup>3</sup> lamb	Lucerne	5.01
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Red Clover	2.54
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Red Clover	2.56

---

<sup>1</sup>*Longissimus lumborum* muscle, <sup>2</sup>*Semimembranous* muscle, <sup>3</sup>Mixed sex

### 2.7.5 Water Holding Capacity

Studies have not found differences in measures of water holding capacity (cooking loss and drip loss) of lambs finished on different forage diets (Table 2.7). This reflects that water holding is generally altered as a consequence of processing factors rather than on farm treatments (Schreurs and Kenyon 2017).

**Table 2.7: Cooking loss and purge loss of meat from lambs finished on ryegrass-based pasture, herbs, brassicas or legumes**

Reference	Origin		Treatment	Cooking Loss (%)	Purge Loss (%)	Drip Loss (48h) (%)
<b>Ryegrass based pasture</b>						
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, LL <sup>1</sup>	Irrigated pasture	34.93		
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, SM <sup>2</sup>	Irrigated pasture	36.63		
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Ryegrass/clover	27.0		2.6
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Ryegrass/clover	29.3		3.1
<b>Herbs</b>						
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid lamb	Chicory	37.1		
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb	Chicory/Arrowleaf Clover	20.0	6.7	
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Chicory	26.8		2.8
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Chicory	29.3		3.1
<b>Brassicas</b>						
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, LL <sup>1</sup>	Forage rape	33.96		
Hopkins <i>et al.</i> (1995a)	Aus	Cryptorchid lamb, SM <sup>2</sup>	Forage rape	36.69		
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb	Hybrid Forage Brassica	20.4	6.0	
<b>Legumes</b>						
Hopkins <i>et al.</i> (1995b)	Aus	Cryptorchid lamb	Lucerne	36.6		
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb	Bladder Clover	20.5	8.1	
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb	Lucerne/Phalaris	21.4	8.2	
De Brito <i>et al.</i> (2016)	Aus	MS <sup>3</sup> lamb	Lucerne	21.2	5.9	
Ye <i>et al.</i> (2020)	NZ	Ewe lamb	Red Clover	27.9		2.9
Ye <i>et al.</i> (2020)	NZ	Wether lamb	Red Clover	26.2		2.7

<sup>1</sup>Longissimus lumborum muscle, <sup>2</sup>Semimembranosus muscle, <sup>3</sup>Mixed sex

### 2.7.6 Intramuscular fat

Intramuscular fat (IMF or marbling) is an important carcass characteristic as it has a positive effect on eating quality with increasing levels of IMF being associated with increasing tenderness, flavour and juiciness (Lambe *et al.*, 2017; Pannier *et al.*, 2014; Phelps *et al.*, 2018). Its role in tenderness and palatability has been summarised in Section 2.4.3.1.

Intramuscular fat levels can be influenced by several factors including sex, castration, liveweight, age and diet (Hopkins *et al.*, 2006; McPhee *et al.*, 2008). Nutritional manipulation of an animal's diet is an effective way to increase IMF deposition and is faster than genetic strategies. Diets containing higher levels of energy such as concentrates or total mixed rations that include grains, oils or seeds are

associated with more intramuscular fat. A meta-analysis by Santos Torres et al., (2024) indicated a total mixed ration diet will produce an IMF in lamb of 4.64% compared to a pasture diet at 3.89%.

In forage-based lamb production systems, lambs generally have a low IMF%. Analysis of 1705 pasture finished lambs identified a mean IMF% of 2.69%, ranging from 0.91 to 6.42% (Craigie et al., 2017). Chicory fed lambs have been shown to have greater IMF deposition in the loin than perennial ryegrass fed lambs (Ye, Schreurs, et al., 2020). Alternative forages that are more digestible and have less fibre can provide a diet that can allow for a greater energy intake that encourages faster growth but also supply energy above growth requirements that can be directed to the deposition of fat. There has been very little work done in New Zealand on the effect of forage diet on IMF%, and not on the range of forage diets commonly grazed by lambs so it would be beneficial to understand the effect alternative forage diets can have on IMF% levels and eating quality.

### 2.7.7 Fatty acid composition of lamb meat

Consumers are becoming increasingly aware of how their food choices affect their health (Fowler et al., 2019), which creates a challenge for red meat producers and processes as consumers look for food options which are high in omega 3 fatty acids and low in saturated fatty acids (SFA). Ruminant meat is naturally high in SFA and low in polyunsaturated fatty acids (PUFA) levels due to the reducing role of rumen bacteria on double bonds, which saturates dietary fatty acids (Wood et al., 2008). However, dietary fat from meat plays an important role in the delivery of key nutrients in the human diet. These include vitamins A, D & E, carotenoids (Scollan et al., 2006), long chain n-3 polyunsaturated fatty acids and conjugated linoleic acid (CLA), of which red meat and dairy products are one of the only sources (McGuire & McGuire, 1999). Fatty acid composition also plays important sensory roles; it determines the firmness/oiliness of the adipose tissue associated to its melting point and the oxidative stability of muscle, which in turn affects flavour and muscle colour (Wood et al., 2008). Monounsaturated fatty acids are characterised by lower melting points than saturated fatty acids, a property that enhances meat flavour, juiciness and tenderness (Hayakawa et al., 2015).

Fatty acid profile and content play an important role in human health, with a diet high in n-3 fatty acid reported to have benefits in health maintenance and disease prevention, including reducing the risk of coronary heart disease (Hu et al., 2001). Conversely, diets high in n-6 PUFA, along with high n-6:n-3 ratios (which are common in modern Western diets) have negative health implications, being linked to diseases such as cardiovascular disease, cancer and inflammatory and autoimmune diseases (Simopoulos, 2008). Fortunately, the nutritional manipulation of animals diets provides a useful strategy to change or improve the fatty acid composition in meat (Howes et al., 2015). Animal production factors other than diet can also affect the fatty acid profile of lamb meat, such as breed, sex and age at slaughter (Diaz et al., 2005). The strategy of diet offers the advantage of being

comparatively quicker than genetic strategies, with heritability estimates for fatty acids being low to moderate (Mortimer et al., 2014).

Ruminants that consume pasture diets have been shown to have a more desirable fatty acid composition than those fed concentrates, and offer potential to be further enhanced by using specific plant species (Howes et al., 2015; Rodríguez-Pereira et al., 2025). Monocotyledon or dicotyledon plants differ in the way they are digested (Hejzmanová et al., 2020; Merchen & Bourquin, 1994) so there is potential for the end products of digestion to be altered and hence these two types of plants could influence the delivery of fatty acid into muscle. However, there is no research to look at impacts of monocot or dicot *per se* but rather, differences forage species are the focus. Forages in general provide high levels of ALA, which is a precursor for PUFA, however levels in forage can vary based on season and maturity of the plant (Dewhurst et al., 2003). Additionally, fatty acids are altered by digestive processes in the rumen meaning levels of forage fatty acids are often not reflected in the meat product (Dierking et al., 2010).

Red clover has been shown to forgo rumen biohydrogenation, which increases the amount of PUFA in animal tissues (Howes et al., 2015). This is due to the protective effects of the polyphenol oxidase (PPO) enzyme (Lee et al., 2004) allowing more ALA to escape biohydrogenation. An Australian study found that forage diets of chicory + arrowleaf clover and brassica increased 18:3 omega-3 ALA in the loin ( $p < 0.05$ ) compared to other forage types (De Brito et al., 2017). This suggests that the ALA provided by these treatments was better digested and absorbed by the animal and fixed in muscles at a higher rate. Other studies comparing composite grass swards to mixed leguminous pastures have found that the legume rich pastures produce significantly higher proportions of linoleic and alpha-linolenic acids in the abomasum and subcutaneous fat but not in the rumen, suggesting greater duodenal flow of PUFA's and reduced lipolysis (Lourenço et al., 2007; Lourenço et al., 2008). Botanically diverse swards are gaining momentum as a more sustainable production system compared to monocultures of perennial ryegrass, with an additional benefit of lambs grazing botanically diverse pastures having meat with a more desirable fatty acid profile (Campidonico et al., 2016; Kliem et al., 2018; Lourenço et al., 2007). This due to increased availability of plant PUFA, whether that be from reduced rumen lipolysis, reduction in biohydrogenation or increased rate of passage through the rumen or a combination of these (Kliem et al., 2025). However, there is large variation in what species are included in botanically diverse pastures and so an understanding of the effect of individual species is also needed. There is limited information available on the effects of alternative forage diets on fatty acid composition of lambs in a New Zealand context, with some novel forage types having no published

information. It is important to investigate these effects in a local context, as abiotic and biotic stresses can impact on the ALA levels in forages (Dewhurst et al., 2001). Understanding the effect of different forage diets on red meat fatty acid composition, in particular n-3 fatty acids would provide an opportunity to differentiate red meat products for discerning markets.

## 2.8 Effects of grazing forages on the fatty acid profile of milk

Section 2.7.7 highlighted the potential of a lamb's diet to influence the fatty acid composition of lamb muscle. Following the same trend, numerous studies on dairy ewes have shown that the diet is the most important factor influencing the milk fatty acid profile and the levels of beneficial fatty acids can be improved through dietary means (Nudda et al., 2014). There is a general agreement in the literature that grazing fresh forages increases milk fat and produces milk with increased levels of polyunsaturated fatty acids compared to milk from ruminants fed conserved feeds or concentrates (Kalač & Samková, 2010; Nudda et al., 2020; Ribeiro et al., 2011). This is mainly due to the high amount of alpha-linolenic acid (ALA) in fresh forage, and this strategy is more effective in sheep than goats (Nudda et al., 2020). The amount of beneficial fatty acids in milk from pasture fed ewes is affected by seasonal pasture availability, quality and composition (Nudda et al., 2014). Young, fresh herbage tends to supply greater concentrations of fatty acids and this is reflected in milk fatty acid composition, with lower levels of PUFA and CLA in bovine milk found over summer where there was a decline in concentrations of fatty acids in forage, which was a reflection of reduced forage quality (Thomson & Poel, 2000). A similar result was found with ewe milk, where concentrations of beneficial fatty acids were highest in late winter to early spring when grass availability was highest and decreased as lactation progressed and pasture availability and quality declined (Nudda et al., 2005).

Feeding fresh clovers or botanically diverse pastures increased n-3 PUFA in bovine milk compared to feeding ryegrass-based pastures despite similar intakes of ALA (Lourenço et al., 2008). In ruminants the conversion of ALA into beneficial fatty acids in milk is limited due to biohydrogenation of ALA in the rumen. Thus, the efficiency of transfer of n-3 PUFA through to the product is typically low (<0.05) (Dewhurst et al., 2003). The increased n-3 PUFA in milk could not always be attributed to increased dietary supply of alpha-linolenic acid (Lourenço et al., 2008). Increased duodenal flow of PUFA was thought to be a result of reduced rumen lipolysis, with literature supporting the role of polyphenoloxidase (in clover) in inhibiting this process (Lee et al., 2004). Botanically diverse forages have been suggested to influence rumen lipolysis via plant secondary metabolites or by altering ruminal microbial population but there is a lack of direct evidence supporting this (Lourenço et al.,

2008). Tannins in *Lotus corniculatus* and *Sulla* reduce biohydrogenation in the rumen via selective inhibition of ruminal bacteria species *Butyrivibrio fibrisolvens* (Min et al., 2003).

In addition to PUFA, dairy products are a key source of beneficial ruminant trans fatty acids (CLA, vaccenic acid, rumenic acid) (Kalač & Samková, 2010), which are products of biohydrogenation of ALA. The amount of these trans-fatty acids in sheep milk tends to be greater than that of other ruminant milk potentially due to grazing behaviours such as preferential selection of legumes by sheep (Nudda et al., 2020).

The changes in milk fatty acid composition indicates the forage diet can influence on the fatty acid composition of products from ruminants. However, milk is harvested daily and this gives opportunity for fatty acids to change in reflection to the diet more easily compared to muscle as it presents a more labile pathway for fatty acids (Doreau et al., 2010; Ribeiro et al., 2011). A change in diet altered the fatty acid profile of milk within two days, and most changes took place within four days after transition (Elgersma et al., 2004).

## 2.9 Effects of grazing forages on volatile compounds in lamb meat

In meat, fatty acids undergo oxidation during the cooking process which form various volatiles compounds such as aldehydes, ketones and alcohols. These volatile compounds are perceived by receptors at the back of the mouth and nose and contribute to the flavour profile of cooked meat (Park & Choi, 2025). With advancing technology, techniques like solid phase microextraction (SPME) in combination with gas chromatography-mass spectrometry (GC-MS) are utilized to analyse and discriminate volatile compound profiles. These modern and efficient techniques make it increasingly easy to compare the volatiles and proteomic profiles of meat and relate this to an animal's background (Ye, Eyres, et al., 2020; Ye et al., 2022) and then to link it to the flavour or eating quality perception of consumers (Pavan et al., 2021).

In meat, the presence of sulphur compounds is strongly diet dependant and is linked to a breakdown of the amino acids cysteine and methionine, which have been reported as part of cooked meat aroma (Frank, Watkins, et al., 2016; Young et al., 2003). Dimethyl sulfide is typically associated with sulfurous, onion, cabbage or cauliflower odours, and dimethyl sulfone has sulfurous or burnt odours (Pavan et al., 2021). Dimethyl sulfone has been linked to an unfavourable "milky" flavour in meat from pasture fed sheep (Young et al., 2003). In the study of Pavan et al., (2021), dimethyl sulfide was detected in greater abundance in chicory fed lambs compared grass fed lambs.

Alcohols, ketones and aldehydes are derived from oxidation of unsaturated fatty acids and their higher abundance is usually associated with higher levels of polyunsaturated fatty acid (PUFA) in meat (Young

et al., 2003). Lipid volatiles are believed to contribute to desirable meat flavour, however increased levels of PUFAs and high levels of oxidation in phospholipids may negatively impact the palatability of cooked meat (Gkarane et al., 2018). These volatiles have high odour thresholds, which reduces their influence on flavour in lipid based foods (Gkarane et al., 2018). The volatile Z-2-penten-1-ol is associated with green and fruity flavours (Pavan et al., 2021). Greater abundance of this compound was detected in meat from 4-month-old, weaned lambs compared to 6-8 month-old lambs (Ye et al., 2020). In 6-8 month old lambs, those fed chicory had higher Z-2-penten-1-ol than grass fed lambs or 12 month old lambs (Pavan et al., 2021). The volatile 1-octen-3-ol arises from the oxidation of C18:2n-6 (Gkarane et al., 2018) and is typically described as having green, mushroom, earthy or oily odours (Pavan et al., 2021). In the study of Pavan et al., (2021) 1-octen-3-ol was more abundant in 4-month-old weaned lambs than 6–8-month-old lambs fed on red clover or grass, but not different to lambs fed chicory.

The volatile 1-hexanol has been associated with green, fruity, oily and fusel flavours (Pavan et al., 2021). Chicory feeding was also found to result in a greater abundance of 1-hexanol in the lamb meat (Pavan et al., 2021). This volatile is negatively correlated with sensory scores from some consumers but positively correlated with sensory scores for others when a cluster analysis was undertaken, suggesting the impact of oxidation and the formation of 1-hexanol is not consistent across all consumers (Pavan et al., 2021). This was also found when lambs that grazed chicory after weaning had higher levels of PUFAs and compounds arising from lipid oxidation (Ye, Eyres, et al., 2020).

Acetone and butyrolacetone are ketones are associated with lipid oxidation in sheep meat. Acetone also, increases over time in storage, regardless of aging method (Li et al., 2021). The increase of acetone in the gas chromatography analytical headspace of sheep meat is also reported to be linked to microbial metabolism during storage (Senter et al., 2000). This volatile is linked to earthy odours, common in dry-aged beef (Li et al., 2021). Differences in ketones between lambs fed different forages is an indicator of the diet to induce or suppress lipid oxidation and microbial activity. In the study of Ye et al., (2020), acetone was less abundant in the gas chromatography analytical headspace of meat from lambs fed chicory compared to lambs fed red clover, mixed pasture or perennial ryegrass.

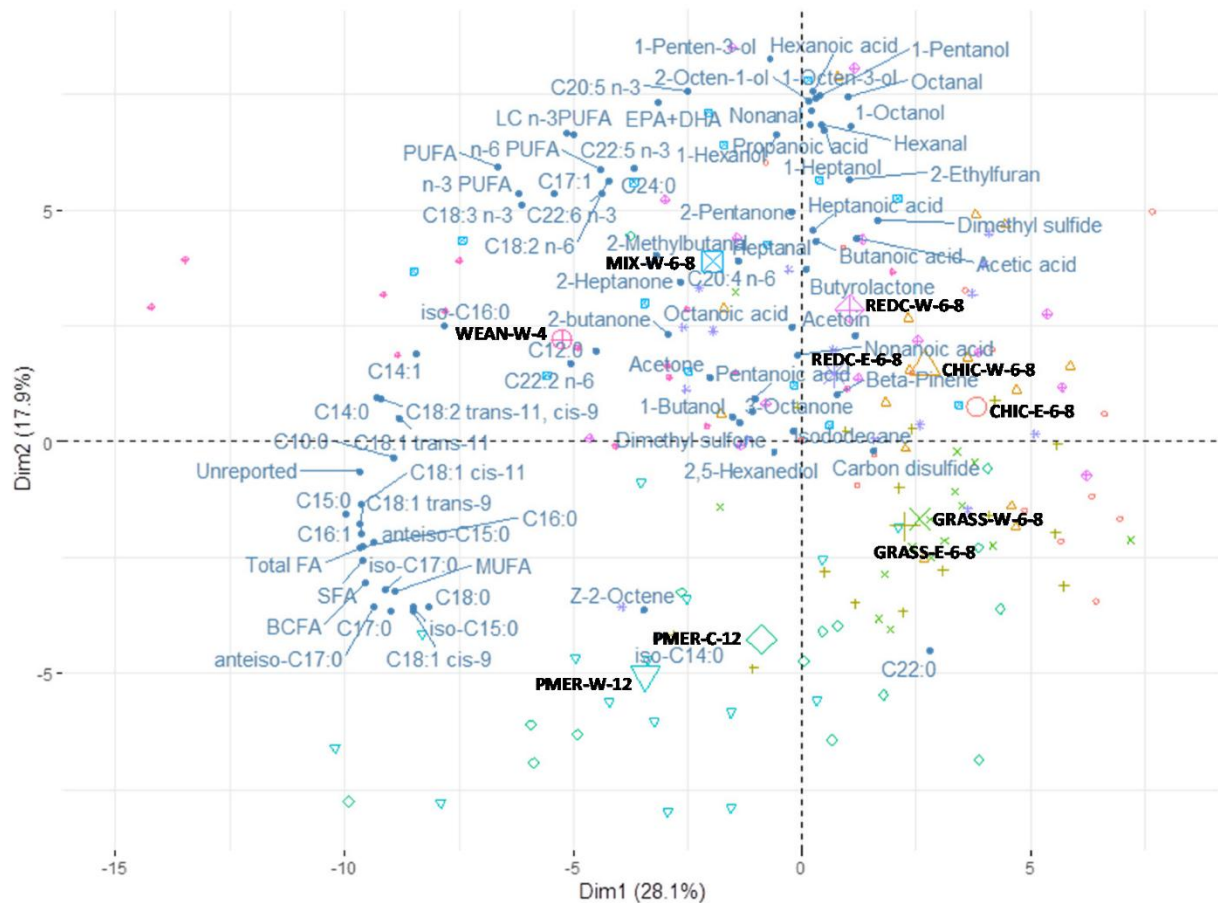
Hydrocarbons are non-lipid volatiles and are influenced by production system via fatty acid profile differences (Ye, Eyres, et al., 2020). Terpenes such as toluene and limonene originate directly from the diet, and toluene is very often detected in lamb tissues (Sivadier et al., 2010). Terpene biosynthesis occurs exclusively in plants, it is used as a marker of lambs having been fed a forage based diet (Vasta & Priolo, 2006).

Aldehydes have been shown to play important roles in the flavour of beef, particularly during cooking (Mottram, 1998). Nonanal is a straight chain aldehyde, which is formed during lipid oxidation and is

used as an indicator of lipid oxidation in meat (Li et al., 2021). It is associated with green, fatty and sweet odours (Calkins & Hodgen, 2007). In beef, flavour-liking scores are positively correlated with nonanal (Li et al., 2021). In lamb, it has been weakly linked to off-flavours (Gkarane et al., 2018). Chicory feeding has been associated with higher abundance of nonanal compared to lambs fed perennial ryegrass (Ye, Eyres, et al., 2020). Frank et al., (2016) found the highest abundance of aldehydes in meat from lambs fed forage rape, and the lowest with lambs fed ryegrass.

In the study of Ye, Eyres et al (2020) lambs fed on chicory, red clover or mixed pasture had a greater overall abundance of meat volatiles and produced distinctive volatile patterns compared with lambs that grazed perennial ryegrass, identified in a principal component analysis (Figure 2.1).

Volatile compounds can be utilised as biomarkers in raw meat products to support traceability of the animals production system (Horcada et al., 2024). Labelling to show country of origin or production system is an important way to build confidence in product authenticity (Bernabéu et al., 2018) and biomarkers are a key way to support this. A recent review identified 53 volatile compounds as potential biomarkers to indicate finishing diet in ruminants at a high level (e.g. fresh forages, conserved forages or concentrates) (Horcada et al., 2024). Currently, knowledge does not extend to using volatile compounds for identifying specific forage species fed and thus this is an area for future research. Differences in relative abundance of key volatile compounds in the headspace of cheeses produced from nutrient-poor pastures compared to nutrient-rich pastures suggest that differences may also be identified when comparing products from different forages (Aprea et al., 2016).



**Figure 2.1: Principal Component Analysis (PCA) overlaying fatty acids and volatiles for samples of meat from lambs that were slaughtered prior to weaning (WEAN) or at 6-8 months of age after grazing chicory (CHIC), perennial ryegrass (GRASS) a pasture mixture (MIX) or red clover (REDC), or were merino labs slaughtered at 12 months of age (MXME). Lambs were also identified by their sex class as either a wether (W), cryptorchid (C) or ewe (E). The PCA identifies distinct fatty acid and volatile patterns for lambs that had grazed different diets (Ye, Eyres et al., 2020).**

## 2.10 Sensory characteristics of lamb from different forages

Eating quality of meat is a combination of meat tenderness, flavour and juiciness (Miller, 2020). Intramuscular fat has been shown to have a positive effect on eating quality, with a recent New Zealand study reporting consumer overall liking of lamb increased significantly as intramuscular fat in the lamb reached 3%, achieving maximum scores at 4% (Realini et al., 2021). In contrast to beef, where tenderness is the most influential attribute on consumer liking, flavour is considered the most important attribute for lamb (Miller, 2020).

Generally research has found no difference in sensory scores when comparing meat from lambs fed different forages including comparisons of Perennial ryegrass, Clovers, Chicory, Brassicas, Lucerne or botanically diverse forages (Campbell et al., 2011; De Brito et al., 2016; Kliem et al., 2025; Scales, 1993). But some studies indicate that meat from lambs fed forage rape has stronger flavour compared to meat from lambs fed perennial ryegrass or lucerne (Elmes, 2013; Hopkins, Beattie, et al., 1995).

Previous research has delivered mixed results when considering the effect of a forage brassica diet on lamb meat. Australian research utilised a trained panel, a consumer panel and volatile data to compare two forage rape cultivars to lucerne and perennial ryegrass and found no evidence of brassica lamb taint and brassica feeding improved sensory properties and consumer liking over perennial ryegrass (Frank, Watkins, et al., 2016).

The same Australasian studies that investigated effect of forage brassica on lamb meat flavour also investigated consumer acceptance, again finding inconsistent results. Frank, Watkins et al., (2016) found that brassica feeding increased consumer liking but, Hopkins et al., (1995) found meat from lambs fed forage rape less acceptable for consumers. Due to the greater lamb growth rates on forage rape compared to perennial ryegrass, the forage rape lambs had significantly greater carcass weights and fat scores so these effects could have been influencing panellist acceptability.

More recent research found a positive relationship between total BCFA's and consumer and sensory scores, where feeding lambs high quality forage rape resulted in greater concentrations of BCFAs in their meat and improved sensory scores over meat from lambs fed perennial ryegrass (Frank, Watkins, et al., 2016). This effect was evident across both Chinese and non-Chinese Australian consumers, suggesting that up to a certain threshold, BCFAs play a role in defining lamb flavour and acceptance for some consumers (Frank, Watkins, et al., 2016).

Finishing lambs on perennial ryegrass dominant pastures was associated with lower sensory scores (less preferential) for tenderness and overall liking by consumers (Pavan et al 2021) but this was more so for New Zealand consumers rather than Chinese consumers (Pavan et al., 2022). In a study comparing the grazing of perennial ryegrass in comparison to forage mixes on both trained panel and consumer sensory evaluations, it was found that the mix containing plantain was associated with lower scores (less preferential) for tenderness and flavour intensity and meat from lambs grazed on forage mixes containing clovers and chicory were equally liked to the meat from lambs that had grazed pure perennial ryegrass swards (Woodmartin et al., 2024).

Although there are some studies out of New Zealand that have looked at forage diet effects on the sensory ranking of lamb meat, the studies are often confounded by uncontrolled factors, such as different ages at slaughter or lack of sufficient replication that result from obtaining meat from commercially finished lambs. Also new forage varieties that have shown agronomic success on-farm need assessing for their impact on meat quality and eating characteristics.

## 2.11 Summary and Research objectives

Product quality for consumers is a strong driver for ensuring market share, maintaining sales and guaranteeing the sustainability of sheep meat production systems. Meat quality for consumers is driven by several factors (Prache et al., 2022) including eating experience and nutritional benefits. Decisions made on-farm can influence carcass composition and meat nutrient composition and therefore impact on the intrinsic properties of meat that define its quality in terms of tenderness, flavour and nutritive value (Watkins et al., 2013; Prache et al., 2022).

On-farm efficiencies for sheep and lamb meat production rely on growing animals fast, reducing feed costs and the time they are on-farm. Forage-based systems of sheep production allow for the use of a feed resource that does not compete with human food sources. However, pasture systems can be limiting for some meat quality and nutritional factors. Research is increasingly identifying alternative forage species that can be grazed by lambs to enhance not only the performance of lambs but also alter the intramuscular fat content of meat producing a more favourable nutritional profile (primarily through fatty acids). This is showing promise as a tool for farmers to follow a consumer-focused approach to their farm management.

Forage grazing can result in advantages for the eating and nutritional quality of sheep meat, although it also carries risks in terms of greater variability in product quality. Additionally, carcass production, per lamb and per hectare are key metrics for productivity of lamb finishing operations, as at this point in time lamb producers are paid for lamb on a yield basis rather than a quality based model. This highlights the research needs for a forage-based sheep meat value chain looking at the carcass production, meat quality, fatty acid profile and sensory characteristics.

As there is a move to consider the influence of alternative forage diets on the growth of lambs for sheep meat there is also opportunity to consider the impact of precision nutrition for lamb finishing on meat quality. There is a need to look at alternatives to perennial ryegrass that maybe limiting in their quantity and balance of nutrients for lamb production at some times of the year. Several forages have been identified as being able to more effectively meet the demands for lamb growth, promote fat deposition and alter the fatty acid profiles of lamb meat so it is more favourable for human health (De Brito et al., 2017, Ye et al., 2020) but more work needs to be done to validate the results with different forages available in New Zealand.

## Research questions

The following research questions were addressed in this PhD thesis:

1. How does the meat quality and fatty acid composition of lamb meat differ between lambs fed alternative forages compared to perennial ryegrass/white clover?
2. How does the summer production of alternative forages effect lamb growth and carcass performance?
3. How much lamb production per hectare can be produced off three forage types over summer?
4. Does the length of time grazing a forage influence the degree of change to meat quality and fat characteristics of lamb meat?
5. Does feeding alternative forages to perennial ryegrass/white clover affect the volatile profile and sensory characteristics of lamb meat?

## Chapter 3

### Experiment 1: Lamb performance during summer when grazing six forage treatments



Lambs on D<sub>1</sub> marked according to treatment replicate

### 3.1 Introduction

New Zealand's sheep production systems are traditionally based on perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) as our climate and soils typically allow for year-round growth of these pastures (Hodgson et al., 2019). Lambing primarily occurs in spring to match the production curve of perennial ryegrass/white clover, with most lambs finished over summer and autumn (Cranston, 2017). Seasonal oscillations, climatic variability and differences in management systems can result in summer pastures with poor nutritional value, particularly within dryland systems (White & Hodgson, 1999). Due to the maturing of perennial ryegrass, summer pasture is characterised by increasing levels of seedhead, stem and dead matter, which in turn increases neutral detergent fibre levels and reduces the crude protein content and organic matter digestibility (White & Hodgson, 1999). The increased fibre content and reduced digestibility restrict intake and affects lambs capacity to achieve their potential for liveweight gain (Nardone et al., 2010). Whilst the white clover component of pastures has a higher feeding value, it is difficult to maintain sufficient percentage of white clover in these swards when lambs are being grazed for finishing (Lindsay et al., 2007).

Alternative forages to perennial ryegrass/white clover can be included in the farm system to provide additional dry matter yield and increased nutritive value at times of year when perennial ryegrass/white clover pasture is not providing sufficient quantity or quality to meet animal demands (Cranston et al., 2015). Additionally, these forages can be used as part of a pasture renovation programme to replace old or damaged pastures with more modern pasture genetics. Improving lamb growth rates is desirable to increase efficiency of lamb production systems, with less energy being partitioned to maintenance reducing the finishing time.

Improved summer live weight gain on alternative forages such as brassicas, herbs and legumes is well documented (Campbell et al., 2011; Fraser et al., 2004; Fraser & Rowarth, 1996; Lindsay et al., 2007; Somasiri et al., 2015). When researching the effects of different forages on lamb performance, carcass weights and dressing out percentages are important to understand, as these directly influence the economic sustainability of a lamb finishers business. There is limited New Zealand data for lamb performance on monoculture swards of alternative forages where replicated farmlet studies are used. Notably, there is no published lamb performance data on Raphanobrassica which was released to the New Zealand market in 2016 (Dumbleton et al., 2021). Studying modern cultivars is important, as over time plant breeders create cultivars with superior agronomic characteristics that in turn improve animal performance. Plantain is a good example of this, where the cultivar Ceres Tonic had higher liveweight gains (222 g/day) than the older cultivar, Grasslands Lancelot (50-141 g/day) due to the reduction in the production of seedhead by Ceres Tonic, and better understanding of optimal grazing management (Fraser & Rowarth, 1996; Moorehead et al., 2002).

Concentrate feeding is used heavily overseas for finishing livestock, particularly in the US where up to 90% of lambs are estimated to be finished on grain (Male, 2012), however the high costs involved limits its use in New Zealand. Energy is often the first limiting nutrient in a perennial ryegrass/white clover based system so it is proposed that the supplementation of perennial ryegrass/white clover with a concentrate could increase energy levels and improve animal performance. The performance of lambs fed perennial ryegrass/white clover supplemented with concentrate has not been compared to the performance of lambs fed alternative summer forages under New Zealand conditions. New Zealand lamb has relatively low intramuscular fat levels (Craigie et al., 2017) and increasing intramuscular fat (IMF) levels in meat is desirable for eating quality of lamb, as increasing levels in meat are associated with increasing flavour, juiciness and tenderness (Lambe et al., 2017; Pannier et al., 2014). Utilising concentrates as a strategy to increase the plane of nutrition and achieve a state of “energy overflow” may encourage the deposition of fat (Hegarty et al., 2006; Hopkins et al., 2007; Schreurs & Kenyon, 2017).

The hypothesis is that grazing lambs on alternative forages to perennial ryegrass/white clover will result in increased animal growth rates and carcass performance over summer. The primary aim of this thesis is to investigate the quality of meat from lambs that had grazed on a range of forages under New Zealand conditions. To support this research, it is important to understand if the forages are impacting animal performance. Farmers are paid for their lambs on carcass weight if sent for slaughter or, liveweight if sold store, so ensuring the forages promote fast growth is important for economic sustainability of lamb finishing operations. The research presented here provided a large scale, replicated study where six forage treatments are compared under the same conditions, to identify the effect that they have on lamb growth and carcass production.

## 3.2 Materials and Methods

### 3.2.1 Experimental Design

This study was located at Massey University's Keeble Farm (40°23'52.6"S 175°35'57.2"E), 5 km Southeast of Palmerston North, Manawatu, New Zealand on a Tokomaru Silt Loam soil. The forage treatments were sown on 25 October 2018 with a roller drill and chain harrows. The animal experiment ran for 65 days, from 18 December 2018 to 20 February 2019. When referring to a day of the study, the day will be written in subscript after the letter D (i.e. day 6 = D<sub>6</sub>). The design involved 6 forage treatments, each replicated 3 times in a random block design (Table 3.1). There was 1.2 hectares of each forage type, split over 3 replicates (0.4 hectares for each treatment replicate) (Figure 3.1). The forage types are all commonly used forages for lamb finishing systems in the Lower North Island. The perennial ryegrass/white clover + concentrate treatment was included in an attempt to increase the metabolisable energy (ME) intake of these lambs compared to the perennial ryegrass/white clover only treatment, hereafter noted as PRG/WC.

### 3.2.2 Forage Treatments

**Table 3.1: Forage species, cultivars, sowing rates and number of lambs used in Farmlet study 1**

Treatment	Cultivar	Sowing Rate (kg/ha)	Lambs per replicate (D <sub>1</sub> )	Lamb Numbers D <sub>1</sub> -D <sub>40</sub>	Lamb Numbers D <sub>41</sub> -D <sub>64</sub> <sup>1</sup>
<b>Chicory</b> ( <i>Chicorium intybus</i> )	Puna II	8	18	54	48
<b>Leafy Turnip</b> ( <i>Brassica rapa</i> ; syn. <i>B. campestris</i> )	HT-LT46	4	18	54	46
<b>Perennial ryegrass</b> ( <i>Lolium perenne</i> ) + <b>white clover</b> ( <i>Trifolium repens</i> )	PRG: Platform AR37 WC: Quartz	20 5	18	54	42
<b>Perennial ryegrass</b> ( <i>Lolium perenne</i> ) + <b>white clover</b> ( <i>Trifolium repens</i> ) + <b>concentrate</b> (D <sub>-4</sub> -D <sub>49</sub> 300g/lamb/day, D <sub>50</sub> -D <sub>64</sub> 500g/lamb/day))	PRG: Platform AR37 WC: Quartz Sheep Nut: Denver Stockfeeds (ME=11.8, CP=12.1%)	20 5	18	54	42
<b>Raphanobrassica</b> ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	Pallaton	8	18	54	50
<b>Red Clover</b> ( <i>Trifolium pratense</i> )	Amigain	12	18 <sup>2</sup>	54	52

<sup>1</sup>Lamb numbers stated here are all lambs grazed on each treatment, including those that did not meet the criteria for slaughter at the conclusion of the study.

<sup>2</sup>18 lambs per replicate were assigned to the Red Clover treatment but due to insufficient dry matter growth of this forage type these lambs did not start grazing their allocated treatment until D<sub>23</sub>.

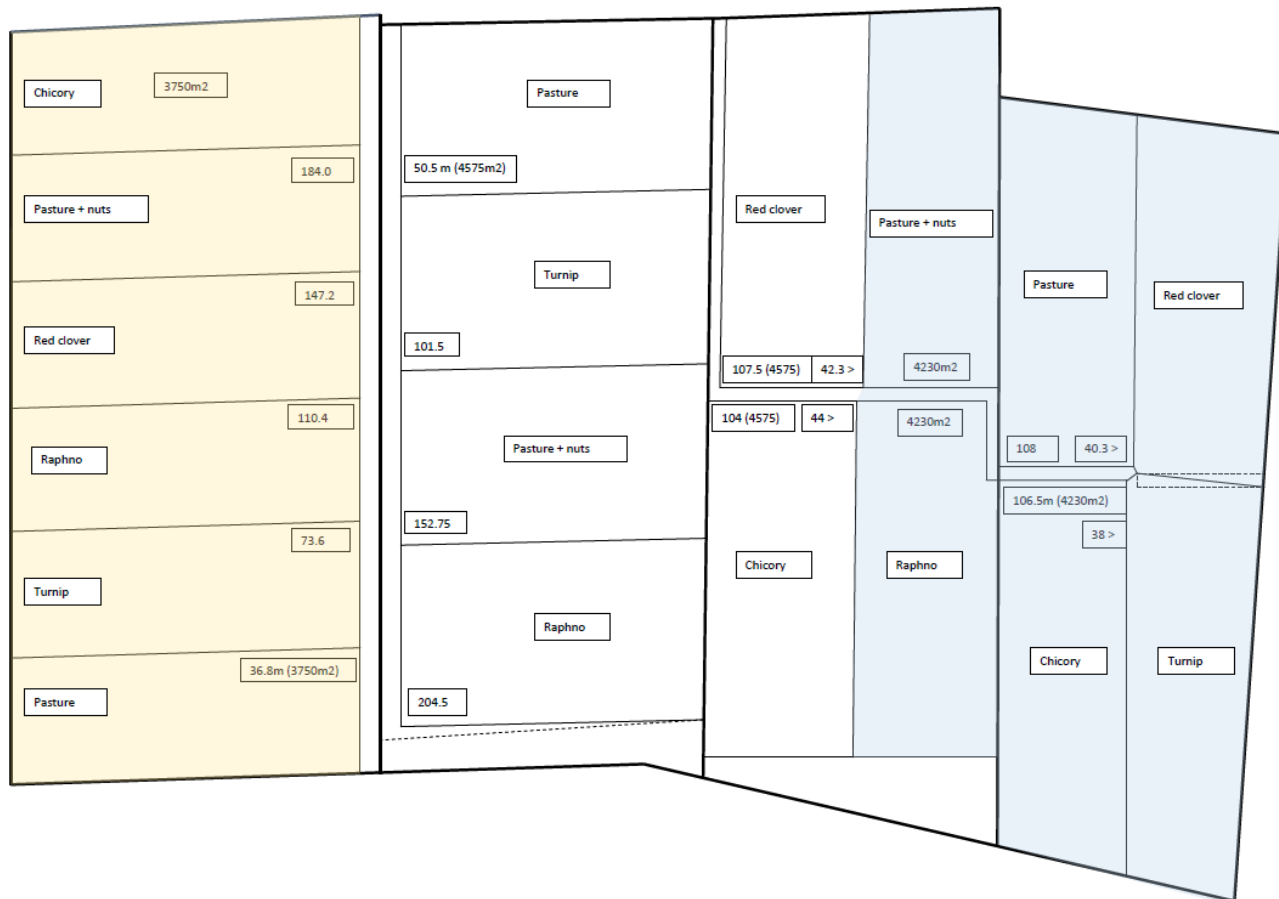


Figure 3.1: Farmlet study 1 trial design. 6 forage treatments: PRG/WC (labelled as Pasture in figure), PRG/WC + concentrate (labelled as Pasture + nuts in figure), Chicory, Red Clover, Leafy Turnip (labelled as Turnip in figure) and Raphanobrassica (labelled as Raphno in figure). Figure details the 3 replicates and area of each treatment within a replicate (replicate 1 = yellow (3750 m<sup>2</sup>), replicate 2 = white (4575 m<sup>2</sup>) and replicate 3 = blue (4230 m<sup>2</sup>)).



**Figure 3.2: Drone picture of Farmlet study 1 at the end of the experiment after a period of dry weather in February 2019. Photo taken as a side view from Replicate 3 end (Replicate 3 Leafy Turnip bottom left corner, Replicate 1 Chicory top right corner)**

### 3.2.3 Animals and Management

All animal procedures were approved by the Massey University Animal Ethics Committee (Protocol No. 18/103).

Three hundred and twenty-four Romney-cross, cryptorchid lambs aged approximately 4 months were utilised for the trial. Lambs were selected from the Massey University Tuapaka farm flock to ensure sufficient lambs with the same breeding and management were available and represented a typical New Zealand lamb for finishing. Lambs were assigned an electronic identification (EID) tag and weighed prior to being allocated to a treatment group. Lambs were balanced for liveweight, resulting in a mean starting liveweight of  $27.7\text{kg} \pm 0.6\text{ kg}$  across the treatment groups, ranging from 22.2 kg to 41.6 kg. Eighteen lambs were allocated to each treatment replicate (18 lambs x 3 replicates x 6 treatments = 324 lambs), which was a stocking rate of 45 lambs/hectare. Once the lambs had been allocated, they were tagged with a coloured Flexi-tag and spray marked in the relevant treatment colour, with a different location on the body depending on which replicate they were assigned to. Replicate 1 had head marks, replicate 2 had rump marks and replicate 3 had shoulder marks to ensure easy identification when drafting.

All lambs were orally drenched with Ancare 'Matrix' triple combination drench (active ingredients abamectin, levamisole and oxfendazole, and 0.5 g/L selenium and 2.2 g/L cobalt) at D<sub>-7</sub>, D<sub>23</sub> and D<sub>51</sub>. All lambs were shorn and vaccinated with Ultravac '7 in 1' vaccine on D<sub>-6</sub>.

Lambs allocated to the 'Perennial ryegrass/white clover + concentrate' treatment were gradually adjusted to the concentrate in the 4 days prior to the trial commencing. They were offered 300 g/lamb/day from D<sub>1</sub> to D<sub>49</sub>. From D<sub>50</sub> to D<sub>64</sub> lambs were offered 500 g/day to help compensate for the reduction of pasture quality.

Lambs were introduced to their herbage treatments on the 18<sup>th</sup> of December 2018 (D<sub>1</sub>). However, the Red Clover treatment and one of the Chicory replicates was slow to establish, and insufficient dry matter was available on D<sub>1</sub> to feed the lambs *ad libitum*. Therefore, from D<sub>1</sub>-D<sub>22</sub>, these lambs were grazed on established perennial ryegrass/white clover pasture in other paddocks neighbouring the trial area. On D<sub>23</sub>, when sufficient herbage was available these lambs began grazing their allocated treatment forages. All lambs were given access to hay for the first seven days to assist with the transition to a different feed type. Unrestricted access to fresh water was always available.

### 3.2.4 Grazing Management

Each treatment replicate was split into four cells (Figure 3.3), and the allocated lambs rotationally grazed the cells throughout the duration of the trial. Each treatment replicate was grazed according to best practice for each forage type, with lambs being shifted approximately weekly, or as they reached the desired post grazing residual, of 1400 kgDM/ha (Morris & Kenyon, 2014). Grazing was managed so that lambs on all treatments had *ad libitum* feed, with herbage allowance two times their predicted daily intake of 1.5 kgDM/day (Kerr, 2000).

On D<sub>41</sub>, when environmental conditions limited herbage growth of some treatments, lamb numbers were reduced to 14 lambs per treatment replicate on the Leafy Turnip, Chicory, Perennial ryegrass/white clover, and Perennial ryegrass/white clover + concentrate treatments.

Forage quality within the replicates was maintained throughout the study by utilising mechanical topping or bringing in additional non-treatment livestock to graze surplus dry matter.

### 3.2.5 Animal Measurements

Unfasted lamb liveweights were recorded on all lambs at D<sub>1</sub>, D<sub>9</sub>, D<sub>16</sub>, D<sub>23</sub>, D<sub>30</sub>, D<sub>37</sub>, D<sub>44</sub>, D<sub>51</sub>, D<sub>58</sub> and D<sub>64</sub>. At D<sub>65</sub> all lambs ≥36kg (n=256) were slaughtered at Alliance Meats Dannevirke, with hot carcass weight measured, and dressing out percentage calculated by dividing the hot carcass weight by the final live weight.

The animal performance data presented in the results is on the 247 lambs that met the requirements for slaughter and had meat samples with accurate identification collected to align with the meat quality data in subsequent chapters.

### 3.2.6 Pasture Measurements

Pre and post grazing herbage cuts were taken to assess herbage mass. Three random quadrat cuts (0.1 m<sup>2</sup> each) were taken to ground level from each cell using an electric shearing handpiece (Frame, 1993) immediately prior to lambs grazing a cell and after being shifted to the next cell. Samples were oven dried (80°C) to a constant weight to estimate pre and post grazing herbage mass (kgDM/ha) of the forages in each cell.

At the beginning and end of the study, three quadrats were cut at random across each treatment replicate mixed together and a 100g subsample taken back to the lab. This was sorted into sown species, broadleaf weeds, grass weeds and dead matter, then oven-dried and weighed to obtain the botanical composition.

Pluck samples were taken from each replicate on the 22<sup>nd</sup> of January (D<sub>35</sub>) and stored frozen at -30°C until analysis. Pluck samples were taken from ungrazed cells within a treatment replicate to a residual height representative of what the lambs were selecting. Forage samples were analysed for: dry matter digestibility (DMD (Roughan and Holland, 1977), crude protein (CP; Dumas' procedure, AOAC method 968.06 using a Leco total combustion method, LECO Corporation, St. Joseph, MI, USA (AOAC, 2007). Acid detergent fibre (ADF) was analysed by a Tecator Fibretec System (Robertson & Van Soest, 1981). Metabolisable energy content of forages was calculated (MJ ME/kg DM = 0.16 × DOMD) using the organic matter digestibility (Roughan & Holland, 1977).

### 3.2.7 Weather data

Weather data was provided by the AgResearch Grasslands site, located 3km from the experimental site. Rainfall was 92% higher in December 2018 than the 10 year average, whilst both January and February were 41% and 45% lower than the 10 year average, respectively. Maximum air temperatures were higher than the 10 year average throughout the study period (Table 3.2).

**Table 3.2: Monthly rainfall (mm), minimum and maximum air temperatures (°C) for the study period and the 10 year average. Data provided by AgResearch Grasslands site, 3km from the experimental site**

	Dec-18	Jan-19	Feb-19
Rainfall (mm)	173	30.8	30
10 year average	90	52	55
Maximum air temp (°C)	22.9	23.7	23.7
10 year average	20.8	22.5	23.3
Minimum air temp (°C)	12.9	15.1	12
10 year average	12.1	12.7	13.3

### 3.2.8 Statistical analysis

All data was tested for normality and outliers using Genstat 24.0 (VSN-International, 2024) before analysis.

Lamb liveweight gain, start and final live weight, carcass weight and dressing out percentage were analysed using a Restricted Maximum Likelihood (REML) variance components analysis in Genstat 24.0 (VSN International, 2024). Each treatment had a different number of lambs (due to the slaughter threshold of 36kg) and thus this model was utilised due to the unbalanced design. The standard error of the mean (SEM) presented where generated using REML and are the average SEM across the treatments (as SE is different for each treatment due to unbalanced design), however variation in the standard errors is less than 5% and so the average is a good approximation.

Forage quality measures, pre and post grazing dry matter yields and botanical composition were analysed using an analysis of variance (ANOVA). Pre and post grazing dry matter yields were averaged by month. Missing values were estimated by the Genstat ANOVA and degrees of freedom adjusted to give an unbiased estimation of treatment means.

The replicates for each forage treatment were analysed as a nested fixed effect as animal within replicate used in the model. The replicate effect for the variables analysed were found to be non-significant ( $p>0.05$ ).

Differences among least square means were assessed according to Fisher's unprotected least significant difference test and were considered significant at a probability level of  $<0.05$ .

### 3.3 Results

Daily live weight gain (g/day) of lambs grazing the six forage treatments differed throughout the study ( $p < 0.001$ , Table 3.3). Chicory and PRG/WC+ concentrate lambs had the greatest live weight gain (g/day) in the first part of the study (D<sub>1</sub>-D<sub>23</sub>), growing at 182g/day and 174g/day respectively. Raphanobrassica had the slowest growth rate at 89g/day, with Leafy Turnip and PRG/WC lambs intermediate ( $p < 0.001$ ). However, this changed in the second part of the study (D<sub>23</sub>-D<sub>64</sub>), where Chicory, Red Clover and Leafy Turnip fed lambs had the greater live weight gain ( $p < 0.001$ ), however Leafy Turnip and Raphanobrassica did not differ ( $p > 0.05$ ). PRG/WC fed lambs had the slowest growth rate at 50g/day, the addition of concentrate to the diet of the lambs in the PRG/WC + concentrate group resulted in higher live weight gain than PRG/WC, but not as high as the alternative forage treatments ( $p < 0.001$ ).

**Table 3.3: Liveweight gain (LWG) (g/day) for lambs grazing six forage treatments on D<sub>1</sub>-D<sub>23</sub> and D<sub>23</sub>-D<sub>64</sub>**

	Forage Treatment						SEM	P-value
	PRG/WC	PRG/WC + Concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica		
n	29	35	46	51	44	42		
LWG D <sub>1</sub> - D <sub>23</sub> (g/day)	144 <sup>b</sup>	174 <sup>a</sup>	182 <sup>a1</sup>	n/a <sup>2</sup>	123 <sup>b</sup>	89 <sup>c</sup>	9.98	<0.001
LWG D <sub>23</sub> - D <sub>64</sub> (g/day)	50 <sup>d</sup>	185 <sup>c</sup>	256 <sup>a</sup>	276 <sup>a</sup>	251 <sup>ab</sup>	225 <sup>b</sup>	9.48	<0.001

<sup>a,b,c,d</sup> Different letters within the same row denote significant difference between means

<sup>1</sup> 182 g/day calculated based on 2/3 treatment replicates as one was slower to establish.

<sup>2</sup> Red clover was not ready to start grazing on D<sub>1</sub> of the experiment so was started on D<sub>23</sub>. One treatment replicate of Chicory was also started on D<sub>23</sub>.

Chicory, Leafy Turnip and Red Clover fed lambs had the heaviest final liveweight ( $p < 0.001$ ; Table 3.4), however Raphanobrassica fed lambs had a similar final liveweight to the Red Clover fed lambs. PRG/WC fed lambs had the lightest final live weight ( $p < 0.001$ ), but they were no different to PRG/WC + concentrate. Chicory and Leafy Turnip fed lambs had the heaviest hot carcass weight, PRG/WC and PRG/WC + concentrate fed lambs had the lightest hot carcass weight and Red Clover and Raphanobrassica fed lambs were intermediate to the other two groups ( $p < 0.001$ ). Dressing out percentage of all alternative forage treatments (Chicory, Red Clover, Leafy Turnip and Raphanobrassica) was greater than both PRG/WC and PRG/WC + concentrate fed lambs.

**Table 3.4: Start liveweight (kg), carcass weight (kg), final live weight (kg) and dressing out percentage (%) for lambs on six forage treatments**

	Forage Treatment						SEM	P-value
	PRG/WC	PRG/WC + Concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica		
n	29	35	46	51	44	42		
Average time on treatment	64	64	56	41	64	64		
Start Liveweight (kg)	28.1	28.0	27.7	27.2	27.8	27.7	0.557	0.877
Final Liveweight (kg)	37.3 <sup>d</sup>	40.2 <sup>cd</sup>	46.6 <sup>a</sup>	43.8 <sup>ab</sup>	45.2 <sup>a</sup>	41.8 <sup>bc</sup>	1.083	0.001
Hot carcass weight (kg)	13.9 <sup>c</sup>	15.1 <sup>c</sup>	19.6 <sup>a</sup>	17.8 <sup>b</sup>	19.6 <sup>a</sup>	17.2 <sup>b</sup>	0.495	<0.001
Dressing out (%)	37.2 <sup>c</sup>	37.5 <sup>c</sup>	42.0 <sup>ab</sup>	40.6 <sup>b</sup>	43.3 <sup>a</sup>	41.1 <sup>b</sup>	0.689	<0.001

<sup>a,b,c,d</sup> Different letters within the same row denote significant difference between means

When measured at the midpoint of the study ( $D_{35}$ ), NDF% and ADF% levels were highest in Red Clover and Raphanobrassica, with all other treatments being similar ( $p < 0.001$ ; Table 3.5)

Red Clover and Raphanobrassica had the lowest values in all measures of digestibility ( $p < 0.001$ ). PRG/WC (from the PRG/WC + concentrate treatment) had lower digestibility than PRG/WC, Chicory and Leafy Turnip when considering In vivo DMD and In vivo OMD. Leafy Turnip had the highest digestibility numerically, but it was no different to Chicory or PRG/WC ( $p < 0.001$ ).

Following a similar pattern to the digestibility measures, ME was highest in Leafy Turnip, and lowest in Red Clover and Raphanobrassica ( $p < 0.001$ )

Of the three months of the study, January had the highest recorded pre grazing dry matter yields ( $p < 0.05$ ; Table 3.6). Of the forage treatments, Raphanobrassica had the highest pre and post grazing dry matter yields ( $p < 0.05$ ).

**Table 3.5: Forage quality measures (crude protein, neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin, dry matter digestibility (DMD), digestible organic matter in the dry matter (DOMD), organic matter digestibility (OMD) and metabolisable energy**

	Forage Treatment						SEM	P-value	
	PRG/WC	Chicory	Red Clover	Leafy Turnip	Raphano-brassica	PRG/WC + concentrate			
						PRG/WC			Concentrate
Crude protein (%)	20.0	16.9	19.8	17.6	19.9	22.8	12.1	1.6	0.223
NDF (%)	19.8 <sup>b</sup>	17.7 <sup>b</sup>	45.1 <sup>a</sup>	16.9 <sup>b</sup>	44.2 <sup>a</sup>	24.5 <sup>b</sup>	24.5	2.7	<0.001
ADF (%)	11.6 <sup>bc</sup>	12.6 <sup>b</sup>	25.4 <sup>a</sup>	7.5 <sup>c</sup>	22.8 <sup>a</sup>	14.6 <sup>b</sup>	11.6	1.4	<0.001
Lignin (%)	2.2 <sup>b</sup>	5.9 <sup>a</sup>	2.6 <sup>b</sup>	3.1 <sup>b</sup>	2.0 <sup>b</sup>	2.4 <sup>b</sup>	1.5	0.7	0.016
Organic matter (%)	86.3 <sup>e</sup>	87.2 <sup>d</sup>	88.0 <sup>c</sup>	88.7 <sup>b</sup>	88.1 <sup>c</sup>	90.6 <sup>a</sup>	95.5	0.2	<0.001
DMD % (DM)	81.0 <sup>a</sup>	81.0 <sup>a</sup>	67.7 <sup>c</sup>	82.4 <sup>a</sup>	68.4 <sup>c</sup>	77.0 <sup>b</sup>	76.6	0.9	<0.001
DOMD % (DM)	74.4 <sup>ab</sup>	74.8 <sup>ab</sup>	61.3 <sup>c</sup>	77.0 <sup>a</sup>	62.0 <sup>c</sup>	71.9 <sup>b</sup>	73.6	1.0	<0.001
OMD % (DM)	85.0 <sup>a</sup>	85.1 <sup>a</sup>	69.0 <sup>c</sup>	86.8 <sup>a</sup>	69.7 <sup>c</sup>	80.2 <sup>b</sup>	80.2	1.1	<0.001
ME KJ/g (DM)	11.9 <sup>ab</sup>	12.0 <sup>ab</sup>	9.8 <sup>c</sup>	12.3 <sup>a</sup>	9.9 <sup>c</sup>	11.5 <sup>b</sup>	11.8	0.2	<0.001

<sup>a,b,c</sup> Different letters within the same row denote significant difference between means

**Table 3.6: Pre and post grazing dry matter yields (kgDM/ha) for December, January & February**

Treatment	December		January		February	
	Pre	Post	Pre	Post	Pre	Post
PRG/WC	2771	2198	3888	2988	3529	2108
PRG/WC + concentrate <sup>1</sup>	2791	2453	3786	3086	3667	1632
Chicory	2552	1686	3227	1720	2572	1087
Red Clover	n/a	n/a	4410	3790	3915	2075
Leafy Turnip	5266	2899	4507	3057	2660	1955
Raphanobrassica	6516	2979	5297	3134	4866	3273
<b>SEM and Probabilities</b>	Pre		Post		Post	
SEM	392		344		344	
P value for month	0.002		0.026		0.026	
P value for forage treatment	0.001		<0.001		<0.001	
P value for month x forage	<0.001		0.042		0.042	

<sup>1</sup> PRG/WC component of PRG/WC + concentrate treatment

Except for dead matter percentage, the components of the botanical composition did not differ between treatments at the start of the study ( $p>0.05$ , Table 3.7). The percentage of weeds and dead matter were low across the treatments. The Pasture and the Pasture component of the Pasture + concentrate treatments had similar compositions and a low clover content.

By the end of the study, Leafy Turnip had a lower leaf percentage than Chicory, Red Clover and Raphanobrassica ( $p=0.003$ ) and had the highest amount of dead matter, with Raphanobrassica and Red Clover having the lowest ( $p<0.001$ ). Weed content was highest in Red Clover ( $p=0.003$ ), with no difference between the other 5 treatments.

Percentage of leaf changed over the study period, with Chicory and Leafy Turnip having a significant decline in the proportion of leaf on offer ( $p<0.05$ ). The amount of dead matter increased across all treatments, with Leafy Turnip having the biggest increase of 48% ( $p<0.05$ ). Pasture, the Pasture component of Pasture + concentrate and Chicory had all increased by a similar amount, which was significantly more than Raphanobrassica ( $p<0.05$ ).

**Table 3.7: Botanical composition of the six forage treatments on D3 (21/12/18) and D62 (18/2/19) of the study**

	Forage Treatments						LSD 5%	P value
	PRG/WC	PRG/WC + concentrate <sup>1</sup>	Chicory	Red Clover	Leafy Turnip	Raphanobrassica		
<b>21.12.18 (D4)</b>								
PRG (%)	83	84					6	0.665
WC (%)	6	9					14	0.541
Leaf (%)			93	n/a	91	90	7	0.456
Weed (%)	6	2	4	n/a	0	0	6	0.196
Dead/Yellow (%)	5	6	4	n/a	9	10	3	0.014
<b>18.2.19 (D62)</b>								
PRG (%)	61	61					10	0.814
WC (%)	1	2					7	0.428
Leaf (%)			73	78	43	84	16	0.003
Weed (%)	0	2	4	15	0	0	6	0.003
Dead/Yellow (%)	39	34	23	7	57	16	11	<0.001
<b>Change between dates</b>								
PRG (%)	-23	-23					16.7	0.986
WC (%)	-6	-6					7.5	0.698
Leaf (%)			-26	n/a	-48	-7	17.9	0.012
Weed (%)	-6	1	-1	n/a	0	0	6.4	0.225
Dead/Yellow (%)	34	28	24	n/a	48	7	12.1	0.001

<sup>1</sup> PRG/WC component of PRG/WC + concentrate treatment

### 3.4 Discussion

The objective of the current study was to evaluate the effect of six forage-based diets on lamb growth rate and carcass weight. Forage type influenced lamb growth and carcass characteristics (carcass weight and dressing out percentage) and the forage quality and botanical composition helps to explain the differences in weights of the lambs.

#### 3.4.1 Forage characteristics

Pre and post dry matter yields in Table 3.6 indicate that all treatments provided *ad libitum* feed to the lambs throughout the study. The high pre and post yields show that forage growth exceeded lamb intakes earlier in the study, resulting in high residuals needing to be left to ensure lambs could select the highest quality feed.

The forage quality samples were taken at the mid-point (D<sub>35</sub>) of the study period. Forage quality was observed to be good in all forages until this point, after this low rainfall and high air temperatures meant that nutritional quality declined, particularly in the PRG/WC treatment. When we consider the botanical composition at the end of the study, we can see the PRG/WC treatment had a 34% increase in the proportion of dead and yellow matter, indicating a decline in the forage quality.

All forages provided more than 15% crude protein, which is the minimum protein requirement for finishing lambs (Hodgson & Brookes, 1999). At 12% crude protein, the concentrate on its own wouldn't provide sufficient crude protein as a sole diet (Hodgson & Brookes, 1999). The high levels of NDF, ADF and low digestibility were unexpected for Red Clover and Raphanobrassica given the lamb growth rates measured. The stocking rates of these forages were insufficient to manage the dry matter grown, and hence stem production was observed in both forages. Under best practice management these forages would produce a very low proportion of stem, as grazing pressure is used to maintain the plants in a vegetative state. Grazing Raphanobrassica at a maximum pre grazing height of 400mm is recommended for optimising nutritional value and regrowth potential (Dumbleton et al., 2021) and the Raphanobrassica grown in this study was observed to exceed this height.

The botanical composition data showed that weed levels were very low, which is important when investigating the effect of an individual forage, as presence of other species can be grazed by the animals and skew results. The composition of the PRG/WC treatment and the PRG/WC from the PRG/WC + concentrate treatment was very similar, which is useful when considering the effect of the concentrate. The amount of white clover in the PRG/WC and PRG/WC + concentrate treatments was low at 1-6%.

### 3.4.2 Lamb Growth Rates

Growth rates of the lambs were fastest when grazing Chicory (182 g/day) and PRG/WC + concentrate (174 g/day) in the first part of the study ( $D_1 - D_{22}$ ). In the second part of the study ( $D_{23} - D_{64}$ ) lamb growth was fastest in Red Clover (276 g/day), Chicory (256 g/day) and Leafy Turnip (251 g/day), although Raphanobrassica (225 g/day) was no different to Leafy Turnip. Lamb growth rates changed over time as seen by the change in ranking in the second part of the study, with lamb growth rates on all alternative forages exceeding lamb growth rates on PRG/WC (Table 2.3). Lamb growth over the study period can be explained by the rumen transition effect and the botanical composition of the forages.

The fast lamb growth rates on Chicory and Red Clover align with previous research, where both forages are described as having high feeding values and fast animal growth (Fraser et al., 2004; Kemp et al., 2010; Li & Kemp, 2005; Speijers et al., 2004). Likewise, lamb growth rates on Leafy Turnip in the second part of the study were similar to other studies of weaned lambs grazing summer brassicas (Barry, 2013; Lindsay et al., 2007). While there is no published data on lamb growth rates on Raphanobrassica, forage quality measures indicate it has very similar nutritional qualities to forage rape (Dumbleton et al., 2021), which typically has lamb growth rates of 225g/day when grazed during summer (Barry, 2013). This aligns with the lamb growth rates observed for Raphanobrassica fed lambs in the second part of the study ( $D_{23}-D_{64}$ ).

Overall, the growth rates of lambs on the alternative forage treatments increased over time as the lambs transitioned to their new feed source. The lower growth rates on the brassica treatments (Raphanobrassica and Leafy Turnip) in the early part of the study are expected given previous research has shown it takes the rumen at least 14 days to adjust the ruminal microbiota and epithelium to the new feed type (Silvestre et al., 2023). Despite Chicory lambs (and to a degree PRG/WC + concentrate lambs) also experiencing a diet change at the beginning of the study, the transition effect was more pronounced in the brassica treatments. The “time to adjust to brassicas effect” is something that has been observed in multiple studies where young sheep abruptly introduced to brassica have an initial period of slow growth before the high feeding value and faster growth is realised (Barry, 2013).

The forage quality results of Red Clover and Raphanobrassica do not align with the lamb growth rates measured. The lambs were laxly grazed on the treatments to allow them to select the best quality, however this resulted in the Red Clover and Raphanobrassica developing more stem than they would under typical grazing management. Whole plant quality of forages is influenced by the ratio of leaf to stem and quality of stem (Westwood & Mulcock, 2012) and would result in lower liveweight gains if animals were forced to eat stem rather than select leaf. The forage samples collected for quality analysis included some stem however it is likely that the lambs selected a diet of predominantly leaf

material representing a higher overall quality. Timing of grazing is a compromise between yield and nutritive value (White & Hodgson, 1999) and thus grazing management of these alternative forages is crucial to optimise nutritional quality and lamb performance.

The growth rate of PRG/WC fed lambs declined over the study, starting at 144 g/day and reducing to 50g/day in the second period. Lamb growth on PRG/WC pastures over summer is highly variable, depending on forage quality and botanical composition (White & Hodgson, 1999). Lamb performance on PRG/WC was lower than what would be expected based on the forage quality (Table 3.4) and forage dry matter yield (Table 3.6) results. The post grazing dry matter yields were above the threshold of 1400 kgDM/ha, which is the recommended residual to ensure intakes are not restricted (Morris & Kenyon, 2014) and the measures of forage quality (CP%, In vivo OMD, NDF% and ME) at the mid-point of the trial indicate a feed which could support a higher growth rate. The botanical composition samples indicated low clover content in the PRG/WC throughout the study, with 6% at the start and 1% at the finish. Legume content in NZ PRG/WC swards is low, a survey of dairy pastures in three regions averaging 13% clover in new swards and 8% in old swards (Tozer et al., 2014). Optimal clover content for lamb preference and growth would be at least 70% clover (Parsons et al., 1994) however, agronomic reasons restrict this in practice, and it is challenging to maintain high levels of white clover in perennial ryegrass based swards, especially when lambs are being grazed for finishing (Lindsay et al., 2007). Dead matter also increased over the study period, ending at 39%, indicating only 60% of the available forage was green leafy material, which was selected for the pluck samples. Webby (1990) found that the amount of dead matter in pasture negatively impacted lamb growth rates, where pastures with 2000 kgDM/ha that had 50% dead matter only resulted in liveweight gains of 80 g/day. Additionally, Crown rust (*Puccinia coronate*) was identified on the perennial ryegrass, which likely affected palatability and reduced dry matter intake (Smit et al., 2005).

The addition of Concentrate to the diet of the lambs in the PRG/WC + concentrate group resulted in higher live weight gain than PRG/WC over the length of the study. The difference was greater in the second part of the study when PRG/WC quality declined, and the amount of concentrate offered to the PRG/WC + concentrate lambs was increased from 300g to 500g per lamb per day in an attempt to counter this. Though the supplementation of concentrate increased growth rates, they were not as high as the alternative forage treatments. Intake was not measured directly (only in Pre and Post quadrat cuts) and due to group feeding in grazing situation the individual intake of concentrate wasn't measured so it was not possible to know if the intake of concentrate was fully compensating for a lower ME intake with PRG/WC. A study in Ireland which fed similar amounts (300g/lamb/day) of concentrate to lambs on low sward height pasture (5cm), found lamb growth rates increased which

reduced age at slaughter by 28 days. However, it was noted that due to the high cost of concentrate, the increased carcass value did not cover the cost of the concentrate (Grennan, 2005).

### 3.4.3 Carcass measures

The alternative forages provided greater final liveweight than the PRG/WC and PRG/WC + concentrate treatments. Chicory and Leafy Turnip fed lambs were the heaviest but no different to Red Clover. The differences in final liveweight can be explained by the different daily liveweight gains on each treatment, where the ranking of treatments followed the same trend. Red Clover had the highest daily liveweight gain, but due to the late starting of this treatment, these lambs had 41 days on their treatment, compared to the other treatments at 64 days. It could be expected that if the Red Clover lambs had been on for the same length of time as the other treatments, then it would have had a higher final liveweight and carcass weight. The same effect could be expected (to a lesser degree) with Chicory, as one of the three replicates started on D<sub>23</sub>, giving this treatment an average time on treatment of 56 days. Each forage selected for the study has different agronomic characteristics and fit in a farm system. Red Clover was slower to establish than some of the other forages (Leafy Turnip, Raphanobrassica, Chicory) but it is a forage that can be grazed for multiple years if well managed (Ford & Barrett, 2011).

Hot carcass weight followed a similar pattern to final liveweight where the alternative forages provided higher hot carcass weights and dressing out percentages than PRG/WC and PRG/WC + concentrate treatments. Dressing out percentage and carcass composition are a primary focus for lamb producers as these directly influence carcass weight, with heavier carcass weights achieving a higher price provided they meet carcass classification (Pethick et al., 2014). Hot carcass weight was greatest in Chicory and Leafy Turnip lambs at 19.6kg, and Red Clover and Raphanobrassica were intermediate at 17.8 and 17.2kg respectively.

Dressing out percentage differed between forage treatments, with the alternative forages having higher dressing out percentages compared to PRG/WC and PRG/WC + concentrate. This result has also been found in other research where lambs fed PRG/WC had a lower dressing out percentage than lambs fed herb mixes (Somasiri et al., 2015). Dressing out percentage can be influenced by several factors, including liveweight, carcass fat level, breed, diet and time off feed (Litherland et al., 2010). The higher dressing out percentage is partially due to the alternative forage treatments having higher carcass weights, as the dressing out percentages of lambs tends to be higher at a set weight if they are fatter, and level of fatness is influenced by nutrition (Schreurs & Kenyon, 2017). The largest influencing factor is the weight of gutfill at pre-slaughter weighing, which can account for between 10% and 22% of liveweight prior to fasting (Litherland et al., 2010). In turn, level of feed intake and digestibility of the feed type affects gutfill, where highly digestible forages such as herbs and legumes result in lower

gutfill compared to a less digestible perennial ryegrass sward (Somasiri et al., 2015). When a forage has low digestibility, this slows the rumen outflow rate and thus a higher proportion of the liveweight is attributed to rumen fill (Litherland et al., 2010). Studies in both lambs and deer have found greater particle breakdown and rumen outflow rates on chicory compared to perennial ryegrass (Niderkorn et al., 2019; Shimada & Barry, 1997). The digestibility results from the mid-point of the trial don't reflect this, but the increase in dead matter (Table 3.6) helps to explain the loss of green leafy growth that was observed under the dry conditions. The benefit on farm of using high quality forages to increase dressing out percentage in summer dry environments means lambs can achieve a higher carcass weight at a set live weight and helps producers optimise carcass value by placing lambs in the most profitable carcass weight/GR classes (Litherland et al., 2010)

#### 3.4.4 Conclusion

Overall, alternative forages (Chicory, Leafy Turnip, Red Clover and Raphanobrassica) delivered greater lamb growth rates and carcass performance than PRG/WC over the summer period. Greatest lamb growth was achieved with Chicory and Red Clover. Slow establishment of Red Clover meant that lambs were grazed for less time than other treatments and thus greatest final live weight and carcass weight was achieved on Chicory and Leafy Turnip. Differences between these alternative forages and PRG/WC were greater in the second part of the study, where the effect of transition to a new diet was lessened, and forage quality of the PRG/WC declined under dry conditions. These findings support the use of summer-active forage crops to increase lamb performance during summer. Using alternative forages to improve lamb performance increases efficiency of lamb production, as the lambs reach desired live weight targets earlier and so are on farm for a shorter period.

## Chapter 4

### Experiment 1: Meat Quality and Fat Characteristics of Lambs Finished on Six Forage Treatments during Summer



## 4.1 Introduction

Consumers are becoming increasingly aware of how their food choices affect their health (Fowler et al., 2019), which creates a challenge for red meat producers and processors to provide food options that have desirable nutritive value characteristics such as a high omega 3 fatty acids or low saturated fatty acids (SFA). Ruminant meat is naturally high in SFA and low in polyunsaturated fatty acids (PUFA) levels due to rumen bacteria saturating dietary fatty acids (Wood et al., 2008). The nutritional manipulation of an animal's diet provides a strategy to change or improve the fatty acid composition in meat (Howes et al., 2015). Animal production factors other than diet can also affect the fatty acid profile of lamb meat, such as breed, sex and age at slaughter (Diaz et al., 2005; Wood & Enser, 1997). The strategy of changing the diet on offer to alter meat fat content and composition is comparatively quicker compared to genetic strategies, with heritability estimates for fatty acids being low to moderate (Mortimer et al., 2014).

Different finishing diets can act directly on the meat, or indirectly through factors such as animal growth rate or level of fatness (Purchas, 1989). Lamb production systems in New Zealand have traditionally relied on perennial ryegrass (*Lolium perenne*) based pastures, however summer conditions often limit the dry matter production and quality of perennial ryegrass (Kemp et al., 2010). Summer-active forage crops such as legumes, herbs and brassicas can be used as part of the farm system to provide a diet that promotes faster animal growth (Kemp et al., 2010; Somasiri et al., 2015) and encourages the deposition of fat, as they provide a better quality diet in terms of metabolisable energy (ME) concentration as well as greater herbage yield to encourage intake (Fraser et al., 2004; Speijers et al., 2004).

Ruminants that consume pasture diets have been shown to have a more desirable fatty acid composition than those fed concentrates (Ponnampalam et al., 2021) and offer potential to be further enhanced by using specific plant species (Howes et al., 2015). There is limited information available on the effects of alternative forage diets on fatty acid composition of lambs in a New Zealand context, with some novel forage types having no published information. The hypothesis is that meat from lambs grazing forages alternative to perennial ryegrass/white clover over summer would yield meat of similar quality but would have greater intramuscular fat deposition and a more desirable fatty acid profile for human health. Additionally, the supplementation of concentrate to lambs grazing PRG/WC, would result in meat with a less desirable fatty acid profile for human health.

Therefore, the objective of this study was to investigate the meat quality and fatty acid composition of meat from lambs grazing six different forage-based diets used for lamb finishing in New Zealand. The range of forages were selected to provide different species used for lamb finishing in

comparison to perennial ryegrass/white clover pasture. A treatment where perennial ryegrass/white clover was supplemented with concentrate was included to identify if ME intake was a driver of change rather than forage type. The forages were compared on their ability to grow a carcass, deposit fat and the effect on meat quality and fatty acid composition. Understanding the effects of forage diets on these measures could provide an opportunity to differentiate lamb products for discerning markets.

## 4.2 Materials and methods

### 4.2.1 Experimental design and treatments

All animal procedures were approved by the Massey University Animal Ethics Committee (Protocol No. 18/103). Experimental design was fully described in Materials and Methods of Chapter 3.

The study compared six treatments: Chicory, Red Clover, Leafy Turnip, Raphanobrassica, Perennial ryegrass/white clover (PRG/WC) and Perennial ryegrass/white clover + concentrate (PRG/WC + concentrate), each replicated 3 times. The PRG/WC + concentrate treatment was used to increase the ME intake of the lambs on a perennial ryegrass/white clover pasture to help understand if any potential benefits of grazing summer crops on meat quality and intramuscular fat content are due directly a consequence of increased ME intake than the from the forages *per se*.

Three hundred and twenty-four Romney-cross, cryptorchid lambs aged approximately 4 months were utilised for the trial. Lambs were selected from the Massey University Tuapaka farm flock to ensure sufficient lambs with the same breeding and management were available and represented a typical New Zealand lamb for finishing. Eighteen lambs were allocated to each replicate (total of 54 lambs per forage treatment) with a total of 324 lambs (18 lambs x 3 replicates x 6 treatments = 324 lambs).

**Table 4.1: Treatments, cultivars and number of lambs allocated per replicate within treatment**

Treatment	Cultivar	Number of lambs per replicate
<b>Chicory</b> ( <i>Chicorium intybus</i> )	Puna II	18
<b>Leafy Turnip</b> ( <i>Brassica rapa</i> ; syn. <i>B. campestris</i> )	HT-LT46	18
<b>Perennial ryegrass</b> ( <i>Lolium perenne</i> ) + <b>white clover</b> ( <i>Trifolium repens</i> )	Platform AR37 + Quartz	18
<b>Perennial ryegrass</b> ( <i>Lolium perenne</i> ) + <b>white clover</b> ( <i>Trifolium repens</i> ) + <b>concentrate</b>	Platform AR37 + Quartz + Sheep Nut (Denver Stockfeeds)	18
<b>Raphanobrassica</b> ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	Pallaton	18
<b>Red clover</b> ( <i>Trifolium pratense</i> )	Amigain	18

Lambs grazed each forage type for 65 days from 18 December 2018 to 21 February 2019. The lambs were tagged with electronic identification (EID) tags and weighed 5 days prior to the start of the trial and allocated to their treatment groups, balanced for starting liveweight (average of  $27.7 \pm 0.6$ kg, ranged from 22.2 kg to 41.6 kg). The lambs were weighed on Day 1 ( $D_1$ ) of the trial then weekly and finally on the day prior to slaughter ( $D_{64}$ ) ( $43 \pm 0.4$  kg).  $D_{64}$  weight is referred to as Final liveweight throughout this paper. A pluck herbage sample was collected from each plot at the mid point of the trial ( $D_{34}$ ). The samples were collected by walking randomly across the paddock, sampling down to the post grazing height of the most recently grazed cell, to reflect likely diet composition (Cook, 1964). These were frozen at  $-30^\circ\text{C}$  then freeze dried and analysed using wet chemistry for crude protein (CP) (AOAC 968.06 (Dumas method) N-P = 6.25), neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin (Fibertec, AOAC 2002.04, 973.18), organic matter digestibility (Roughan & Holland, 1977) and moisture and ash (AOAC 930.15/925.10/942.05).

#### 4.2.2 Slaughter

On  $D_{65}$  all lambs over 36kg were sent for slaughter. Where there were less than 10 lambs in a replicate over the 36kg threshold, then the 10 heaviest in the group were selected (Table 4.2). Lambs ( $n=256$ ) were transported to a commercial abattoir (Alliance Group Ltd, Dannevirke), where they were held in lairage overnight and slaughtered in a single group the following morning in accordance with the New Zealand welfare code for the slaughter of commercial animals.

**Table 4.2: Number of lambs from each treatment that were sent for slaughter, and where applicable the number that were below a liveweight of 36kg**

Treatment	Number sent for slaughter	Number under 36kg
Chicory ( <i>Chicorium intybus</i> )	48	0
Red clover ( <i>Trifolium pratense</i> )	51	0
Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> ) + concentrate	35	0
Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	32	13
Raphanobrassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	44	0
Leafy Turnip ( <i>Brassica rapa</i> ; syn. B. <i>campestris</i> )	44	0

#### 4.2.3 Carcass preparation and measurements

Carcasses were prepared following standard commercial dressing procedures for New Zealand export lamb. Each carcass was given an identification number that linked to the slaughter order and electronic identification tag, allowing traceability of each individual lamb. Hot carcass weight (HCW) was recorded; the lean meat yield (LMY) and depth of tissue at the GR site (tissue depth 110 mm from the midline on the 12<sup>th</sup> rib) was obtained using the Alliance Group VIAscan® system (Hopkins et al., 2004).

#### 4.2.4 Meat Sampling

The carcasses were chilled at -4°C for 12 hours then both the left and right bone-in short loin (*Longissimus lumborum*, LL) were removed from each carcass and vacuum-packed with their respective carcass identification tag. The samples were then transported to the Massey University Pilot Plant and aged at 1°C for 21 days, followed by frozen storage at -30°C.

Short loin samples (LL) (n=247) were analysed over a 6-week period. Of the 256 carcasses, 9 meat samples had missing identification tags and could not be analysed, leaving a final sample number of 247. The samples were thawed at 1°C for 24 hours prior to analysis. The packaged bone-in short loin was weighed, then the short loin and the packaging dried with paper towels and weighed. The loin was boned out and partitioned into sections (Figure 4.1) for each of the tests.

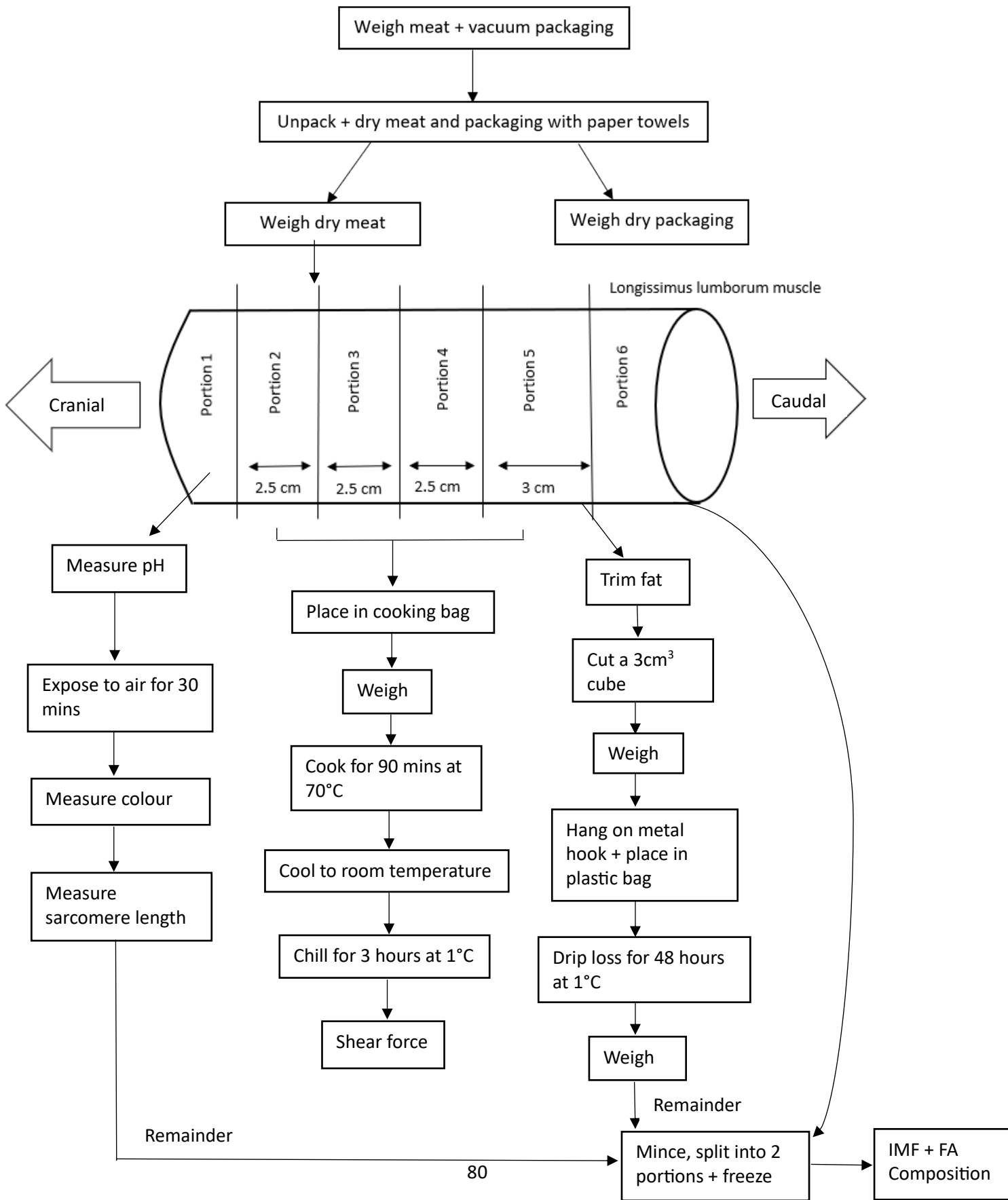
#### 4.2.5 Ultimate pH

The ultimate pH was measured at three points, across a transverse internal cut of the loin with a pH spear (Portion 1; Eutech Instruments, Singapore). The pH spear was calibrated on Day 1 of assessments using three standard pH buffers (pH 4.01, 7.00 and 10.01). Three measurements were taken and averaged to provide a single pH value for each sample.

#### 4.2.6 Instrumental colour measurement

The cut surface of Portion 1 was bloomed at ambient temperature for 30 minutes and fresh meat colour measured using a Minolta Colour Meter (Model CR-200, Konica Minolta Photo Imaging Inc. Mahwah, NJ, USA) set on the CIE  $L^*$ ,  $a^*$ ,  $b^*$  system (whereby  $L^*$  measures relative lightness,  $a^*$  relative redness and  $b^*$  relative yellowness). This chromometer was calibrated to a standard white tile provided by the manufacturer (colour variables:  $Y = 92.8$ ,  $x = 0.3160$ ,  $y = 0.3323$ ). Three readings were taken across the measured surface (one in each third) and averaged to obtain the average  $L^*$ ,  $a^*$  and  $b^*$  for each sample.

Figure 4.1: A schematic diagram for the partitioning of the lamb Longissimus lumborum (LL) muscle for meat quality analysis. FA = Fatty Acid, IMF = Intramuscular fat



#### 4.2.7 Water holding capacity (WHC)

Three measures of water holding capacity were taken: thaw loss, drip loss of raw meat and cooking loss.

Thaw loss (Equation 1 below) was measured using the weight of the bone-in loin in the vacuum pack, the weight of the bone-in loin after being blotted dry with a paper towel and the weight of the packaging that had also been dried with a paper towel and expressing it as a percentage of the bone-in loin weight. (Figure 4.1)

Equation 1:

$$\text{Thaw loss (\%)} = \frac{[(\text{Whole weight} - \text{Packaging weight}) - (\text{Dried whole loin weight})]}{(\text{Whole weight} - \text{Packaging weight})} \times 100$$

Drip loss (Equation 2) was measured by cutting and weighing a 3cm<sup>3</sup> cube of raw meat from portion 5 (Figure 4.1), hanging it on a metal hook in a plastic bag and refrigerating it at 1°C. After 48 hours, the raw meat cube was removed from the plastic bag, then patted dry with paper towels and re-weighed. Drip loss was measured by the difference in weight of the cube and was expressed as a percentage of the initial weight.

Equation 2:

$$\text{Drip loss (\%)} = \frac{\text{Weight}_{0 \text{ hours}} - \text{Weight}_{48 \text{ hours}}}{\text{Weight}_{0 \text{ hours}}} \times 100$$

To measure cooking loss (Equation 3), three portions of 2.5cm (Sections 2-4; Figure 4.1) were cut from each loin and weighed (before cook weight), before being placed in a plastic bag and immersed in a 70°C water bath (Contherm Model 370HL, Australia) for 90 minutes. Following this, they were cooled at room temperature for 30 minutes, then placed in a chiller at 1°C for 3 hours. Samples were then removed from bags, dried using a paper towel and re-weighed to determine the after-cook weight. Cooking loss was calculated as by the difference in weight of the sections before and after cooking and was expressed as a percentage of the before cook weight.

Equation 3:

$$\text{Cooking Loss (\%)} = \frac{\text{Before cook weight} - \text{After cook weight}}{\text{Before cook weight}} \times 100$$

#### 4.2.8 Shear force and sarcomere length

Shear force was measured as the force required to shear through a 13mm diameter core from the cooked samples (Portions 2-4; Figure 4.1). Six cores (13 x 13mm cross sectional area) per sample were cut parallel to the muscle fibre direction, with care taken to avoid connective tissue or fat. The cores were sheared perpendicular to the direction of the muscle fibres using a texture analyser standard vee-shaped Warner-Bratzler cutting blade (TMS-Pilot Texture analyser, USA) connected to a tablet running TL-Touch software (version 1.18-408). The cutting speed was set to 20cm/min and six

measurements of peak area (total work done) and peak load (peak force) were obtained for each sample. The average of the six subsamples was calculated for each sample.

Sarcomere length was measured by laser diffraction as described by Bouton *et al.*, (1973). A small subsample from Portion 1 (Figure 4.1) was taken parallel to the muscle fibres, approximately 8-10mm long and 1mm thick. The muscle strand was teased out on a microscope slide using a scalpel blade, then 1-2 drops of distilled water was added and the muscle was compressed between two microscope slides. The muscle strand was then passed through a helium-neon laser (632.8nm, Melles Griot, Carlsdae, CA, USA) to create a diffraction pattern on a plate 10cm from the sample. Ten measures of the distance between the diffraction bands were taken using a ruler, and the average of these 10 measurements was used to calculate sarcomere length using the following equation (Equation 4)

$$\text{Equation 4: Sarcomere length } (\mu\text{m}) = 0.6328 \times \sqrt{\frac{\left(\left(\frac{x}{10 \times 2}\right)^2 + 100\right)}{\left(\frac{x}{10 \times 2}\right)}}$$

#### 4.2.9 Intramuscular Fat (IMF) and fatty acid profile

The remainder of the LL (Portion 6; Figure 4.1), along with the remaining portion for pH/colour (Portion 1; Figure) and remaining drip loss portion (Portion 5; Figure 4.1) were finely minced (Kenwood MG540, 3mm hole plate). The mince was split into two zip lock bags, the first allocated to IMF determination and the second for fatty acid profile. Both subsamples were frozen at -30°C until analysis.

##### 4.2.9.1 Intramuscular Fat (IMF)

Eight samples from each treatment were randomly selected for IMF content, and measured using Soxhlet extraction method (AOAC 991.36, Foss Soxtec 2050), as described by Hopkins *et al.* (2014).

##### 4.2.9.2 Fatty Acid Derivatisation using Optimised One-Step Procedure

The same eight samples that were selected for IMF per treatment were split, with half freeze dried and used for fatty acid analysis. Samples were weighed into a kimax 15 mL tube (300 mg). Internal standard (tri C11) was added to the samples (3 mg of tri C11 in Toluene), followed by toluene (4 mL) and 5% sulfuric acid in methanol

(4 mL). Samples were tightly sealed with a Teflon-lined cap and vortexed well before incubation at 70 °C for 2 h with interim mixing by inversion at 30, 60 and 90 min for 15 s. After cooling to room temperature for 20 min, saturated NaCl solution in distilled water was added to each tube (5 mL). Samples were shaken for 10s, and then centrifuged at 1000× g for 10 min. An aliquot of the top layer was transferred into a 1.5 mL GC vial and analysed by GC-FID.

FAMEs, prepared as described above, were analysed with a GC-2010 (Shimadzu, Kyoto, Japan) and a RTX 2330 (90% biscyanopropyl—105m × 0.25 mm i.d × 0.2 μm film thickness) from Restek.

The column temperature was kept at 175 °C for 17 min, then raised to 220 °C at a rate of 6 °C/min and held for 10 min. The carrier gas was hydrogen at a constant linear velocity of 50 cm/sec. The split ratio 50, injector temperature was 260°C and detector 300°C. An aliquot of 1 µL of the FAME sample, prepared as described before, was injected in the instrument. Identification of individual FAME isomers (including CLA and C18:1 isomers) was done by comparing with commercial standards.

#### 4.2.10 Statistical Analysis

All data was tested for normality and outliers using Genstat 24.0 (VSN-International, 2024) before analysis.

Final live weight, carcass weight, dressing out percentage and carcass characteristics were analysed using an analysis of variance by Restricted Maximum Likelihood (REML) in Genstat 24.0 (VSN International, 2024). Each treatment had a different number of lambs (due to the slaughter threshold of 36kg) and thus, this model was utilised due to the unbalanced design. The standard error of the mean (SEM) presented where generated using REML and are the average SEM across the treatments (as SE is different for each treatment due to unbalanced design), however variation in the standard errors is less than 5% and so the average is a good approximation. For the analysis of intramuscular fat an analysis of covariance was used where carcass weight was included as a covariate.

Objective meat quality was analysed using an analysis of covariance. Muscle pH was included as a covariate in the model for all the meat quality characteristics. Fatty acid composition of forages was analysed using ANOVA and fatty acid composition of meat was analysed using an analysis of covariance with intramuscular fat as the covariate in the model. Covariates were included in models to assess any treatment effects over and above the effect of the covariate as it is known that ultimate meat pH can have an influence on meat quality and likewise, intramuscular fat concentration will be an influence on fatty acid composition in the meat.

The replicates for each forage treatment were analysed as a nested fixed effect with animal within replicate used in the model. The replicate effect for the variables analysed were found to be non-significant ( $p>0.05$ ).

Differences among least square means were assessed according to Fisher's unprotected least significant difference test and were considered significant at a probability level of  $<0.05$ .



Figure 4.2: Lamb meat partitioned for meat quality testing at Massey University Food Pilot Plant

### 4.3 Results

Lambs that had grazed Chicory and Leafy Turnip had the heaviest final liveweight and carcass weight, followed by Raphanobrassica and Red Clover lambs and the lightest lambs had grazed PRG/WC and PRG/WC + concentrate treatments ( $p < 0.001$ ; Table 4.3). The dressing out percentage was greater for lambs that had grazed on the Chicory, Red Clover, Leafy Turnip and Raphanobrassica compared to PRG/WC and PRG/WC + concentrate treatments ( $p < 0.001$ ). Intramuscular fat of the loin was greatest for lambs that had grazed Chicory and Leafy Turnip ( $p < 0.001$ ) but this effect was not evident when IMF was adjusted to compare at an equal carcass weight ( $p > 0.05$ ).

The V-GR of lambs followed a similar pattern across the forage treatments to the hot carcass weight and IMF results. Lambs that had grazed Chicory and Leafy Turnip had the highest GR values, followed by Red Clover and Raphanobrassica fed lambs, and the PRG/WC and PRG/WC + concentrate lambs had the lowest GR values ( $p < 0.001$ ). PRG/WC and PRG/WC + concentrate lambs had greater leg yields than other treatments ( $p < 0.001$ ). Total yield was higher for PRG/WC and PRG/WC + concentrate lambs than Leafy Turnip lambs ( $p < 0.05$ ).

**Table 4.3: Mean values for hot carcass weight (kg), final liveweight (kg), dressing out %, intramuscular fat (IMF)% and carcass characteristics of lambs grazed on six forage treatments**

	Forage Treatments						SEM	P-value	Significance of HCW covariate
	PRG/WC	PRG/WC + concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica			
n	29	35	46	51	44	42			
Hot carcass weight (kg)	13.9 <sup>c</sup>	15.1 <sup>c</sup>	19.6 <sup>a</sup>	17.8 <sup>b</sup>	19.6 <sup>a</sup>	17.2 <sup>b</sup>	0.50	<0.001	
Final Liveweight (kg)	37.3 <sup>d</sup>	40.2 <sup>cd</sup>	46.6 <sup>a</sup>	43.8 <sup>ab</sup>	45.2 <sup>a</sup>	41.8 <sup>bc</sup>	1.08	0.001	
Dressing out (%)	37.2 <sup>c</sup>	37.5 <sup>c</sup>	42.0 <sup>ab</sup>	40.6 <sup>b</sup>	43.3 <sup>a</sup>	41.1 <sup>b</sup>	0.69	<0.001	
IMF (%)	1.0 <sup>d</sup>	1.2 <sup>cd</sup>	2.4 <sup>a</sup>	1.8 <sup>b</sup>	2.1 <sup>ab</sup>	1.7 <sup>bc</sup>	0.16	<0.001	
IMF <sup>1</sup> (%)	1.9	1.9	1.8	1.7	1.5	1.8	0.16	0.319	<0.001
V-GR <sup>2</sup>	1.9 <sup>c</sup>	3.2 <sup>c</sup>	8.4 <sup>a</sup>	6.5 <sup>b</sup>	9.3 <sup>a</sup>	7.1 <sup>b</sup>	0.39	<0.001	
Leg yield (% of carcass) <sup>2</sup>	23.4 <sup>a</sup>	22.9 <sup>a</sup>	21.7 <sup>bc</sup>	22.0 <sup>b</sup>	21.2 <sup>c</sup>	21.9 <sup>b</sup>	0.23	<0.001	
Loin yield (% of carcass) <sup>2</sup>	14.8	15.1	15.2	15.1	15.1	15.1	0.13	0.460	
Shoulder yield (% of carcass) <sup>2</sup>	17.0	17.1	17.3	17.1	17.1	17.2	0.41	0.727	
Total Yield (% of carcass) <sup>2</sup>	55.2 <sup>a</sup>	55.1 <sup>a</sup>	54.3 <sup>ab</sup>	54.2 <sup>ab</sup>	53.4 <sup>b</sup>	54.3 <sup>ab</sup>	0.42	0.045	

<sup>a,b,c,d</sup> Different letters within the same row denote significant difference between means

<sup>1</sup>IMF adjusted for HCW (Hot Carcass Weight)

<sup>2</sup>V-GR, leg, loin, shoulder and total yield were estimated by ViaScan

Meat from PRG/WC fed lambs had a higher pH value than meat from lambs fed other forage types ( $p < 0.05$ ; Table 4.4). Meat from lambs fed Leafy Turnip had the lowest pH of the treatment groups ( $p < 0.05$ ). Analysis of the remaining objective meat quality measures with and without the pH covariate resulted in a pattern of differences that was comparable. When adjusted for pH, meat from PRG/WC fed lambs was lighter ( $L^*$ ) than meat from Chicory, Red Clover, Raphanobrassica and Leafy Turnip fed lambs ( $p < 0.05$ , Table 4.5). Meat from lambs fed Red Clover and Leafy Turnip had lower peak shear force values than meat from lambs fed PRG/WC + concentrate and less cooking loss than meat from lambs fed PRG/WC, PRG/WC + concentrate or Raphanobrassica ( $p < 0.05$ ). No differences were detected in the meat redness ( $a^*$ ), yellowness ( $b^*$ ), shear force work done, drip loss, thaw loss or sarcomere length ( $p > 0.05$ ).

**Table 4.4: Mean values for objective meat quality tests on the Longissimus lumborum (loin) for lambs that had grazed PRG/WC, PRG/WC + concentrate, Chicory, Red Clover, Leafy Turnip or Raphanobrassica**

	Forage treatments						SEM	P-value
	PRG/WC	PRG/WC + concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica		
n	29	35	46	51	44	42		
Ultimate pH	5.93 <sup>a</sup>	5.83 <sup>b</sup>	5.80 <sup>bc</sup>	5.82 <sup>bc</sup>	5.77 <sup>c</sup>	5.82 <sup>b</sup>	0.02	0.003
Lightness ( $L^*$ )	36.36	37.24	36.96	36.33	36.76	36.27	0.30	0.220
Redness ( $a^*$ )	14.40	14.51	14.81	14.56	14.74	14.78	0.18	0.585
Yellowness ( $b^*$ )	4.55	4.96	5.05	4.92	5.22	5.17	0.17	0.193
Work done (kgf)	12.31 <sup>ab</sup>	13.13 <sup>a</sup>	12.66 <sup>a</sup>	11.65 <sup>b</sup>	11.58 <sup>b</sup>	12.46 <sup>ab</sup>	0.39	0.033
Peak force (kgf)	2.80 <sup>abc</sup>	3.08 <sup>a</sup>	2.85 <sup>ab</sup>	2.53 <sup>cd</sup>	2.48 <sup>d</sup>	2.71 <sup>bcd</sup>	0.10	<0.001
Drip loss %	3.17	3.19	3.54	3.24	3.62	4.03	0.35	0.517
Cook loss %	32.39 <sup>ab</sup>	33.35 <sup>a</sup>	32.45 <sup>ab</sup>	31.54 <sup>b</sup>	32.03 <sup>b</sup>	33.43 <sup>a</sup>	0.40	0.035
Thaw loss %	0.60	0.59	0.43	0.57	0.44	0.53	0.05	0.168
SL ( $\mu\text{m}$ )	1.67	1.69	1.70	1.68	1.69	1.68	0.01	0.747

<sup>a,b,c,d</sup> Different letters within the same row denote significant difference between means

**Table 4.5: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, PRG/WC + concentrate, Chicory, Red Clover, Leafy Turnip or Raphanobrassica. The means were statistically analysed with pH as a covariate.**

	Forage treatments						SEM	P-value	Sig of pH covariate
	PRG/WC	PRG/WC + concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica			
n	29	35	46	51	44	42			
Ultimate pH	5.93 <sup>a</sup>	5.83 <sup>b</sup>	5.80 <sup>bc</sup>	5.81 <sup>bc</sup>	5.77 <sup>c</sup>	5.82 <sup>b</sup>	0.02	0.003	
Lightness ( <i>L</i> *)	37.78 <sup>a</sup>	37.37 <sup>ab</sup>	36.68 <sup>bc</sup>	36.25 <sup>c</sup>	36.09 <sup>c</sup>	36.32 <sup>c</sup>	0.28	0.030	0.008
Redness ( <i>a</i> *)	15.18	14.58	14.65	14.52	14.36	14.81	0.22	0.524	0.035
Yellowness ( <i>b</i> *)	5.01	5.00	4.96	4.90	5.00	5.18	0.24	0.899	0.228
Work done (kgf)	12.42	13.14	12.65	11.69	11.51	12.45	0.55	0.168	0.888
Peak force (kgf)	2.84 <sup>ab</sup>	3.08 <sup>a</sup>	2.84 <sup>abc</sup>	2.54 <sup>bcd</sup>	2.45 <sup>bd</sup>	2.71 <sup>abcd</sup>	0.13	0.021	0.805
Drip loss %	3.67	3.14	3.45	3.18	3.38	4.05	0.46	0.582	0.511
Cook loss %	33.72 <sup>a</sup>	33.45 <sup>a</sup>	32.17 <sup>ab</sup>	31.50 <sup>b</sup>	31.39 <sup>b</sup>	33.48 <sup>a</sup>	0.48	0.017	0.094
Thaw loss %	0.73	0.60	0.40	0.56	0.38	0.53	0.06	0.102	0.167
SL (µm)	1.71	1.70	1.69	1.67	1.67	1.68	0.02	0.758	0.190

<sup>a,b,c,d</sup> Different letters within the same row denote significant difference between means

Meat from Chicory-fed lambs had more fatty acids in total, branched-chain fatty acids (BCFA), saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), n-3 PUFA and n-6 PUFA compared to meat from PRG/WC and PRG/WC + concentrate fed lambs ( $p < 0.05$ ; Table 4.6). Meat from lambs fed Leafy Turnip and Chicory had a similar fatty acid profile apart from the PUFA and n-6 PUFA fatty acids which were greater in meat from Chicory-fed lambs ( $p < 0.001$ ). Meat from Red Clover and Raphanobrassica fed lambs were intermediate to the other groups for their fatty acid profile.

Meat from PRG/WC fed lambs had a greater amount of EPA + DHA and long chain n-3 PUFA, compared to meat from all other treatments ( $p < 0.001$ ). Meat from PRG/WC fed lambs had the highest PUFA:SFA ratio, greater than all treatments except meat from lambs fed PRG/WC + concentrate ( $p < 0.05$ ). Meat from Leafy Turnip fed lambs had the lowest PUFA:SFA ratio but was no different to meat from lambs fed Raphanobrassica ( $p < 0.05$ ). Meat from Leafy Turnip fed lambs had the lowest n-6:n-3 ratio, followed by lambs fed Raphanobrassica and Chicory ( $p = 0.021$ ). PRG/WC + concentrate fed lambs had the highest n-6:n-3 ratio, with lambs fed PRG/WC and Red Clover intermediate to meat from the other treatments ( $p < 0.05$ ).

**Table 4.6: Fatty acid content (mg/100g raw meat) of the Longissimus lumborum (loin) from lambs that had grazed six forage treatments**

	Forage Treatments						SEM	P-value
	PRG/WC	PRG/WC + Concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica		
n	29	35	46	51	44	42		
Sum FA	2542.90 <sup>d</sup>	2721.93 <sup>cd</sup>	4032.37 <sup>a</sup>	3336.25 <sup>bc</sup>	3814.99 <sup>ab</sup>	3171.53 <sup>cd</sup>	201.15	0.002
Unreported FA	218.82	263.35	235.46	269.83	223.80	200.46	39.22	0.792
BCFA <sup>1</sup>	34.44 <sup>cd</sup>	32.14 <sup>d</sup>	47.24 <sup>a</sup>	39.85 <sup>bc</sup>	42.82 <sup>ab</sup>	43.12 <sup>ab</sup>	2.28	0.007
SFA <sup>2</sup>	1108.90 <sup>c</sup>	1162.50 <sup>c</sup>	1782.38 <sup>a</sup>	1465.24 <sup>b</sup>	1641.43 <sup>ab</sup>	1394.89 <sup>bc</sup>	92.48	0.003
MUFA <sup>3</sup>	915.63 <sup>c</sup>	1016.42 <sup>bc</sup>	1609.79 <sup>a</sup>	1268.89 <sup>b</sup>	1630.33 <sup>a</sup>	1283.46 <sup>b</sup>	92.02	0.001
PUFA <sup>4</sup>	299.55 <sup>bc</sup>	279.66 <sup>c</sup>	404.75 <sup>a</sup>	332.28 <sup>b</sup>	319.44 <sup>bc</sup>	292.72 <sup>bc</sup>	13.55	<0.001
EPA + DHA <sup>5</sup>	41.14 <sup>a</sup>	34.51 <sup>d</sup>	36.97 <sup>bc</sup>	34.91 <sup>cd</sup>	37.66 <sup>b</sup>	35.21 <sup>cd</sup>	0.70	<0.001
C18:3 n-3 (ALA)	51.60 <sup>d</sup>	46.22 <sup>d</sup>	112.21 <sup>a</sup>	76.75 <sup>bc</sup>	92.74 <sup>ab</sup>	65.84 <sup>cd</sup>	6.385	<0.001
n-3 PUFA <sup>6</sup>	122.53 <sup>cd</sup>	106.83 <sup>d</sup>	176.34 <sup>a</sup>	137.70 <sup>bc</sup>	156.91 <sup>ab</sup>	127.45 <sup>cd</sup>	7.03	<0.001
n-6 PUFA <sup>7</sup>	147.51 <sup>bc</sup>	144.89 <sup>bc</sup>	188.35 <sup>a</sup>	157.28 <sup>b</sup>	130.02 <sup>c</sup>	135.69 <sup>c</sup>	5.83	<0.001
LC n-3 PUFA <sup>8</sup>	70.93 <sup>a</sup>	60.61 <sup>c</sup>	64.13 <sup>b</sup>	60.95 <sup>bc</sup>	64.17 <sup>b</sup>	61.62 <sup>bc</sup>	1.06	<0.001
PUFA:SFA	0.28 <sup>a</sup>	0.25 <sup>ab</sup>	0.23 <sup>b</sup>	0.24 <sup>b</sup>	0.20 <sup>c</sup>	0.22 <sup>bc</sup>	0.010	0.003
n-6:n-3	1.21 <sup>b</sup>	1.38 <sup>a</sup>	1.08 <sup>c</sup>	1.15 <sup>b</sup>	0.83 <sup>d</sup>	1.07 <sup>c</sup>	0.021	<0.001

<sup>a, b, c, d</sup> Different letters within the same row denote significant difference between means. <sup>1</sup>BCFA =  $\sum$  iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>2</sup>SFA =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>3</sup>MUFA =  $\sum$  C14:1, C16:1, C17:1 C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11, <sup>4</sup>PUFA =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3, C18:2 *cis*-9, *trans*-11, <sup>5</sup>EPA + DHA =  $\sum$  C20:5n-3, C22:6n-3, <sup>6</sup>n-3 PUFA =  $\sum$  C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3, <sup>7</sup>n-6 PUFA =  $\sum$  C18:2n-6, C20:4n-6, <sup>8</sup>LC n-3 PUFA =  $\sum$  C20:5n-3, C22:5n-3, C22:6n-3.

Intramuscular fat percentage was significant as a covariate for saturated fatty acids (SFA), polyunsaturated fatty acids (PUFA), EPA + DHA, n-3 PUFA, n-6 PUFA and LC n-3 PUFA ( $p < 0.05$ ; Table 4.7).

Meat from PRG/WC fed lambs had the greatest levels of EPA + DHA and long chain n-3 PUFA ( $p < 0.001$ ), compared to meat from lambs that grazed all other treatments. Levels of PUFA were greatest in meat from PRG/WC and Chicory fed lambs, but no different to meat from Red Clover fed lambs ( $p < 0.001$ ). When looking at n-3 PUFA specifically, meat from PRG/WC and Chicory fed lambs had the greatest levels but these were not different to meat from Leafy Turnip fed lambs ( $p < 0.001$ ). Similarly with n-6 PUFA, meat from PRG/WC and Chicory fed lambs had the greatest levels but were not different to meat from PRG/WC + concentrate fed lambs ( $p < 0.001$ ).

There were no significant differences between treatments for total fatty acids, branched chain fatty acids or saturated fatty acids once adjustments had been made for IMF% ( $p > 0.05$ ).

**Table 4.7: Fatty acid content (mg/100g fresh meat) of the Longissimus lumborum (loin) adjusted for IMF % from lambs that had grazed 6 forage treatments**

	Forage Treatments						SEM	P-value	Sig of IMF CoV
	PRG/WC	PRG/WC + concentrate	Chicory	Red Clover	Leafy Turnip	Raphano-brassica			
Sum of FA	3051.68	3037.24	3523.30	3304.70	3549.57	3166.08	226.35	0.725	0.041
Unreported FA	260.05	289.51	193.22	267.22	201.78	200.00	54.479	0.721	0.432
BCFA <sup>1</sup>	38.48	34.47	43.47	39.62	40.86	43.07	2.975	0.342	0.212
SFA <sup>2</sup>	1345.78	1308.44	1546.75	1450.64	1518.57	1392.37	103.529	0.801	0.039
MUFA <sup>3</sup>	1097.50	1128.59	1428.69	1257.67	1535.91	1281.53	115.989	0.325	0.132
PUFA <sup>4</sup>	348.35 <sup>a</sup>	310.69 <sup>bc</sup>	354.65 <sup>a</sup>	329.18 <sup>ab</sup>	293.31 <sup>c</sup>	292.18 <sup>c</sup>	8.220	<0.001	<0.001
EPA + DHA <sup>5</sup>	42.47 <sup>a</sup>	35.50 <sup>b</sup>	35.37 <sup>b</sup>	34.81 <sup>b</sup>	36.83 <sup>b</sup>	35.19 <sup>b</sup>	0.746	<0.001	0.049
C18:3 n-3 (ALA)	75.23 <sup>bc</sup>	61.28 <sup>d</sup>	87.90 <sup>a</sup>	75.25 <sup>bc</sup>	80.06 <sup>ab</sup>	65.58 <sup>cd</sup>	3.301	0.002	<0.001
n-3 PUFA <sup>6</sup>	148.23 <sup>a</sup>	123.47 <sup>d</sup>	149.48 <sup>a</sup>	136.04 <sup>bc</sup>	142.91 <sup>ab</sup>	127.17 <sup>cd</sup>	3.514	<0.001	<0.001
n-6 PUFA <sup>7</sup>	169.10 <sup>a</sup>	158.63 <sup>bc</sup>	166.18 <sup>ab</sup>	155.91 <sup>c</sup>	118.46 <sup>e</sup>	135.45 <sup>d</sup>	3.005	<0.001	<0.001
LC n-3 PUFA <sup>8</sup>	73.01 <sup>a</sup>	62.19 <sup>b</sup>	61.58 <sup>b</sup>	60.79 <sup>b</sup>	62.84 <sup>b</sup>	61.59 <sup>b</sup>	1.082	<0.001	0.034

<sup>a, b, c, d</sup> Different letters within the same row denote significant difference between means. <sup>1</sup>BCFA =  $\sum$  iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>2</sup>SFA =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0. <sup>3</sup>MUFA =  $\sum$  C14:1, C16:1, C17:1, C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11. <sup>4</sup>PUFA =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3, C18:2 *cis*-9, *trans*-11. <sup>5</sup>EPA + DHA =  $\sum$  C20:5n-3, C22:6n-3. <sup>6</sup>n-3 PUFA =  $\sum$  C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3. <sup>7</sup>n-6 PUFA =  $\sum$  C18:2n-6, C20:4n-6. <sup>8</sup>LC n-3 PUFA =  $\sum$  C20:5n-3, C22:5n-3, C22:6n-3.

The concentrate, fed as part of the diet for the PRG/WC + concentrate lambs, had the highest amount of all fatty acid measures except for C18:3 n-3 ALA, which was greater in all forage types ( $p < 0.001$ ; Table 4.8). Of the five forages analysed, Chicory and Red Clover had the highest total fatty acids, SFA, PUFA, C18:3 n<sup>3</sup> ALA and n<sup>6</sup> PUFA ( $p < 0.001$ ). The two brassica treatments, Leafy Turnip and Raphanobrassica, had the highest levels of MUFA ( $p < 0.001$ ). Both the PRG/WC based treatments had lower amounts of fatty acids, but were not different to the brassica treatments in levels of C18:3 n<sup>3</sup> ALA ( $p < 0.001$ ).

**Table 4.8: Fatty acid content (mg/g dry weight) of forage (PRG/WC, Chicory, Red Clover, Leafy Turnip and Raphanobrassica) and concentrate collected on D<sub>34</sub>**

	Forage Treatment							SEM	P-value
	PRG/WC + Concentrate			Chicory	Red Clover	Leafy Turnip	Raphano-brassica		
	PRG/WC	PRG/WC	Concentrate						
Sum FA	18.60 <sup>e</sup>	20.32 <sup>de</sup>	46.44 <sup>a</sup>	27.51 <sup>bc</sup>	29.37 <sup>b</sup>	23.73 <sup>cd</sup>	20.91 <sup>de</sup>	1.35	<0.001
SFA <sup>1</sup>	7.53 <sup>c</sup>	7.88 <sup>b</sup>	8.39 <sup>a</sup>	7.91 <sup>b</sup>	7.64 <sup>bc</sup>	7.02 <sup>d</sup>	6.49 <sup>e</sup>	0.10	<0.001
PUFA <sup>2</sup>	9.55 <sup>d</sup>	10.90 <sup>cd</sup>	24.94 <sup>a</sup>	18.39 <sup>b</sup>	20.51 <sup>b</sup>	13.43 <sup>c</sup>	11.04 <sup>cd</sup>	1.22	<0.001
MUFA <sup>3</sup>	1.52 <sup>c</sup>	1.54 <sup>c</sup>	13.12 <sup>a</sup>	1.21 <sup>c</sup>	1.23 <sup>c</sup>	3.28 <sup>b</sup>	3.38 <sup>b</sup>	0.11	<0.001
C18:3 n-3 (ALA)	7.49 <sup>b</sup>	8.62 <sup>b</sup>	0.94 <sup>c</sup>	14.29 <sup>a</sup>	15.95 <sup>a</sup>	10.53 <sup>b</sup>	8.43 <sup>b</sup>	1.06	<0.001
n-6 PUFA <sup>4</sup>	2.06 <sup>d</sup>	2.28 <sup>d</sup>	24.00 <sup>a</sup>	4.10 <sup>b</sup>	4.56 <sup>b</sup>	2.90 <sup>c</sup>	2.62 <sup>cd</sup>	0.19	<0.001

<sup>a, b, c, d</sup> Different letters within the same row denote significant difference between means. <sup>1</sup>SFA =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, C24:0. <sup>2</sup>PUFA =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3. <sup>3</sup>EPA + DHA =  $\sum$  C20:5n-3, C22:6n-3. <sup>4</sup>MUFA =  $\sum$  C14:1, C16:1, C17:1, C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11, C20:1. <sup>5</sup>n-6 PUFA = C18:2n-6.

## 4.4 Discussion

The objective of the current study was to evaluate the effect of six forage-based diets on lamb carcass characteristics, meat quality and fatty acid composition. Forage type influenced carcass characteristics (carcass weight, dressing out percentage and IMF%), and some objective measures of meat quality (pH, colour, peak shear force & water holding capacity), and fatty acid composition.

### 4.4.1 Carcass measures

Lambs that had grazed Chicory and Leafy Turnip had the highest carcass weights and V-GR (a VIAscan estimated measure of soft tissue depth over the ribs). The lowest values for these measures were seen in lambs that had grazed PRG/WC or PRG/WC + concentrate, with Red Clover and Raphanobrassica fed lambs being intermediate to these two groups (Table 4.3). PRG/WC fed lambs had lower IMF values than all other treatment groups, and Chicory fed had the highest IMF values. These results indicate that feeding alternative forages to perennial ryegrass/white clover during summer can provide a higher feeding value that encourages faster growth and greater deposition of fat. Within the alternative forages studied, Chicory and Leafy Turnip allowed for the fastest growth. Compared to muscle, fat is a later developing tissue (McPhee et al., 2008) and within the fat depots, intramuscular fat is the last to be deposited (Kempster, 1981). Thus, as an animal grows closer to its mature weight, the proportion of fat increases and increased fat deposition has also been linked with heavier carcass weights (Schreurs and Kenyon, 2017) so, greater subcutaneous fat depths and higher IMF values are seen in animals that are older or heavier at slaughter. This explains the differences seen in this study, as the animals were all similar age at slaughter, however the different growth rates on the forages resulted in differences in final liveweight and carcass weight. This was confirmed by adding carcass weight as a covariate to the statistical model to analyse IMF, with the effect of treatment no longer being significant. Intramuscular fat is an important factor to consider, given its influence on eating quality (Hopkins et al., 2006; Lambe et al., 2017). Increasing IMF aligns with New Zealand's goal of consistently producing lamb with desirable eating quality characteristics (Craigie et al., 2017) and these results show that diet is a useful strategy to help achieve this through allowing for faster growth and heavier carcasses.

Differences in the meat yield measures estimated by ViaScan were evident between the forage treatments. This is likely a consequence of differences in fat that had been deposited in the carcass as evidenced by the GR and IMF values. Lean meat yield is a measure of how much muscle is in the carcass so, more fat in the carcass will lower the proportion that is muscle and give a lower lean meat yield percentage. Chicory and Leafy Turnip were associated with more fat deposition (greater V-GR

and IMF% values) and so this resulted in the carcasses of lambs from these treatments having a lower lean meat yield compared to the PRG/WC-based treatments.

The supplementation of concentrate provided to PRG/WC was unable to drive up carcass weights or result in deposition of additional fat compared to solely PRG/WC fed lambs. Intake was not measured directly in this study, rather pre and post grazing dry matter yields to ensure adequate feed was on offer. Due to the group feeding in a grazing situation the amount of concentrate consumed by individual lambs was unable to be measured. Thus, it was not possible to know if the intake of concentrate was fully compensating for a lower ME intake from low quality PRG/WC. This study design made an attempt to understand the impact of supplementing concentrate, however to fully ascertain this we would need an indoor feeding study with individual pens to allow for individual measuring and monitoring. The focus of the study was the effect of forages under grazing conditions; hence an indoor study was not considered.

Due to the slower establishment of the Red Clover sward, the lambs that grazed Red Clover were grazed on their treatment for an average of 41 days, a shorter feeding duration compared to the other treatments (Chicory at 56 days and the remaining treatments at 64 days). Their growth rates (from Study 1, Chapter 3) were similar to those from lambs that had grazed Chicory and Leafy Turnip, suggesting that their carcass weight and other carcass characteristics will have been similar to those observed for the Chicory and Leafy Turnip treatment had they grazed Red Clover for the same length of time as the other treatments.

#### 4.4.2 Objective meat quality measures

Meat from lambs fed PRG/WC had the highest pH at 5.93, significantly higher than all other forage treatments. The pH of meat is an important determinant of quality, because it directly affects other measures of quality such as meat colour, tenderness, water holding capacity and oxidation (Prache et al., 2022; Savell et al., 2005). As there were significant differences between the pH of different forage treatments, pH was included as a covariate in the statistical model when analysing the other objective meat quality measures (Table 4.5). Meat from all other treatments had a pH of 5.8, which is the acceptable threshold for meat quality (Egan & Shay, 1988). Differences in pH are usually attributed to exposure to stressors pre slaughter, or low energy intake causing glycogen stores to be depleted in the muscle (Pethick & Rowe, 1996). Due to the hot, dry weather conditions experienced during the trial period, the quality of the PRG/WC was observed to decrease rapidly in the second half of the study, with the proportion of dead matter increasing significantly. Potentially the increase in pH seen in meat from the PRG/WC fed lambs was a consequence of lower glycogen reserves in their muscles, however glycogen was not measured directly in this study.

There were statistically significant differences in meat colour independent of pH. Meat from lambs fed a PRG/WC diet was lighter than all other treatments except PRG/WC + concentrate. It is difficult to explain why the meat from PRG/WC fed lambs was lighter in colour. In the study of Mashele et al., (2017) greater IMF resulted in lower redness values when measured objectively and it was concluded that the fat cells were diluting the colour of the muscle fibres. A similar effect may have happened in this study as the Leafy Turnip treatment had higher IMF and numerically lower redness results compared to PRG/WC. While meat from concentrate fed animals is typically lighter than meat from grass fed animals (Priolo et al., 2001), there is usually minimal differences between forage diets (De Brito et al., 2016; Ye, Schreurs, et al., 2020). Values for lightness ( $L^*$ ) below 34 and redness ( $a^*$ ) below 9.5 were reported by Khlijji et al. (2010) as being considered dark and unacceptable to average consumers. Meat from all forage treatments were above these lightness and redness thresholds, indicating that they would all be deemed acceptable by consumers. Although the objective measures of colour did create statistical differences, the relative difference in the values is small and are unlikely to be detected subjectively by consumers (Priolo et al., 2001).

Tenderness is an important determinant of consumer acceptance for lamb (Prache et al., 2022). Shear force measures have been correlated with tenderness scored by trained taste panellists (Perry et al., 2001). Small differences in shear force were detected in this study with meat from lambs fed PRG/WC + concentrate and Chicory having a higher work done and peak force than meat from Leafy Turnip and Red Clover fed lambs. When pH was included as a covariate, differences in peak force between meat from PRG/WC + concentrate and meat from Red Clover and Leafy Turnip lambs remained. This indicates there are additional intrinsic determinants other than pH affecting the shear force of meat from PRG/WC + concentrate fed lambs. However, peak force values were low for all treatments, well below the threshold of 40 N (4.08 kgF) proposed by Hopkins et al. (2006) for consumer acceptance of lamb. In fact, all forage treatments were closer to the conservative target of 27 N (2.75 kgF) for ensuring eating quality of lamb (Hopkins et al., 2006). The low peak force values observed in this study may be partially attributed to the long aging period of 21 days and the age of the lambs at slaughter (6-8 months) (Duckett et al., 1998; Pethick et al., 2005).

Water holding capacity measurements indicate whether muscles lose water easily during refrigeration, storage, in retail packaging and during cooking. These water holding measures are a predictor for overall liking of meat (Hopkins et al., 2006). In this study, differences were observed in cook loss and thaw loss measurements. Meat from lambs fed PRG/WC, PRG/WC + concentrate diets and Raphanobrassica had higher cook loss than other treatments. The review of (Pearce et al., 2011) identified several factors that altered water holding capacity in meat, however, many are unrelated to forage or dietary treatments. The differences in cooking loss in this study for the meat of lambs

from different forage treatments are difficult to explain without considering further testing to clarify the results.

#### 4.4.3 Fatty acid composition

Fatty acids were present in the highest amounts in meat from lambs fed Chicory, with meat from lambs fed Leafy Turnip very similar in fatty acid profile except for total PUFA and n-6 PUFA which were lower. The high amounts of fatty acids resulting from feeding these forages can be explained by the greater amounts of IMF deposited. PUFA proportion is negatively correlated to total lipid content, whereby older or heavier animals have a relative increase in tissue deposition of neutral lipids (Warren et al., 2008). To account for this, the fatty acid results were adjusted for IMF (Table 4.7) which reduced some of the dietary effects. SFA and MUFA were no longer different between forage treatments and treatment differences were less for the long chain fatty acids, with PRG/WC being highest and no other differences between treatments observed. Fatty acid values in the meat observed for this study were similar to other studies of lambs in grazed production systems (Fowler et al., 2019; Ye, Eyres, et al., 2020). It is well established that pasture based diets produce meat with more n-3 PUFA than diets based on grain feeding (Ponnampalam et al., 2021). Green leafy forages contain more ALA in their chloroplasts, compared to concentrates which contain more LA (Ponnampalam et al., 2021). ALA is a precursor of EPA + DHA (Kitessa et al., 2010) which are the fatty acids with the most benefits to human health (McAfee et al., 2010). In this research, Chicory and Red Clover forage samples had the highest amount of PUFA and ALA, but this only translated into the meat of lambs fed Chicory. In a study comparing fatty acid composition of traditional and novel forages chicory had greater ALA than perennial ryegrass at the first sampling date, but less at later sampling dates and varied between cultivars (Clapham et al., 2005). In this study, levels of ALA in meat from lambs fed Chicory were more than double that of meat from lambs fed PRG/WC, which were comparable to previous studies of meat from lambs grazing PRG (Fisher et al., 2000; Ponnampalam et al., 2012). De Brito et al., (2017) also reported elevated levels of ALA in meat from lambs grazing Chicory + Arrowleaf clover compared to Bladder Clover, Lucerne and Lucerne + Phalaris.

Levels of ALA can vary in forages depending on season and state of maturity, with the greatest amounts found in the leaf blade and less found in stem and seedhead (Boufaïed et al., 2003; Elgersma et al., 2003) thus management and environmental conditions can result in an inconsistent delivery of dietary fatty acids to the grazing animal. All forages included in this study had levels of ALA comparable to previous research (Alvarenga et al., 2015; Boufaïed et al., 2003). An extensive study done by Ponnampalam, Butler, Jacob, et al., (2014) found that the greatest variation in long chain n-3 PUFA in Australian lamb finished extensively at 21kg carcass weight (approximately 10 months of age) was environmental, with the lambs finishing diet being the most important factor. Lambs finished on high

quality forages consistently produced meat with greater levels of EPA + DHA, compared to those finished on concentrate or on poor quality feeds. Recent climate variation has led an increased frequency of prolonged droughts which reduces the availability of high quality pasture and increases reliance on concentrates and hay which are higher in n-6 PUFA (Ponnampalam et al., 2021). New Zealand farming systems are able to grow a combination of forage types to fill gaps where perennial ryegrass/white clover pasture production or quality is low, helping to provide a year-round supply of fresh forage rich in ALA.

The mechanisms of why grazing high quality forages results in higher levels of beneficial fatty acids in meat is not fully elucidated. Rumen metabolism of fatty acids means that ALA intakes do not directly reflect in muscle tissue, with biohydrogenation of unsaturated fatty acids in the rumen resulting in meat with high SFA and low PUFA (Wood et al., 2008). However, a proportion of unprotected fats bypass degradation in the rumen, becoming available for absorption and deposition in muscle and other tissues (Ponnampalam et al., 2024). A potential explanation is high quality forages are digested quickly by grazing animals, resulting in faster rumen outflow rates. Differences between the anatomical structure and arrangement of fibres in monocot plants (PRG) and dicot plants (Chicory, Red Clover, Raphanobrassica & Leafy Turnip) influence rumen digestion patterns, with monocots having slower rumen outflow. With faster rumen outflow, the forage spends less time in the rumen and there is less time for biohydrogenation to occur, resulting in increased duodenal flow of PUFAs. This helps to explain some of the differences in fatty acid profile of meat in this study, even when digestibility of some alternative forages (Red Clover and Raphanobrassics) was not high. Additionally, greater daily intakes are possible with highly digestible forage which will increase overall intake of ALA (Howes et al., 2015). This helps to explain the higher ALA and n-3 PUFA measured in the meat of Chicory and Leafy Turnip fed lambs.

In the current study, 100g of fresh lamb muscle could provide 35 to 41 mg EPA + DHA, with the greatest concentration in meat from PRG/WC fed lambs. Similar EPA + DHA content in lambs fed forage diets has been reported in previous research (Ponnampalam, Butler, Jacob, et al., 2014; Ye, Eyres, et al., 2020), and the results from this study are higher than others (De Brito et al., 2017). All treatments had EPA + DHA values that exceed the threshold of 23 mg/100g muscle to be considered a 'source' of EPA + DHA under Food Standards of Australia and New Zealand (FSANZ, 2012), however no treatment provided enough to be considered a 'good source' at 44mg/100g muscle (FSANZ, 2012). Given that a large proportion of New Zealand lamb is exported, it is important to consider the nutritional guidelines and regulations of those markets. Only the PRG/WC treatment provided sufficient EPA + DHA to be considered a source (40mg/100g muscle) under the Commission Regulation of European Union (EU)

and none of the forage diets provided a 'good source' at 80 mg/100g muscle (Commission Regulation of European Union, 2010).

The levels of EPA + DHA and long chain n-3 PUFA were highest in the PRG/WC fed treatment, which was not expected given the poorer quality of the forage and slower growth rates of the lambs observed in this treatment. This effect could be explained by the low amount of fat deposited in the PRG/WC fed lambs. Even when comparing at an equal IMF, the process of depositing more fat is associated with fat that is more saturated. PRG/WC fed lambs had the lowest IMF%, V-GR depth and were the lightest at slaughter so likely to have a fatty acid composition that is more unsaturated. (Itoh et al., 1999) showed this effect where animals with lower IMF had higher levels of EPA. IMF is important for eating quality so forages that increase IMF whilst also depositing a favourable fatty acid profile is desirable for consumer satisfaction.

The n-6:n-3 ratio, in contrast to the PUFA:SFA ratio, is highly influenced by the fatty acid composition of the diet fed to the animal (Bas & Morand-Fehr, 2000). High intakes of n-6 PUFA and high n-6:n-3 ratios are prevalent in Western diets and are associated with a range of diseases including cardiovascular disease, cancers, autoimmune and inflammatory diseases (Simopoulos, 2008). Interestingly, this was lowest in Leafy Turnip fed lambs, followed by Raphanobrassica and Chicory. Typically this ratio is lower in forage fed lambs compared to concentrate fed lambs, as C18:3 n-3 is the major fatty acid in green forages and C18:3 n-6 is the predominant fatty acid in concentrate (Diaz et al., 2005). As expected, the PRG/WC + concentrate treatment had the highest n-3:n-6 ratio, but the reason the two brassica treatments had the lowest ratio is more difficult to explain as these forages had lower levels of C18:3 n-3 than Chicory and Red Clover, but they did also have lower levels of C18:3 n-6 (n-6 PUFA).

Meat from lambs fed Red Clover was no different to the other forage only treatments, despite it being long identified as a forage with the potential to increase the proportion of PUFA in animal tissues due to elevated activity of the enzyme polyphenol oxidase, which reduces lipolysis and allows for the passage of C18:3 n-3 and C18:3 n-6 through the rumen without being biohydrogenated (Lee et al., 2007; Lee, Tweed, et al., 2009). This may be attributed to the shorter feeding duration of Red Clover in this study, or the stem production observed with this forage. We didn't measure proportion of stem and leaf and this may be something to consider with future studies investigating fatty acid profiles. Most studies regarding Red Clovers effect on fatty acid composition have been on animals fed red clover silage (Lee, Evans, et al., 2009; Lee et al., 2003; Lourenço et al., 2007), whereas lamb finishing systems in New Zealand mainly graze red clover in situ so further research is required to see if the same effects are seen under New Zealand production systems.

Previous studies have shown significant differences between the fatty acid composition of lambs grazing fresh forage, compared to lambs fed concentrate, with lambs fed fresh forage having a composition that is more favourable for human health (Howes et al., 2015; Ponnampalam et al., 2021). Grain supplementation at pasture typically reduces these benefits, especially as concentrate intake increases (Montossi et al., 2013). The addition of concentrate to lambs diet in this study did not have a large impact on the fatty acid composition, however it did increase the n<sup>6</sup>:n<sup>3</sup> ratio of the meat to be greater than all other treatments, and lower LC n3 PUFA and EPA + DHA values compared to PRG/WC, Chicory or Leafy Turnip. Given that the level of concentrate fed was low, it is not surprising that the differences measured in this study between PRG/WC + concentrate and the solely forage treatments were smaller than other studies comparing PRG/WC and concentrate feeding (Fisher et al., 2000) and were similar to another study where a PRG/WC diet was supplemented with 500g/head/day of concentrate (Ponnampalam et al., 2017).

#### 4.5 Conclusion

The results of this study indicate that feeding alternative forages to perennial ryegrass/white clover during summer can provide a higher feeding value that encourages faster growth and greater deposition of fat. Meat from lambs fed PRG/WC had a higher pH than other forage treatments. Independent of pH, differences in meat quality were small, with all treatments producing meat of high quality. Differences in fatty acid composition were minor, with differences explained by IMF deposition. The addition of concentrate to the diet of lambs grazing PRG/WC increased the n<sup>6</sup>:n<sup>3</sup> ratio and lowered the concentration of long chain polyunsaturated fatty acids, but the effect on energy intake was difficult to ascertain in an extensive group feeding scenario.

## Chapter 5

### Experiment 2: Lamb Performance Per Hectare on Chicory, Raphanobrassica or Perennial Ryegrass/White Clover during Summer and Autumn



## 5.1 Introduction

The aim of this study was to further investigate lamb growth and carcass production on three forage types. In New Zealand, lambing primarily occurs in spring to match the production curve of perennial ryegrass/white clover, with most lambs finished over summer and autumn (Cranston, 2017). Late summer/autumn is a key time in New Zealand farming systems, as spring born lambs are finished to reduce stock numbers prior to winter, and ewes are mated during this time, so ensuring there is adequate quantity and quality of feed for both of these purposes is an important consideration for utilising forages other than a perennial ryegrass-based sward in the lamb finishing system.

Seasonal oscillations, climatic variability and differences in management systems can result in summer pastures with poor nutritional value, particularly within dryland systems (White & Hodgson, 1999). Alternative forages to perennial ryegrass/white clover such as herbs, legumes and forage brassicas can be included in the farm system to provide additional dry matter yield and increased nutritive value at times of year when perennial ryegrass/white clover pasture is not providing sufficient quantity or quality to meet animal demands (Cranston et al., 2015). The increase in dry matter production and nutritive value of alternative forages allows for faster lamb live weight gains and greater carcass production per head and per hectare (Kenyon et al., 2017; Somasiri et al., 2015). Each forage type has different agronomic and nutritive value characteristics which should be considered when selecting a forage to include within a farm system. In addition to this, from a farm management perspective we want to know how long a forage needs to be grazed to influence lamb growth so grazing duration becomes a consideration.

Lamb liveweight gain on an individual lamb basis is often discussed but stocking rate should also be considered. Combined understanding of both live weight gain and carcass weight produced on a per hectare basis is a better reflection of the impact the forage will have on overall productivity and profitability. This has been researched in herb/clover mixes, where over a three year period, 3353 kg/ha of live weight was produced on a ryegrass/white clover mixture compared to 3838 kg/ha on a plantain/clover mixture and 3768 kg/ha on a chicory/clover mixture (Kenyon et al., 2017). Anecdotally farmers report that they can graze more lambs per hectare on Raphanobrassica than other summer forages, but live weight gain and carcass weight obtained per hectare is yet to be studied.

Like with perennial ryegrass, grazing management of these alternative forages is crucial to optimise nutritional quality and lamb performance. This effect was seen in plantain, where using a modern cultivar and grazing management to prevent seedhead production resulted in lamb liveweight gains of

222 g/day, where older research without the management to maintain nutritive value had measured lamb liveweight gains at between 84 and 141 g/day over three years (Fraser & Rowarth, 1996; Moorehead et al., 2002). Leaf to stem ratio has been shown to influence whole plant quality of brassicas such as forage rape, as leaf has higher nutrient value than stem (Kaur et al., 2011; Westwood & Mulcock, 2012). Forage brassicas such as Raphanobrassica are recommended to be grazed at a pre-grazing height of 350 – 400mm to minimise stem production and maximise quality of regrowth (Dumbleton et al., 2021). To expand on the findings of Study 1 (Chapter 3 and 4), this study looks at lamb performance on three of the six forage treatments over a longer time period (105 days vs 65 days in Chapter 3) as well as using a partial crossover design to assess the impact different lengths of time grazing a forage has on lamb growth, and whether timing of grazing a forage has an influence on lamb performance. The three forages selected were Perennial ryegrass/white clover (*Lolium perenne/trifolium repens*), Chicory (*Cichorium intybus*) and Raphanobrassica (*Brassica oleracea x Raphanus raphanistrum subsp. sativus*). Perennial ryegrass/white clover was retained as a control treatment because New Zealand's sheep production systems are traditionally based on perennial ryegrass/white clover pastures (Hodgson et al., 2019). Chicory was included as it had the highest lamb growth rates in the first study (Chapter 3 & 4), and Raphanobrassica was continued with as it had the highest forage growth throughout the first study under low rainfall conditions and there is very limited published information available on this relatively new species of forage brassica. In the first study the Raphanobrassica treatment stocking rate used was too low and forage growth exceeded lamb demand, resulting in stem production and reduced forage quality. For this study, stocking rates were set for each treatment based on pre-grazing mass and expected forage growth rather than being the same for all treatments. In addition to maintaining forage quality, setting the stocking rate allowed us to measure per hectare performance.

The primary aim of this thesis was to investigate the quality of meat from lambs that had grazed on a range of forages under New Zealand conditions. As described in Study 1 (Chapter 3), it was important to understand if the forages were impacting animal performance. To build on the outcomes of the first study, this study looked at a smaller number of forages but expanded the results by setting stocking rate, including autumn rather than summer only, and by investigating the effect of different lengths of time grazing on the forage. The research presented here provided a large scale, replicated farmlet study where three forage treatments were compared under the same conditions, to identify the effect that they had on lamb growth and carcass production per hectare. The hypothesis was that Chicory and Raphanobrassica would deliver greater lamb liveweight gain and carcass weight obtained per hectare over summer and autumn, either by providing more dry matter production (and thus

stocking rate of lambs) or providing higher quality forage (and thus greater lamb liveweight gain). Grazing duration would influence lamb growth rates and lamb performance per hectare, particularly in the case of Raphanobrassica where the lambs would need time to transition onto a new forage type.

## 5.2 Materials and Methods

### 5.2.1 Experimental Design and Animal Management

All animal procedures were approved by the Massey University Animal Ethics Committee (Protocol No. 19/114).

This study was carried out at Massey University's Keeble Farm (40°23'52.6"S 175°35'57.2"E), 5 km Southeast of Palmerston North, Manawatu, New Zealand on a Tokomaru Silt Loam soil. The forage treatments were sown on 25 November 2019 with a roller drill and chain harrows. The study ran for 105 days, from 17 January 2020 to 1 May 2020. When referring to a day of the study, the day is written in subscript after the letter D (i.e. day 6 = D<sub>6</sub>). The study was split into three phases: Phase 1 (D<sub>1</sub> – D<sub>35</sub>), Phase 2 (D<sub>36</sub> – D<sub>67</sub>) and Phase 3 (D<sub>68</sub> – D<sub>105</sub>) with 2 slaughter dates (D<sub>35</sub> and D<sub>67</sub>), to determine if length of time on a forage influenced fat characteristics and meat quality.

The design involved 5 treatments, each replicated 3 times in a farmlet study (Table 5.1). Three forages (Perennial ryegrass/white clover, Chicory & Raphanobrassica) were utilised for the study, and a partial crossover design was included where two treatments started on Perennial ryegrass/white clover for the first 35 days of the study and then transferred to either Chicory or Raphanobrassica for the final 32 days of the study (total of 67 days grazing). For the crossover treatments, 2.4 hectares of Perennial ryegrass/ white clover was sown and 1.5 hectares of Chicory or Raphanobrassica, split over 3 replicates (0.8 ha of PRG/WC, 0.5 ha of Chicory or Raphanobrassica per replicate). For the non-crossover treatments, 2.4 hectares of each forage type was sown, split over 3 replicates (0.8 hectares for each replicate).

Five hundred and sixty-nine weaned Romney-cross, wether lambs, that were approximately 5 months old were utilised for the trial. Of these, 375 were utilised for the meat quality aspect of the trial, the remaining 194 were used to set the stocking rate to allow us to look at production per hectare over the summer autumn growing period. Lambs were selected from the Massey University Tuapaka farm flock to ensure sufficient lambs with the same breeding and management were available and represented a typical New Zealand lamb for finishing.

Lambs were tagged with electronic identification (EID) tags and weighed prior to being allocated to a treatment group. For the meat quality lambs, 25 lambs were allocated to each treatment replicate, a total of 75 lambs per treatment. These lambs were balanced for liveweight, refer to tables 5.5 & 5.6 for starting liveweights of the treatment replicates.

The meat quality aspect of the study was completed at the end of Phase 2 (25 March). In Phase 3, only the non-crossover treatments (Perennial ryegrass/white clover, Chicory & Raphanobrassica) were included and again stocking rate was set to allow us to capture production per hectare in the autumn

growing period. In study 1 (Chapters 3 & 4) the Raphanobrassica treatment stocking rate used was too low and forage growth exceeded lamb demand, resulting in stem production and reducing forage quality. For study 2, a higher stocking rate was used relative to the other forage types.

To determine how many additional lambs would be assigned to the Raphanobrassica & Chicory treatments to set the stocking rate, each treatment replicate was sampled for pre grazing mass (kgDM/ha) on D<sub>-3</sub> and a feed budget was calculated. Number of lambs was determined by using the pre grazing mass, rotation length, expected forage growth, lamb live weight, expected lamb live weight gain and estimated lamb intakes. Additional lambs were allocated on a per replicate basis based on the results of the feed budget. Once the lambs had been allocated, they were tagged with a coloured Flexi-tag and spray marked to represent their treatment and replicate to ensure easy visual identification. Stocking rates were reduced when lambs reached slaughter weight or adjusted based on forage growth over time (refer to Table 5.1 for lamb numbers over the study period).

All lambs were orally drenched with Ancare 'Matrix' triple combination drench (active ingredients abamectin, levamisole and oxfendazole, and 0.5 g/L selenium and 2.2 g/L cobalt) at D<sub>-31</sub>, D<sub>11</sub>, D<sub>39</sub> and D<sub>67</sub>. All lambs were shorn and vaccinated with Ultravac '7 in 1' vaccine on D<sub>-20</sub>, then given a booster on D<sub>11</sub>.

All lambs were given access to hay for the first seven days of the study to assist with the transition to a different feed type. Access to fresh water was unrestricted.

**Table 5.1: Area sown per replicate (ha), forage sowing rate (kg/ha), lamb numbers per replicate and forage diet for each of the five treatments over Phase 1 (17 Jan – 20 Feb), Phase 2 (21 Feb – 25 Mar) and Phase 3 (26 Mar – 1 May). Numbers presented here are for all lambs utilised in the study (n=569), both those for meat quality (n=375) and those used to set the stocking rate (n=194). Lambs in Phase 2 are a subset of Phase 1 lambs as they continued on into Phase 2 if they had not reached suitable slaughter weight (39kg). New lambs were introduced for Phase 3.**

Treatment	Area sown per replicate (ha)	Sowing rate (kg/ha)	Phase 1 (D <sub>1</sub> -D <sub>35</sub> )		Phase 2 (D <sub>36</sub> -D <sub>67</sub> )		Phase 3 (D <sub>68</sub> – D <sub>105</sub> )	
			Lamb numbers per replicate	Forage diet	Lamb numbers per replicate	Forage diet	Lamb numbers per replicate	Forage diet
Perennial ryegrass + White clover (PRG/WC) <i>Cultivars: Base AR1 + Quartz</i>	0.8	26 + 6	25	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	15	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	14	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )
Chicory <i>Cultivar: Puna II</i>	0.8	8	25	Chicory ( <i>Chicorium intybus</i> )	12	Chicory ( <i>Chicorium intybus</i> )	0	Chicory ( <i>Chicorium intybus</i> )
Raphanobrassica <i>Cultivar: Pallaton</i>	0.8	8	37	Raphano brassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	27	Raphano brassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	28	Raphano brassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)
Crossover 1: Perennial ryegrass/ White clover → Chicory <sup>1</sup> (PRG/Chic)	0.8 PRG + WC 0.5 Chicory	26 + 6 → 8	25	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	15	Chicory ( <i>Chicorium intybus</i> )	n/a	
Crossover 2: Perennial ryegrass/ White clover → Raphano brassica <sup>1</sup> (PRG/Raph)	0.8 PRG + WC 0.5 Raphano brassica	26 + 6 → 8	25	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	15	Raphano brassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	n/a	

<sup>1</sup>Crossover treatments (1 and 2) started on Perennial ryegrass/white clover for the first 35 days of the study then transferred to either Chicory or Raphanobrassica for the final 32 days of the study

## 5.2.2 Grazing Management

Each replicate within the treatment was split into four cells, and the allocated lambs rotationally grazed the cells throughout the duration of the trial. Each replicate was grazed so that lambs on all treatments had *ad libitum* feed, with lambs being shifted to the next cell as they reached the target post-grazing residual of 1400 kgDM/ha (Morris & Kenyon, 2014). While lambs were shifted approximately weekly, the rotation length for each individual treatment depended on forage growth, and therefore movement of lambs in each forage treatment did not necessarily occur at the same time. When it was apparent *ad-lib* feed requirements could not be met for a replicate within a treatment, then lamb numbers were reduced accordingly.

## 5.2.3 Animal Measurements

Unfasted lamb liveweights were recorded on all lambs at D<sub>1</sub>, D<sub>11</sub>, D<sub>25</sub>, D<sub>34</sub>, D<sub>39</sub>, D<sub>53</sub>, D<sub>67</sub>, D<sub>77</sub> and D<sub>108</sub>. There were two slaughter dates for meat quality lambs, 20<sup>th</sup> Feb (D<sub>35</sub>) and 25<sup>th</sup> March (D<sub>67</sub>), where the 10 heaviest lambs of the 25 allocated to that replicate were selected for slaughter (10 lambs x 3 replicates x 5 treatments = 150 lambs per slaughter day). Carcass weight was obtained from the abattoir for each slaughter event. More detail on the slaughter process can be found in Chapter 4. Dressing out percentage (DO%) was calculated using the final on-farm live weight and hot carcass weight for each lamb. The additional lambs (used to set stocking rate) were slaughtered if they exceeded 39 kg liveweight on D<sub>35</sub>, D<sub>53</sub>, D<sub>67</sub> and D<sub>105</sub>. This minimum liveweight of 39kg was set by the farm to be in line with their commercial lambs. By the end of Phase 2 (D<sub>67</sub>) nearly all the lambs that had started on D<sub>1</sub> were at suitable slaughter weights and subsequently a new line of lambs was started on the Raphanobrassica and Perennial ryegrass/white clover treatments. Number of lambs was assigned per replicate using a feed budget based on pre-grazing mass data last taken for that replicate, as described in section 5.2.1. Due to very dry conditions and consequently low forage mass, no new lambs were introduced to the Chicory treatment on D<sub>67</sub> (Table 5.1).

Live weight gain per hectare was calculated as the product of the individual liveweight gained over the study period (final live weight minus starting liveweight) and the stocking rate per hectare. The total live weight gained was the sum of the live weight gained from each of the three phases of the study. Total carcass weight per hectare was calculated as the sum of the measured carcass weights (from the meat quality lambs) and the calculated carcass weights from the additional lambs using their final live weights and the average dressing out percentage from each treatment.

#### 5.2.4 Pasture Measurements

Pre- and post-grazing herbage cuts were taken to assess herbage mass and animal intakes measured as herbage disappearance. Three random quadrat cuts (0.1 m<sup>2</sup> each) of forage were taken to ground level from each cell using an electric shearing handpiece (Frame, 1993) immediately prior to lambs grazing a cell and after being shifted to the next cell. Samples were oven dried (80°C) to a constant weight to estimate pre- and post-grazing herbage mass (kgDM/ha) of the forages in each cell.

A pluck sample was collected from each replicate on the 3<sup>rd</sup> of February (D<sub>17</sub>) and 12<sup>th</sup> of March (D<sub>55</sub>) to reflect the forage grazed for chemical composition (Cook, 1964). These were frozen at -30°C, then freeze dried and tested for crude protein (CP) (AOAC 968.06 (Dumas method) N-P = 6.25), neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin (Fibertec, AOAC 2002.04, 973.18), organic matter (AOAC 930.15/925.10/942.05) and organic matter digestibility (Roughan & Holland, 1977). Laboratory determination of in vitro digestibility involves comparing samples of unknown digestibility to a standard curve of samples of known in vivo digestibility. A hot neutral detergent rinse is used to remove the soluble cell contents, then one hot and one or more cold H<sub>2</sub>O rinses removes the neutral detergent from the sample. After respectively 5 and 15 hours in cellulase solution the cell walls of the sample are hydrolysed and the remaining undigested material is filtered, dried, weighed, ashed and weighed. The procedure estimates Dry Matter Digestibility (DMD), Organic Matter Digestibility (OMD) and Digestible Organic Matter in the Dry Matter (DOMD) and closely follows the method of Roughan & Holland (1977). The metabolisable energy of the forage (MJ of ME/kg DM) was calculated as DOMD x 0.163 (Roughan & Holland, 1977).

#### 5.2.4 Weather data

Daily rainfall, minimum and maximum air temperature data was captured at a weather station 3km from the experimental site. This was provided by AgResearch Grasslands.

Rainfall levels during the period of the experiment were 29% below the 10 year average for January, February, March and April (Table 5.3). Maximum and minimum air temperatures were similar to the 10 year average for each month of the study period.

**Table 5.2: Rainfall (mm), maximum air temperature (°C) and minimum air temperature (°C) for the months of the study (January - April 2020) compared to the 10 year average. Data provided by AgResearch Grasslands site, 3km from the experimental site.**

	Jan-20	Feb-20	Mar-20	Apr-20
Rainfall (mm)	31	35.5	49	65.6
10 year average	52	55	60	84
Maximum air temp (°C)	22	25	21.5	19
10 year average	22.5	23.3	21.7	18.8
Minimum air temp (°C)	13	13.7	11	8.4
10 year average	12.7	13.3	11.9	9.4

### 5.2.5 Statistical analysis

All data was tested for normality and outliers using Genstat 24.0 (VSN-International, 2024) before analysis.

Forage quality measures, pre and post herbage mass and apparent dry matter harvested were analysed using an analysis of variance (ANOVA). Pre and post grazing dry matter yields were averaged by month. Missing values were estimated by the Genstat ANOVA and the degrees of freedom adjusted to give an unbiased estimation of treatment means.

Calculated herbage disappearance (kg/lamb/day) was calculated by:

Calculated herbage disappearance =

$$\frac{(\text{Pre grazing mass} - \text{post grazing mass})}{(\text{Number of lambs} \times \text{number of days grazing})}$$

Lamb performance data was split into two parts for analysis. Table 5.5 is the per head performance data for the lambs selected for meat quality (n=300) across the 5 forage treatments and 2 grazing durations (Phase 1 & 2). Table 5.6 includes all lambs included in the study to set the stocking rate (n=569) across the entire study duration (Phases 1-3) and includes the analysis of the per hectare results. The two crossover treatments (PRG/Chic and PRG/Raph) were not included in this analysis as these treatments were included for the effect of grazing duration on meat quality specifically and thus these treatments finished at the end of Phase 2 (25 Mar).

Lamb liveweight gain, start and final live weight, carcass weight, dressing out percentage, total liveweight gain and carcass weight produced per hectare were analysed using an analysis of variance (ANOVA) in Genstat 24.0 (VSN International, 2024) with forage treatment as the fixed effect in the model.

The replicates for each forage treatment were analysed as a nested fixed effect with animal within replicate used in the model. The replicate effect for the variables analysed were found to be non-significant ( $p > 0.05$ ).

Differences among least square means were assessed according to Fisher's unprotected least significant difference test and were considered significant at a probability level of  $< 0.05$ .

## 5.3 Results

### 5.3.1 Forage chemical composition

Crude protein was greater in the PRG/WC than on Chicory or Raphanobrassica ( $p < 0.001$ ; Table 5.2). There was no difference in crude protein between Chicory and Raphanobrassica at D<sub>17</sub> or D<sub>55</sub> ( $p < 0.001$ ). Crude protein concentration in the Raphanobrassica used in the crossover treatment was lower than in the Raphanobrassica only treatment on D<sub>55</sub> but no different to the concentration in Raphanobrassica on D<sub>17</sub>. The NDF% and ADF% were higher in the PRG/WC compared to Chicory and Raphanobrassica on both sampling dates and were greater at D<sub>55</sub> ( $p < 0.001$ ). The NDF% and ADF% in Chicory and Raphanobrassica were similar at D<sub>17</sub> but by D<sub>55</sub> Chicory had higher NDF and ADF than Raphanobrassica. The NDF% and ADF% in Chicory and Raphanobrassica from the crossover treatments were similar to the non-crossover Raphanobrassica at D<sub>55</sub> ( $p < 0.001$ ).

On both sampling dates, lignin concentration was the greatest in Chicory and lowest on PRG/WC, with Raphanobrassica intermediate ( $p < 0.001$ ). Lignin concentration was lower on the crossover Chicory than on the non-crossover Chicory at D<sub>55</sub> ( $p < 0.001$ ). PRG/WC had the lowest digestibility while the digestibility of Chicory and Raphanobrassica were no different to each other and similar across both sampling dates ( $p < 0.001$ ). Crossover Raphanobrassica had a higher Digestible Organic Matter in the Drymatter (DOMD) than Chicory, Raphanobrassica and crossover Chicory ( $p < 0.001$ ). Following a similar trend to digestibility, metabolizable energy was lower on PRG/WC compared to Chicory and Raphanobrassica on D<sub>17</sub> and PRG/WC decreased in ME over time ( $p < 0.001$ ). Chicory and Raphanobrassica had similar ME levels and remained the same over the two sampling periods ( $p < 0.001$ ). Crossover Raphanobrassica had higher ME than the other forages, including non-crossover Raphanobrassica ( $p < 0.001$ ).

**Table 5.3: Forage quality measures (crude protein, neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin, dry matter digestibility (DMD), digestible organic matter in the dry matter (DOMD), organic matter digestibility (OMD) and metabolisable energy (ME) of PRG/WC, Chicory and Raphanobrassica on 3 February 2020 (D<sub>17</sub>) and 12 March 2020 (D<sub>55</sub>). Farmlot replicates (3) provided replication at each sampling date.**

	3/02/2020 (D <sub>17</sub> )					12/03/2020 (D <sub>55</sub> )					SEM	P-value (Date x Trt)
	PRG/WC	Chicory	Raphano- brassica	PRG/Chic (PRG/WC) <sup>1</sup>	PRG/Raph (PRG/WC) <sup>1</sup>	Pasture	Chicory	Raphano- brassica	PRG/Chic (Chicory) <sup>1</sup>	PRG/Raph (Raphano- brassica) <sup>1</sup>		
Crude Protein (%)	17.8 <sup>bc</sup>	14.1 <sup>def</sup>	13.7 <sup>ef</sup>	16.3 <sup>bcde</sup>	19.4 <sup>ab</sup>	22.2 <sup>a</sup>	17.0 <sup>bcd</sup>	15.1 <sup>cde</sup>	14.0 <sup>def</sup>	11.7 <sup>f</sup>	1.1	<0.001
NDF (%)	43.1 <sup>c</sup>	20.2 <sup>de</sup>	19.3 <sup>ef</sup>	46.3 <sup>b</sup>	43.2 <sup>c</sup>	54.1 <sup>a</sup>	22.7 <sup>d</sup>	18.9 <sup>ef</sup>	19.3 <sup>ef</sup>	16.5 <sup>f</sup>	1.0	<0.001
ADF (%)	22.5 <sup>bc</sup>	14.7 <sup>de</sup>	12.8 <sup>e</sup>	24.3 <sup>ab</sup>	22.2 <sup>c</sup>	25.6 <sup>a</sup>	16.6 <sup>d</sup>	13.0 <sup>e</sup>	13.5 <sup>e</sup>	10.4 <sup>f</sup>	0.7	<0.001
Lignin (%)	2.1 <sup>ef</sup>	7.8 <sup>ab</sup>	5.3 <sup>cd</sup>	2.1 <sup>ef</sup>	2.0 <sup>f</sup>	3.5 <sup>def</sup>	8.3 <sup>a</sup>	5.4 <sup>cd</sup>	5.9 <sup>bc</sup>	4.3 <sup>cde</sup>	0.8	<0.001
Organic Matter (%)	88.8 <sup>de</sup>	86.9 <sup>c</sup>	89.1 <sup>de</sup>	87.0 <sup>c</sup>	88.0 <sup>cd</sup>	87.0 <sup>c</sup>	83.6 <sup>a</sup>	86.6 <sup>bc</sup>	85.2 <sup>b</sup>	90.1 <sup>e</sup>	0.5	<0.001
DMD (% DM)	69.9 <sup>b</sup>	81.4 <sup>a</sup>	81.3 <sup>a</sup>	68.9 <sup>b</sup>	70.7 <sup>b</sup>	66.1 <sup>c</sup>	82.1 <sup>a</sup>	82.1 <sup>a</sup>	80.9 <sup>a</sup>	82.2 <sup>a</sup>	0.6	<0.001
DOMD (% DM)	64.0 <sup>e</sup>	74.2 <sup>bcd</sup>	75.3 <sup>ab</sup>	62.5 <sup>e</sup>	64.3 <sup>e</sup>	59.1 <sup>f</sup>	73.1 <sup>cd</sup>	74.8 <sup>bc</sup>	72.8 <sup>d</sup>	76.8 <sup>a</sup>	0.6	<0.001
OMD (% DM)	71.6 <sup>b</sup>	84.2 <sup>a</sup>	84.1 <sup>a</sup>	70.6 <sup>b</sup>	72.2 <sup>b</sup>	66.7 <sup>c</sup>	84.8 <sup>a</sup>	85.0 <sup>a</sup>	83.5 <sup>a</sup>	85.4 <sup>a</sup>	0.7	<0.001
ME (MJ/kgDM)	10.2 <sup>e</sup>	11.9 <sup>bcd</sup>	12.0 <sup>ab</sup>	10.0 <sup>e</sup>	10.3 <sup>e</sup>	9.5 <sup>f</sup>	11.7 <sup>cd</sup>	12.0 <sup>bc</sup>	11.7 <sup>d</sup>	12.3 <sup>a</sup>	0.1	<0.001

<sup>a,b,c,d,e,f</sup> Different letters within the same row denote significant difference between means

<sup>1</sup> Forages listed in brackets indicate which forage the lambs on the crossover treatments were grazing at time of sampling

<sup>2</sup> Megajoules of metabolisable energy per kilogram of dry matter

Raphanobrassica had the highest pre-grazing mass for all phases of the study ( $p=0.003$ ; Table 5.4) and accordingly, had the highest stocking rate. It also had the highest post-grazing mass in Phase 2 ( $p<0.001$ ), but there was no difference between treatments for Phase 1. Apparent dry matter harvested was greatest for Raphanobrassica in Phase 1 and 2, but in Phase 2 was no different to crossover Chicory or Raphanobrassica ( $p<0.05$ ). In Phase 1, calculated herbage disappearance was greatest for Raphanobrassica and least for PRG/WC and in Phase 2, calculated herbage disappearance was greatest for crossover Chicory and lowest for PRG/WC.

**Table 5.2: Herbage mass, pre and post (kgDM/ha), lamb numbers (lambs/ha) and calculated disappearance rate (kg/lamb/day) for PRG/WC, Chicory, Raphanobrassica, PRG/Chic or PRG/Raph during Phase 1 (D<sub>1</sub> – D<sub>35</sub>: 17 January 2020 – 20 February 2020) and Phase 2 (D<sub>36</sub> – D<sub>67</sub>: 20 February 2020 – 25 March 2020).**

	Forage Treatments					SEM	P-value
	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph		
<b>Phase 1 (17 Jan – 20 Feb)</b>							
Pre-grazing mass (kgDM/ha)	2978 <sup>b</sup>	3556 <sup>b</sup>	7055 <sup>a</sup>	3386 <sup>b</sup>	3210 <sup>b</sup>	231	<0.001
Post-grazing mass (kgDM/ha)	1986	2299	2569	1930	2190	267	0.495
Apparent DM harvested (kgDM/ha)	992 <sup>b</sup>	1257 <sup>b</sup>	4486 <sup>a</sup>	1455 <sup>b</sup>	1020 <sup>b</sup>	452	0.003
Lamb numbers (lambs/ha)	31	31	46	31	31		
Calculated herbage disappearance (kg/lamb/day)	0.91	1.16	2.79	1.34	0.94		
<b>Phase 2 (20 Feb – 28 Mar)</b>							
Pre-grazing mass (kgDM/ha)	2252 <sup>b</sup>	2062 <sup>b</sup>	4165 <sup>a</sup>	2635 <sup>b</sup>	4001 <sup>a</sup>	302	0.003
Post-grazing mass (kgDM/ha)	1629 <sup>b</sup>	1347 <sup>b</sup>	2402 <sup>a</sup>	1348 <sup>b</sup>	2648 <sup>a</sup>	110	<0.001
Apparent DM harvested (kgDM/ha)	623 <sup>b</sup>	715 <sup>b</sup>	1763 <sup>a</sup>	1287 <sup>ab</sup>	1353 <sup>ab</sup>	226	0.035
Lamb numbers (lambs/ha)	19	15	34	18	23		
Calculated herbage disappearance (kg/lamb/day)	1.03	1.49	1.62	2.23	1.84		

<sup>a,b</sup> Different letters within the same row denote significant difference between means

Chicory fed lambs had the highest live weight and carcass weight at the end of Phase 1 and Raphanobrassica fed lambs had a higher carcass weight than PRG/WC fed lambs ( $p<0.05$ ; Table 5.5). Dressing out percentage was highest at the end of Phase 1 for lambs that had grazed Chicory and Raphanobrassica ( $p<0.001$ ).

Chicory fed lambs starting on Phase 2 were heavier than all other groups of lambs, and lambs crossing over from PRG/WC to Raphanobrassica were lighter than all other groups, despite being on the same forage type as PRG/WC and PRG/Chic in Phase 1 ( $p<0.001$ ). By the end of Phase 2, Chicory fed lambs

still had the highest liveweight, and PRG/Raph the lowest, although these were no different to PRG/WC fed lambs ( $p < 0.001$ ). Following the same pattern, liveweight gain per day was greatest for Chicory fed lambs across both phases and lowest for PRG/Raph fed lambs, but for Phase 2 this was no different to the growth rate of lambs on PRG/WC ( $p < 0.05$ ). Carcass weight was highest for Chicory fed lambs, followed by Raphanobrassica and PRG/Chic fed lambs ( $p < 0.001$ ). Like Phase 1, dressing out percentage was greatest for Chicory and Raphanobrassica fed lambs, however Raphanobrassica fed lambs were no different to PRG/Chic and PRG/Raph fed lambs ( $p < 0.001$ ).

**Table 5.3: Start and final live weight (kg), live weight gain (g/day), carcass weight (kg) and dressing out percentage for lambs grazing PRG/WC, Chicory, Raphanobrassica, PRG/Chic or PRG/Raph for Phase 1 (D<sub>1</sub>–D<sub>35</sub>: 17 Jan – 20 Feb) and Phase 2 (D<sub>36</sub> – D<sub>67</sub>: 21 Feb – 25 Mar). Data presented in this table is for lambs selected for meat quality testing (n=300) rather than the complete set of lambs used to set the stocking rate.**

	Forage Treatment					SEM	P-value
	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph		
<b>Phase 1 (D<sub>1</sub> – D<sub>35</sub>: 17 Jan – 20 Feb)</b>							
Live weight start (D <sub>1</sub> )	36.5	36.9	36.9	36.8	36.4	0.4	0.890
Live weight end (D <sub>35</sub> )	46.5 <sup>b</sup>	48.5 <sup>a</sup>	45.5 <sup>b</sup>	46.1 <sup>b</sup>	46.6 <sup>b</sup>	0.5	0.031
Lwt gain (D <sub>1</sub> – D <sub>35</sub> )	236	290	220	250	244	25	0.410
Carcass weight (kg)	17.8 <sup>c</sup>	20.1 <sup>a</sup>	18.7 <sup>b</sup>	17.4 <sup>c</sup>	17.8 <sup>c</sup>	0.3	<0.001
Dressing out (%)	38.2 <sup>b</sup>	41.6 <sup>a</sup>	41.2 <sup>a</sup>	37.9 <sup>b</sup>	38.1 <sup>b</sup>	0.4	<0.001
<b>Phase 2 (D<sub>36</sub> – D<sub>67</sub>: 21 Feb – 25 Mar)</b>							
Live weight start (D <sub>1</sub> )	35.5 <sup>b</sup>	35.5 <sup>b</sup>	35.5 <sup>b</sup>	35.7 <sup>b</sup>	36.6 <sup>a</sup>	0.2	0.019
Live weight start of phase 2 (D <sub>35</sub> )	43.4 <sup>b</sup>	47.2 <sup>a</sup>	42.8 <sup>b</sup>	41.9 <sup>b</sup>	39.3 <sup>c</sup>	0.6	<0.001
Live weight end (D <sub>67</sub> )	47.3 <sup>bc</sup>	55.6 <sup>a</sup>	48.4 <sup>b</sup>	48.9 <sup>b</sup>	44.6 <sup>c</sup>	0.7	<0.001
Lwt gain phase 1 (D <sub>1</sub> – D <sub>35</sub> )	187 <sup>b</sup>	279 <sup>a</sup>	175 <sup>b</sup>	148 <sup>b</sup>	69 <sup>c</sup>	14	<0.001
Lwt gain phase 2 (D <sub>36</sub> – D <sub>67</sub> )	139 <sup>c</sup>	300 <sup>a</sup>	200 <sup>bc</sup>	249 <sup>ab</sup>	185 <sup>c</sup>	19	0.003
Carcass weight (kg)	18.4 <sup>c</sup>	24.7 <sup>a</sup>	20.9 <sup>b</sup>	20.8 <sup>b</sup>	18.9 <sup>c</sup>	0.3	<0.001
Dressing out (%)	39.0 <sup>c</sup>	44.3 <sup>a</sup>	43.1 <sup>ab</sup>	42.5 <sup>b</sup>	42.3 <sup>b</sup>	0.4	<0.001

<sup>a,b,c</sup> Different letters within the same row denote significant difference between means

When considering all lambs involved in the study, for each phase there were differences between treatments in starting and final live weights, live weight gained and total carcass weight. In Phase 1, Raphanobrassica lambs had lower starting and end of phase live weight due to the additional lambs grazed lowering the average ( $p < 0.05$ ; Table 5.6). Live weight gain (g/day) was higher on Chicory fed lambs than on PRG/WC or Raphanobrassica fed lambs ( $p < 0.05$ ). Live weight gained and total carcass weight was greater on Chicory and Raphanobrassica than on PRG/WC during Phase 1 ( $p < 0.05$ ).

In Phase 2, starting live weight was greatest for Chicory fed lambs and lowest for Raphanobrassica fed lambs, with PRG/WC intermediate ( $p < 0.05$ ). Live weight at the end of Phase 2 was greater for Chicory fed lambs compared to lambs fed Raphanobrassica and PRG/WC ( $p < 0.05$ ). Chicory lambs had the fastest live weight gain (g/day), PRG/WC fed lambs the slowest, with Raphanobrassica fed lambs intermediate ( $p < 0.05$ ).

Raphanobrassica produced the greatest liveweight gain per hectare, PRG/WC the lowest, with Chicory intermediate ( $p < 0.001$ ). Raphanobrassica also produced the greatest total carcass weight per hectare compared to PRG/WC and Chicory ( $p < 0.001$ ).

In Phase 3, only data for PRG/WC and Raphanobrassica is presented as no Chicory lambs were introduced in this Phase due to insufficient pre grazing masses. There was no difference between PRG/WC and Raphanobrassica for live weight at the end of Phase 3 or live weight gain (g/day) ( $p > 0.05$ ). Raphanobrassica had higher live weight gained per hectare and total carcass weight than PRG/WC ( $p < 0.05$ ).

When considering the entire study period (Phases 1-3), Raphanobrassica had the greatest total live weight gain per hectare, followed by Chicory and then PRG/WC ( $p < 0.05$ ). Raphanobrassica also produced the most carcass weight per hectare compared to PRG/WC and Chicory ( $p < 0.001$ ).

**Table 5.4: Stocking rate, starting liveweight (kg), liveweight end of phase (kg) live weight gain (g/day), total live weight gained (kg/ha) and total carcass weight (kg/ha) for PRG/WC, Chicory, Raphanobrassica, PRG/Chic or PRG/Raph grazed during Phases 1 (17 Jan – 20 Feb), 2 (21 Feb – 25 Mar) and 3 (26 Mar – 1 May) of study 2. Data presented in this table is for all lambs utilised in the study (n=569).**

	Treatments			SEM	P-value
	PRG/WC	Chicory	Raphanobrassica		
<b>Phase 1 (D<sub>1</sub> – D<sub>35</sub>: 17 Jan - 20 Feb)</b>					
Stocking rate (lambs/ha)	31	31	46		
Starting lwt (kg)	35.2 <sup>a</sup>	35.4 <sup>a</sup>	33.4 <sup>b</sup>	0.3	0.018
Lwt end of phase 1 (kg)	46.5 <sup>a</sup>	47.0 <sup>a</sup>	44.3 <sup>b</sup>	0.4	0.012
Live weight gain (g/day)	184 <sup>b</sup>	272 <sup>a</sup>	175 <sup>b</sup>	9	0.004
Total live weight gained (kg/ha)	246 <sup>b</sup>	382 <sup>a</sup>	356 <sup>a</sup>	16	0.008
Total carcass weight (kg/ha)	222 <sup>b</sup>	402 <sup>a</sup>	318 <sup>a</sup>	24	0.016
<b>Phase 2 (D<sub>36</sub> -D<sub>67</sub>: 21 Feb - 25 Mar)</b>					
Stocking rate (lambs/ha)	19	15	34		
Lwt start of phase 2 (kg)	42.2 <sup>b</sup>	46.5 <sup>a</sup>	39.0 <sup>c</sup>	0.7	0.003
Lwt end of phase 2 (kg)	42.5 <sup>b</sup>	55.0 <sup>a</sup>	41.6 <sup>b</sup>	0.8	0.001
Live weight gain (g/day)	129 <sup>c</sup>	301 <sup>a</sup>	171 <sup>b</sup>	9	0.001
Total live weight gained (kg/ha)	68 <sup>c</sup>	126 <sup>b</sup>	156 <sup>a</sup>	5	<0.001
Total carcass weight (kg/ha)	335 <sup>b</sup>	366 <sup>b</sup>	687 <sup>a</sup>	9	<0.001
<b>Phase 3 (D<sub>68</sub> – D<sub>105</sub>: 26 Mar – 1 May)</b>					
Stocking rate (lambs/ha)	17	n/a <sup>1</sup>	35		
Final live weight (kg)	41.2	n/a <sup>1</sup>	40.2	0.5	0.254
Live weight gain (g/day)	118	n/a <sup>1</sup>	94	11	0.216
Live weight gained (kg/ha)	71 <sup>b</sup>	n/a <sup>1</sup>	109 <sup>a</sup>	3	0.016
Total carcass weight (kg/ha)	274 <sup>b</sup>	n/a <sup>1</sup>	606 <sup>a</sup>	8	0.001
<b>Cumulative (D<sub>1</sub> – D<sub>105</sub>: 17 Jan – 1 May)</b>					
Total live weight gained (kg/ha)	385 <sup>c</sup>	508 <sup>b</sup>	621 <sup>a</sup>	20	0.003
Total carcass weight (kg/ha)	831 <sup>b</sup>	767 <sup>b</sup>	1611 <sup>a</sup>	22	<0.001

<sup>a,b,c</sup> Different letters within the same row denote significant difference between means

<sup>1</sup>Due to dry conditions and insufficient herbage mass no lambs were introduced to Chicory in Phase 3 of the study

## 5.4 Discussion

The objective of the current study was to evaluate the effect of three forage-based diets, in conjunction with two treatments to look at the crossover from PRG/WC to alternative forages, on lamb growth rate and carcass weight per hectare. Forage type influenced lamb growth and carcass characteristics (carcass weight and dressing out percentage) on a per head and per hectare basis and the forage quality helped to explain the differences in weights of the lambs.

### 5.4.1 Forage measures

The pre and post herbage masses in Table 5.4 indicated that all treatments provided *ad libitum* feed to the lambs throughout the trial. In Phase 1, Raphanobrassica had the highest pre-grazing mass, which aligned with the results from Study 1 (Chapter 3). Due to this high pre grazing mass and expected forage growth, stocking rate was higher on Raphanobrassica than all other treatments. Apparent dry matter harvested was also higher on Raphanobrassica compared to the other treatments which was expected as there were a greater number of lambs grazing this forage, however the calculated herbage disappearance per lamb was also higher for this treatment suggesting greater daily intakes.

Phase 2 results were similar, with Raphanobrassica and crossover Raphanobrassica having the highest pre-grazing masses indicating strong regrowth after the first grazing round, and along with crossover Chicory had the highest apparent dry matter harvested. At 1347 and 1348 kgDM/ha, the post herbage mass of Chicory and crossover Chicory during Phase 2 dropped slightly below the desired post grazing mass of 1400 kg/ha (Morris & Kenyon, 2014) but calculated disappearance rates indicated that intakes were not negatively impacted. In this phase, calculated disappearance rates were lower on PRG/WC compared to all other treatments, which could be explained by the increase in NDF% and reduced digestibility likely to be restricting animal intakes.

Minimum and maximum daily temperatures were close to the 10 year averages throughout the study period, but rainfall was 29% below the 10 year average, with all months of the study having low rainfall. This impacted forage regrowth, particularly in the case of Chicory and prevented lambs from grazing Chicory in Phase 3 of the study.

Crude protein on Chicory and Raphanobrassica on D<sub>17</sub> and on crossover Chicory and crossover Raphanobrassica on D<sub>55</sub> were below the 15% minimum requirement that is recommended for finishing lambs (Hodgson & Brookes, 1999). Crude protein on Raphanobrassica in the first study was 19.9% and another previous analysis found crude protein levels of 22.1% (Dumbleton et al., 2021). Chicory has crude protein levels between 13.4 and 24.4% (Barry, 1998; Crush & Evans, 1990; Fraser & Rowarth, 1996) and was 16.9% in Study 1 (Chapter 3). Studies of similar forages have attributed low crude protein to insufficient plant available nitrogen, grazing frequency and height of post grazing mass (Lee

et al., 2015; Westwood & Mulcock, 2012). In general, Chicory and Raphanobrassica have a lower protein content but, this didn't appear to negatively impact the growth of lambs. The higher calculated herbage disappearance rates (suggestive of intake) achieved suggests that the lambs were able to achieve sufficient protein intake on these forages. Further this may be preventing excess ammonia formation in the rumen allowing for more efficient nitrogen use in the lambs. This aspect of the nutritive value warrants further investigation.

Chicory and Raphanobrassica had lower NDF% and ADF% and were more digestible than PRG/WC throughout the study period. They also remained stable over time where PRG/WC increased in NDF and ADF and decreased in digestibility between the two sampling dates, likely driven by the dry conditions recorded during the study. Metabolisable energy levels followed the trend of digestibility, it was lower on PRG/WC than Chicory and Raphanobrassica and decreased over time. ME levels were as expected for these forage types, demonstrating a key reason Chicory and Raphanobrassica are used as summer forage options for lambs. Raphanobrassica ME levels had increased from 9.9 MJ/kg in study 1 to 12.0 MJ/kg in this study, likely reflecting an improvement in grazing management (high stocking rate and lower residuals) and the result from this study was similar to previous research (Dumbleton et al., 2021).

#### 5.4.2 Lamb performance per head

Live weight gain (g/day), final live weight, carcass weight and dressing out percentage per head of the lambs selected for meat quality differed among the treatments. For the lambs selected for slaughter in phase 1, final live weight, carcass weight and dressing out percentage was highest on Chicory, although the dressing out percentage was equally high on Raphanobrassica. This aligned with the results of Study 1 (Chapter 3), where growth of lambs on Chicory was greater than lambs on other forages in the early stages of the experiment. Previous research has consistently shown Chicory to have high feeding value and animal performance during summer (Barry, 1998; Kemp et al., 2010; Li & Kemp, 2005). Lambs grazed on Raphanobrassica had a higher carcass weight than PRG/WC but was similar in terms of final live weight, the higher carcass weight owing to the higher dressing out percentage on Raphanobrassica compared to PRG/WC. Live weight gain (g/day) was not different between treatments for this group of lambs in Phase 1; however their growth rates overall were higher than the lambs selected for slaughter in Phase 2 and higher than the lambs in study 1.

For the lambs selected for slaughter in phase 2, their live weight gain in the first phase (35 days) was highest on Chicory, with PRG/WC and Raphanobrassica being equal. Live weight gain was lower for the PRG/Raph lambs than other treatments, which is difficult to explain given they were grazing on the same pasture type as the PRG/WC and PRG/Chic lambs. As a result, the starting live weight of the lambs on this treatment was lower than other treatments at the start of phase 2. At the end of phase

1, the lambs grazing the crossover treatments transferred over to their new forage type, either Chicory or Raphanobrassica. The growth rates of the same lambs in phase 2 were highest on Chicory and PRG/Chic (now grazing Chicory), with PRG/Chic being similar to Raphanobrassica. The fast growth of Chicory fed lambs continued despite forage growth of Chicory declining, seen by the lower pre-grazing masses in Table 5.4. This could be explained by the low NDF and high digestibility of Chicory measured in this phase, providing evidence that faster growth rates seen with lambs grazed on Chicory were due to a higher nutritive value rather than solely due to an increased forage availability increasing intake. Growth rates on Raphanobrassica increased from 175 g/day to 200 g/day from phase 1 to phase 2, owing to the lambs having transitioned to the new feed type and allowing the high forage quality of Raphanobrassica to be realised (Barry, 2013). Their growth rates were greater than lambs fed PRG/WC in Phase 2, due to the reduced effect of transition and forage quality testing indicated Raphanobrassica quality measures remained stable where PRG/WC quality declined (increased NDF, lower digestibility and ME) which is typical under summer dry conditions. Despite the decline in phase 2, growth rates of lambs grazing PRG/WC were still greater in study 2 than in study 1 (139 g/day vs 50 g/day in phase 2), likely due to tetraploid perennial ryegrass being used rather than diploid. Growth rates increased as the crossover lambs were shifted from PRG/WC to Chicory or Raphanobrassica at the start of phase 2, however the time taken to transition from PRG/WC to Raphanobrassica limited potential compensatory growth after being on PRG/WC.

Final live weight of the phase 2 lambs was again highest on Chicory, followed by Raphanobrassica, PRG/Chic and PRG/WC, with PRG/WC being no different to PRG/Raph. Similarly, carcass weight was highest on Chicory, followed by Raphanobrassica and PRG/Chic. Dressing out percentages were lower on PRG/WC than all other treatments, including the crossover treatments. This demonstrates that increases in dressing out percentages can be realised over summer pasture within 32 days (the length of phase 2). Both Chicory and Raphanobrassica demonstrated improved lamb production over PRG/WC, especially in phase 2 of the study where weather conditions caused the forage quality of PRG/WC to decline. However, these results highlight that performance on a per lamb basis was consistently highest with Chicory, attributable to its high feeding value and quick time to transition.

#### 5.4.3 Lamb performance per hectare

Considerable research has been undertaken for individual lamb performance on different forage types, however very few consider per hectare performance. Understanding both the individual lamb performance combined with the stocking rate, gives a better indication of the impact of a forage on the overall farm system. Both total live weight gained per hectare and carcass weight produced per hectare are useful measures and with the first having greater relevance when selling lambs, and the latter more important in finishing systems when sending lambs for slaughter.

In Phase 1, both Chicory and Raphanobrassica had higher live weight gained per hectare and carcass weight produced per hectare than PRG/WC. This is similar to what was measured by Somasiri (2014) who investigated live weight gained per hectare on pasture versus a plantain-clover and chicory-clover mixture over two years. For Phase 1 (35 days) of this study, 246 kg/ha of live weight was gained on PRG/WC, 382 kg/ha on Chicory and 356 kg/ha on Raphanobrassica. For comparison, over 49 days in summer, Somasiri (2014) found live weight gained was 173 kg/ha in Year 1 for pasture, 408 kg/ha and 367 kg/ha for plantain and chicory mixes respectively. With a 14-day shorter feeding duration than the study by Somasiri (2014), live weight gained on PRG/WC was higher in this study, and performance of the Plantain and Chicory mixes was similar to the Chicory and Raphanobrassica in this study. The difference in production on PRG/WC is likely due to established diploid perennial ryegrass-based pasture being utilised by Somasiri (2014), and newly sown tetraploid perennial ryegrass/white clover being used in this study which would have higher quality. Nichol et al., (2010) assessed lamb liveweight per hectare on tetraploid perennial ryegrass/white clover pasture, with summer daily liveweight gains per hectare of 6.74 kg/ha/day, which over 35 days equates to 236 kg/ha, very similar to what was gained in the current study.

In Phases 2 and 3 (70 days total), 139 kg/ha of live weight was gained on PRG/WC, 126 kg/ha on Chicory (Phase 2 only) and 265 kg/ha on Raphanobrassica. Comparing again to Somasiri (2014), over 35 days in autumn, live weight gained per hectare was 139 kg/ha on PRG/WC, 282 kg/ha and 258 kg/ha on Plantain and Chicory mixes respectively. Whilst the current study was a longer feeding duration in autumn, there was no spelling of the treatments to allow regrowth as there was in between the summer and autumn grazing in the studies of Somasiri (2014). Live weight gained was similar on PRG/WC in autumn, and Raphanobrassica was similar to the Plantain and Chicory mixes. Chicory from the current study did not perform as well as in the Somasiri study in autumn, however the dry summer conditions restricted forage regrowth. In the Nichol et al., (2010) study, autumn daily liveweight gain was 5.16 kg/ha on tetraploid PRG/WC, which would equate to 361 kg/ha, much higher than the results of the current study but this is again likely to the dry conditions experienced. Overall, the similarities between studies help to provide a benchmark for per hectare production of lamb finishing forages in New Zealand.

Per hectare performance could be driven either by per head liveweight gain of the lambs or by the stocking rate. A study compared performance of 'conventional' tetraploid PRG/WC to a 'switch' treatment where pastures of pure white clover were grazed over spring and summer then overdrilled with Italian ryegrass for the autumn and winter (Nichol et al., 2010). The annual per hectare performance of the two treatments was similar, however they differed seasonally. The 'switch' treatment had greater average daily liveweight gain but had less total grazing days than conventional,

with the authors observing each treatment had advantages and disadvantages. In the current study, while both Chicory and Raphanobrassica had greater production per hectare than PRG/WC, there were different drivers for each forage type. For live weight gained per hectare, the increase seen in Chicory could be explained by the faster growth rates measured for individual lambs as the stocking rate was the same as PRG/WC. However, for Raphanobrassica, the increase can be attributed to an increased stocking rate made possible by higher pre grazing masses measured on this forage type. For both Chicory and Raphanobrassica, their higher dressing out percentages compared to PRG/WC also influenced the greater carcass weight produced per hectare.

Similar trends were seen in Phase 2, with Raphanobrassica having the highest live weight gained and carcass weight produced per hectare. Chicory had a higher live weight gained than PRG/WC, but the same carcass weight produced per hectare. The greater per hectare performance on Raphanobrassica was again primarily driven by the higher stocking rate than the other treatments, however in this phase Raphanobrassica lambs also grew faster on a per lamb basis than PRG/WC fed lambs. The increase in carcass weight produced by Raphanobrassica in phase 2 compared to Phase 1 can also be attributed to many lambs not reaching finishing weight of 39kg in the first phase due to the time taken to transition to a new forage type. Chicory lambs still had the highest growth rate per lamb in this phase, but per hectare performance was not as high as Raphanobrassica due to summer dry conditions restricting regrowth of this forage, reducing the pre-grazing mass and stocking rate to achieve *ad libitum* feeding.

Sheep and beef farms in the east coast and central regions of New Zealand typically have shallow soils and experience dry summers, making soil moisture a major limitation of growth of quality feed (Moot & Davison, 2021). In addition to the known reduction in pasture growth rates and feed quality (Burke et al., 2002), the availability of sufficient soil moisture often limits biomass yield of summer forage crops such as herbs and brassicas. Selection of forage crops which can extract water from deeper in the soil profile or have greater water use efficiency is advantageous where summer rainfall is not reliable to maximise the quantity of quality feed for livestock. Chicory has a tap root which allows for extraction of water from deeper in the profile and greater water use efficiency than pasture (Li & Kemp, 2005; Moot et al., 2008). However, in both of the studies in this thesis, forage growth rates of chicory were considerably reduced under the extreme conditions experienced where rainfall averaged 30% below the 10 year average.

Chicory has similar water use efficiency to forage rape and turnips at 30 kg DM/ha/mm (Brown et al., 2005; Fletcher et al., 2010). Raphanobrassica is an intergeneric hybrid between kale and radish and one key attribute of the radish component is providing improved drought tolerance compared to other forage brassica species (Dumbleton et al., 2021; Percival et al., 1986). The water use efficiency of

Raphanobrassica has been recently compared to forage rape in a very shallow soil and had 38% greater water use efficiency than forage rape (Chakwizira et al., 2021). It would be beneficial to compare the water use efficiency of Raphanobrassica to other commonly used summer forage crops such as chicory under the same soil type and nitrogen applications to assess the drivers of the forage yields.

## 5.5 Conclusion

In summary, both Chicory and Raphanobrassica provided advantages over PRG/WC on a per lamb and per hectare basis. The way they promote lamb growth performance was different, and each had a different impact on the overall farm system. Chicory had superior per lamb performance compared to Raphanobrassica, and the lambs fed this forage transitioned quickly and did not need to be grazed for as long to reach target live weights. However, forage growth under very dry conditions was poor and this forage was not able to support large numbers of grazing lambs. Raphanobrassica had poorer per lamb performance than Chicory, and lambs took longer to transition, meaning that the feeding value of this forage took longer to be realised. The benefit of Raphanobrassica was that superior forage growth under challenging conditions meant that available biomass was high and large numbers of lambs were able to be grazed, which resulted in higher per hectare performance. These results suggest that the two forages would have different uses in the farm system, with larger lambs being grazed on Chicory for faster growth and finishing and increased dressing out percentage. Raphanobrassica would be targeted at smaller lambs which would graze for longer, allowing time for transition and a sustained source of quality feed which also provides a higher dressing out percentage than summer pasture.

## Chapter 6

### Experiment 2: Influence of Chicory, Raphanobrassica or Perennial Ryegrass/White Clover Diet and Grazing Duration on Meat Quality and Fat Characteristics of Lambs



## 6.1 Introduction

Study 2 was designed to help understand if grazing alternative forages and the length of time spent grazing these alternative forages influenced the meat quality, fat characteristics and volatile profile of lamb. Commercial lamb finishing operations require rapid turnover of lambs and so forages that can result in fast lamb growth with a desirable fatty acid profile in a short feeding duration is advantageous. While lamb growth is easily measured, knowledge of the rate of fatty acid uptake from dietary sources into muscle is less understood. There is a knowledge gap regarding the effect of length of time fed a finishing diet on meat quality (Ponnampalam et al., 2024). Some previous research suggested muscle fatty acid composition continues to change until 42 days following a diet change, and thereafter change is minimal (Aurousseau, Bauchart, Faure, et al., 2007; Aurousseau, Bauchart, Galot, et al., 2007; Bessa et al., 2008; Griswold et al., 2003).

New Zealand lamb production systems are predominantly based on perennial ryegrass/white clover (PRG/WC) pasture (White & Hodgson, 1999). Lambs that graze PRG/WC naturally have higher levels of polyunsaturated fatty acids (PUFA), including medium and long chain omega-3 and omega-6, compared to lambs finished on concentrate based diets (Ponnampalam, Butler, Pearce, et al., 2014). Raising levels of long chain PUFA helps to ensure the meat produced meets source labelling standards. For example, Food Standards of Australia and New Zealand (2012) consider eicosapentaenoic acid and docosahexaenoic acid (EPA + DHA) values exceeding 23 mg/100g muscle to be a 'source' of EPA + DHA. Meeting such standards is important as consumers become more aware of the healthiness of their food choices (Fowler et al., 2019). PRG/WC quality is inconsistent throughout the year, with season and maturity influencing forage quality and concentration of fatty acids (Boufaïed et al., 2003; Clapham et al., 2005; Elgersma et al., 2003). Late spring and summer coincide with perennial ryegrass' reproductive growth, where the plants produce stem and seedhead, which is lower quality feed (Litherland & Lambert, 2007). Dry periods exacerbate the change in quality, with increased lignification and less leaf production. Inconsistent delivery of dietary fatty acids under dry conditions makes PRG/WC pasture a less favourable feed for the production of lamb to meet consumer requirements.

The liking of lamb meat is not universal between consumers, with cultural background and previous experience driving preference (Font-i-Furnols & Guerrero, 2014; Miller, 2020). Flavour is a combination of taste and olfactory factors but is primarily driven by volatile chemicals that are perceived by the olfactory epithelium at the back of the nose (Farmer, 1994). Lamb flavour and volatiles are affected by production factors such as lamb age, sex of lamb and finishing diet (Watkins et al., 2013). Identifying the volatile profiles of lamb meat from different finishing diets can help to

distinguish potential differences in flavour to ensure product acceptability or differentiate meat to unique export markets.

It is hypothesised that a longer grazing duration would result in lambs that are heavier at slaughter with greater fat deposition and a fatty acid profile that was more saturated. Based on the findings of Study 1, we expected similar measures of objective meat quality in meat from lambs grazing the 3 forage treatments, but differences in fat deposition would drive change in fatty acid profiles. The volatile profile of lamb meat was expected to be unique to the forage treatments.

Therefore, study 2 was implemented to consider how grazing lambs on the alternative forages of Chicory and Raphanobrassica influenced meat quality, fatty acid composition and volatile profile of the lamb meat, compared to PRG/WC pasture using replicated plots in a farmlet study design. The availability of grown forage feed and the need to get lambs finished for slaughter as quickly as possible for on-farm efficiency implied that length of time on an alternative grazed forage needed to be managed. Study 2 used two slaughter periods providing lambs that grazed forages for two lengths of time to understand the how length of time on a forage influenced meat quality and fat characteristics of lambs. This builds on the findings from Study 1 (Chapter 4), where six commonly used lamb finishing forages were grazed for a 64 day finishing period to assess their impact on meat quality and fat deposition of lambs.

## 6.2 Materials and Methods

### 6.2.1 Experimental design and treatments

This study was located at Massey University's Keeble Farm (40°23'52.6"S 175°35'57.2"E), 5 km Southeast of Palmerston North, Manawatu, New Zealand on a Tokomaru Silt Loam soil. The forage treatments were sown on 25 November 2019 with a roller drill and chain harrows. The study ran for 67 days, from 17 January 2020 to 25 March 2020. When referring to a day of the study, the day will be written in subscript after the letter D (i.e. day 6 = D<sub>6</sub>). The design involved 5 treatments, each replicated 3 times (Table 6.1). Three forages of Perennial ryegrass + white clover (PRG/WC), Chicory & Raphanobrassica were utilised for the study, and a partial crossover design was included where two treatments started on Perennial ryegrass + white clover (PRG/WC) for the first 35 days of the study and then transferred to either Chicory (PRG/Chic) or Raphanobrassica (PRG/Raph) for the final 32 days of the study. For the non-crossover treatments, 2.4 hectares of each forage type was sown, split over 3 replicates (0.8 hectares for each replicate). For the crossover treatments, 2.4 hectares of PRG/WC was sown and 1.5 hectares of Chicory or Raphano brassica, split over 3 replicates (0.8 ha of PRG/WC, 0.5 ha of Chicory or Raphanobrassica per replicate).

**Table 6.1: Details of area sown, lamb numbers and forage diet for each of the five treatments. Number of lambs per replicate represents the number of meat quality lambs grazing, and does not include additional lambs allocated to set the stocking rate**

Treatment	Area sown per replicate (ha)	Lamb numbers per replicate D <sub>1</sub> -D <sub>35</sub>	Forage diet D <sub>1</sub> -D <sub>35</sub>	Lamb numbers per replicate D <sub>36</sub> -D <sub>67</sub>	Forage diet D <sub>36</sub> -D <sub>67</sub>
Perennial ryegrass + White clover (PRG/WC)	0.8	25	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	15	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )
Chicory	0.8	25	Chicory ( <i>Chicorium intybus</i> )	12	Chicory ( <i>Chicorium intybus</i> )
Raphanobrassica	0.8	25	Raphano brassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)	15	Raphanobrassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)
Crossover 1: Perennial ryegrass + White clover → Chicory <sup>1</sup> (PRG/Chic)	0.8 PRG + WC 0.5 Chicory	25	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	15	Chicory ( <i>Chicorium intybus</i> )
Crossover 2: Perennial ryegrass + White clover → Raphanobrassica <sup>1</sup> (PRG/Raph)	0.8 PRG + WC 0.5 Raphano brassica	25	Perennial ryegrass ( <i>Lolium perenne</i> ) + white clover ( <i>Trifolium repens</i> )	15	Raphanobrassica ( <i>Raphanus sativus</i> L. x <i>Brassica oleracea</i> L.)

<sup>1</sup>Crossover treatments (1 and 2) started on Perennial ryegrass/white clover for the first 35 days of the study then transferred to either Chicory or Raphanobrassica for the final 32 days of the study

## 6.2.2 Animals and management

All animal procedures were approved by the Massey University Animal Ethics Committee (Protocol No. 19/114).

Three hundred and seventy-five weaned Romney-cross, wether lambs aged approximately 5 months were utilised for the trial. Lambs were selected from the Massey University Tuapaka farm flock to ensure sufficient lambs with the same breeding and management were available, and represented a typical New Zealand lamb for finishing. Lambs were given an electronic identification (EID) tag and

weighed prior to being allocated to a treatment group. Lambs were balanced for liveweight, resulting in a starting liveweight of 36.2 kg  $\pm$  0.1 kg across the treatment groups, and ranged from 29.6 kg to 42.2 kg. Twenty-five lambs were allocated to each replicate, a total of 75 lambs per treatment. Once the lambs had been allocated, they were tagged with a coloured Flexi-tag and spray marked to represent their treatment and replicate to ensure easy visual identification.

All lambs were orally drenched with Ancare 'Matrix' triple combination drench (active ingredients abamectin, levamisole and oxfendazole, and 0.5 g/L selenium and 2.2 g/L cobalt) at D<sub>-31</sub>, D<sub>11</sub> and D<sub>39</sub>. All lambs were shorn and vaccinated with Ultravac '7 in 1' vaccine on D<sub>-20</sub>, then given a booster on D<sub>11</sub>. All lambs were given access to hay for the first seven days to assist with the transition to a different feed type. Access to fresh water was unrestricted.

### 6.2.3 Slaughter

There were two slaughter dates, one on 20/02/20 (D<sub>35</sub>) and one on 20/03/20 (D<sub>67</sub>). At each slaughter date, the 10 heaviest lambs from each replicate were slaughtered (a total of 30 per treatment) so that a total of 300 lambs were slaughtered over the two days (10 lambs x 3 replicates x 5 treatments x 2 days = 300 lambs). Lambs were transported to a commercial abattoir (Alliance Group Ltd, Dannevirke), where they were held in lairage overnight and slaughtered in a single group the following morning in accordance with the New Zealand welfare code for the slaughter of commercial animals.

### 6.2.4 Carcass preparation and measurements

Carcasses were prepared following standard commercial dressing procedures for New Zealand export lamb. Each carcass was given an identification number that linked to the slaughter order and electronic identification tag, allowing traceability of each individual lamb. Hot carcass weight (HCW) was recorded; the lean meat yield (LMY) and depth of tissue at the GR site (tissue depth 110 mm from the midline on the 12<sup>th</sup> rib) was obtained using the Alliance Group VIAscan<sup>®</sup> system (Hopkins et al., 2004).

### 6.2.5 Loin meat quality, intramuscular fat and fatty acid analyses

The carcasses were chilled at -4°C for 12 hours then both the left and right bone-in short loin (*Longissimus lumborum*, LL) were removed from each carcass and vacuum-packed with their respective carcass identification tag. The samples were then transported to the Massey University Pilot Plant and aged at 1°C for 21 days to mimic typical procedures for export lamb, followed by frozen storage at -30°C.

Short loin samples (LL) (n=300) were analysed over a 6-week period. The samples were thawed at 1°C for 24 hours prior to analysis. The packaged bone-in short loin was weighed, then the short loin and

the packaging dried with paper towels and weighed. The loin was boned out, fat cap removed and partitioned into sections (Figure 4.1; Chapter 4) for each of the objective meat quality tests. Testing methods for objective meat quality (pH, meat colour, shear force, water holding capacity), intramuscular fat and fatty acid composition were fully described in Chapter 4 and only additional tests are described here.

#### 6.2.6 Volatile compounds analysis

Five samples per treatment replicate and per slaughter day (5 samples x 3 replicates x 5 treatments x 2 days = 150 total) that were randomly selected for intramuscular fat and fatty acid analysis (refer to methods in Chapter 4) were also utilised for volatile compound analysis. The lamb was cooked and prepared for analysis as per (Pavan et al., 2021). Of the 150 samples submitted for analysis, 10 per day were randomly selected to be analysed by SPME-GC-MS in duplicate. The order of samples analysed each day, through the SPME-GC-MS, were randomised and blocked by duplicate (i.e., 10 samples of duplicate 1 randomised and then duplicate 2 randomised separately). The samples were stored on the autosampler at 2°C prior to incubation and analysis. The compound identity and compound peak areas were extracted using Paradise (PARAFAC2 based Deconvolution and Identification System; version 3.2) and peak areas normalised to the internal standard. Compounds were identified by comparing the deconvoluted mass spectra and calculated retention indices to the NIST14 GC-MS database.

#### 6.2.7 Statistical analysis

All data was tested for normality and outliers using Genstat 24.0 (VSN-International, 2024) before analysis.

Final live weight, carcass weight, dressing out percentage and carcass characteristics were analysed using an analysis of variance (ANOVA) with a fixed effects of forage treatment, day (grazing duration, 35 or 67 days) and the interacting effect of treatment x day as fixed effects in the statistical model in Genstat 24.0 (VSN International, 2024). An analysis of covariance was utilised for intramuscular fat with carcass weight included as a covariate.

Objective meat quality was analysed using an analysis of covariance, with muscle pH included as a covariate in the model. Fatty acid composition of forages was analysed using an ANOVA and fatty acid composition of meat was analysed using an analysis of covariance with intramuscular fat as the covariate in the model. All models included fixed effects of forage treatment, day (grazing duration) and the interacting effect of treatment x day. Covariates were included in models to assess any treatment effects over and above the effect of the covariate as meat ultimate pH is known to influence meat quality measures and intramuscular fat concentration influences fatty acid profile.

The replicates for each forage treatment were analysed as a nested fixed effect with animal within replicate used in the model. The replicate effect for the variables analysed were found to be non-significant ( $p > 0.05$ ).

Differences among least square means were assessed according to Fisher's unprotected least significant difference test and were considered significant at a probability level of  $< 0.05$ .

Relative abundance of volatiles was analysed using an ANOVA (with fixed effects of forage treatment, day and the interaction of treatment x day) and additionally a stepwise discriminant analysis was used to understand the volatiles of influence (Fisher, 1936). For the ANOVA, the relative abundance was  $\log_{10}$  transformed and the values presented are back transformed. A least significant ratio is presented for the back transformed means which indicates the means are significantly different if the larger mean divided by the smaller mean is greater than the LSR.

A censoring technique was used to remove the impact of outlying values. With this method values above or below the censoring limits are statistically placed within the limits. This is considered a robust method for dealing with outliers (rather than making them missing values) because it still allows them to be part of the analysis but, removes the bias they have on mean values.

The stepwise discriminant analysis identified that 10 volatiles accounted for the greatest variation between treatments. A canonical variate analysis (CVA) was applied to the 10 volatiles and gave 8 canonical variables, with the first two accounting for 71% of the total variability which are presented as the scores 1 & 2 on the axes Figure 6.2. These are the most important two directions of variation that separate the treatment groups.



**Figure 6.1: Drone picture of Experiment 2: Replicates 1 & 2 (12 January 2020)**

## 6.3 Results

### 6.3.1 Final liveweight and carcass measurements

Final liveweight, carcass weight, dressing out percentage, intramuscular fat percentage (IMF%) and VIAScan GR were greater for lambs that had been on their treatments for 67 days compared to those only on their treatments for 35 days (Table 6.2,  $p < 0.001$ ). Within each slaughter group, Chicory fed lambs had a heavier final liveweight and carcass weight ( $p < 0.001$ ). The differences between forage treatments for final liveweight and carcass weight were greater for lambs that had grazed their treatments for 67 days, indicated by the treatment by day interaction ( $p < 0.001$ ). Final live weights were similar for PRG/WC fed and Raphanobrassica fed lambs after both 35 and 67 days, however Raphanobrassica fed lambs had greater carcass weight than PRG/WC fed lambs ( $p < 0.001$ ). Dressing out percentage was greater for Chicory and Raphanobrassica fed lambs compared to the PRG/WC treatment after both 35 and 67 days ( $p < 0.001$ ). Dressing out percentage of lambs that had crossed over to Chicory or Raphanobrassica was greater than PRG/WC fed lambs, and no different to lambs fed Raphanobrassica for 67 days. There were no treatment effects for IMF ( $p > 0.05$ ). However, there were treatment differences for VIAScan estimated GR, where after 35 days grazing, Chicory and Raphanobrassica had greater GR values than the three other treatments grazing PRG/WC (PRG/WC, PRG/Chic, PRG/Raph) ( $p < 0.001$ ). After 67 days grazing, Chicory fed lambs had the greatest GR, followed by Raphanobrassica fed lambs but these were no different to lambs that had crossed over to Chicory for the second part of the study ( $p < 0.001$ ).

There was no treatment effect for VIAScan estimated total yield ( $p > 0.05$ ), however there was a day effect for total yield where yields were lower for lambs that has grazed for 67 days compared to 35 days ( $p = 0.009$ ). There was a treatment by day interaction where lambs that transferred to grazing Raphanobrassica for  $D_{35-D_{67}}$  had a lower total yield compared to the other forage treatments ( $p = 0.002$ ). VIAScan estimated leg yields were greatest on PRG/WC fed lambs ( $p < 0.001$ ). Lambs that had grazed for 67 days had lower leg yields than lambs that had grazed for 35 days ( $p < 0.001$ ). This decrease was evident in lambs fed Chicory for 67 days compared to 35 days, and the two crossover treatments where lambs had switched from PRG/WC to Chicory or Raphanobrassica ( $p < 0.05$ ). VIAScan loin yields were lower when lambs switched from PRG/WC to Raphanobrassica ( $p < 0.05$ ). There were treatment and day effects for shoulder yield, where lambs that had been grazing for 67 days had greater shoulder yields than lambs that had grazed for 35 days ( $p < 0.05$ ) and Chicory fed lambs that had grazed for 67 days had the greatest shoulder yields, but these were no different to Raphanobrassica and PRG/Chicory fed lambs after 67 days, or Chicory fed lambs after 35 days ( $p < 0.05$ ).

### *5.3.2 Objective meat quality*

Chicory fed lambs had the lowest pH after 35 days grazing, with no differences measured between the other treatments (Table 6.3;  $p < 0.05$ ). After 67 days grazing, PRG/WC and PRG/Chic fed lambs had a lower pH than Raphanobrassica and PRG/Raph fed lambs, with Chicory fed lambs intermediate ( $p < 0.05$ ). Analysis of the remaining objective meat quality measures with and without the pH covariate resulted in a pattern of differences that was comparable (Tables 6.3 & 6.4). Differences in lightness were measured for both treatment ( $p < 0.05$ ) and day ( $p < 0.001$ ), but not in other aspects of meat colour (redness & yellowness). Differences in lightness were only recorded in the lambs grazed for 35 days, where Chicory fed lambs had lighter meat than all other treatments ( $p < 0.05$ ). Values for shear force work done and peak shear force were greater for lambs grazed for 67 days compared to 35 days, regardless of treatment ( $p < 0.001$ ). For lambs that had grazed for 67 days, Raphanobrassica fed lambs had a higher work done and peak force than Chicory fed lambs, with no differences between the other treatments ( $p < 0.001$ ). Drip loss was greater in lambs grazed for 67 days ( $p < 0.001$ ).

**Table 6.2: Mean values for hot carcass weight, final liveweight, dressing out percentage, intramuscular fat (IMF) and yield breakdown of lambs grazed on PRG/WC, Chicory or Raphanobrassica for 35 or 67 days**

	35 Days on Treatment (Slaughter 1)					67 Days on Treatment (Slaughter 2)					SEM	P-value			
	PRG/WC	Chicory	Raphano-brassica	PRG/Chic <sup>3</sup>	PRG/Raph <sup>3</sup>	PRG/WC	Chicory	Raphano-brassica	PRG/Chic <sup>3</sup>	PRG/Raph <sup>3</sup>		Trt	Day	Trt x Day	Carcass weight covariate
Start live weight (kg)	36.5 <sup>abc</sup>	36.9 <sup>a</sup>	36.9 <sup>a</sup>	36.8 <sup>a</sup>	36.4 <sup>abcd</sup>	35.5 <sup>cd</sup>	35.5 <sup>cd</sup>	35.5 <sup>d</sup>	35.7 <sup>bcd</sup>	36.6 <sup>ab</sup>	0.35	0.742	<0.001	0.195	
Final live weight (kg)	46.5 <sup>cde</sup>	48.5 <sup>bc</sup>	45.5 <sup>de</sup>	46.1 <sup>de</sup>	46.7 <sup>cde</sup>	47.3 <sup>bcd</sup>	55.6 <sup>a</sup>	48.4 <sup>bc</sup>	48.9 <sup>b</sup>	44.6 <sup>e</sup>	0.73	<0.001	<0.001	<0.001	
Carcass weight (kg)	17.8 <sup>ef</sup>	20.1 <sup>b</sup>	18.7 <sup>cd</sup>	17.4 <sup>f</sup>	17.8 <sup>def</sup>	18.4 <sup>cde</sup>	24.7 <sup>a</sup>	20.9 <sup>b</sup>	20.8 <sup>b</sup>	18.9 <sup>c</sup>	0.32	<0.001	<0.001	<0.001	
Dressing out (%)	38.2 <sup>e</sup>	41.6 <sup>cd</sup>	41.1 <sup>d</sup>	37.9 <sup>e</sup>	38.1 <sup>e</sup>	39.0 <sup>e</sup>	44.3 <sup>a</sup>	43.1 <sup>b</sup>	42.5 <sup>bc</sup>	42.3 <sup>bcd</sup>	0.40	<0.001	<0.001	<0.001	
IMF (%)	1.4 <sup>c</sup>	1.5 <sup>c</sup>	1.7 <sup>bc</sup>	1.4 <sup>c</sup>	1.3 <sup>c</sup>	2.2 <sup>ab</sup>	2.1 <sup>ab</sup>	1.7 <sup>abc</sup>	2.1 <sup>ab</sup>	2.3 <sup>a</sup>	0.19	0.995	<0.001	0.159	
IMF <sup>1</sup> (%)	1.4 <sup>c</sup>	1.5 <sup>c</sup>	1.7 <sup>bc</sup>	1.5 <sup>c</sup>	1.3 <sup>c</sup>	2.2 <sup>ab</sup>	1.9 <sup>ab</sup>	1.7 <sup>abc</sup>	2.0 <sup>ab</sup>	2.3 <sup>a</sup>	0.35	0.168	0.002	0.201	0.752
V-GR <sup>2</sup>	6.1 <sup>e</sup>	9.3 <sup>cd</sup>	8.5 <sup>d</sup>	6.0 <sup>e</sup>	5.7 <sup>e</sup>	6.4 <sup>e</sup>	13.1 <sup>a</sup>	10.7 <sup>b</sup>	9.8 <sup>bc</sup>	9.1 <sup>cd</sup>	0.44	<0.001	<0.001	0.004	
Leg yield % <sup>2</sup>	22.2 <sup>a</sup>	21.5 <sup>bc</sup>	21.3 <sup>cd</sup>	21.9 <sup>ab</sup>	22.3 <sup>a</sup>	21.8 <sup>ab</sup>	21.0 <sup>de</sup>	20.9 <sup>de</sup>	21.3 <sup>cd</sup>	20.6 <sup>e</sup>	0.16	<0.001	<0.001	0.002	
Loin yield % <sup>2</sup>	14.7 <sup>a</sup>	14.8 <sup>ab</sup>	14.5 <sup>bc</sup>	14.9 <sup>a</sup>	15.0 <sup>a</sup>	14.8 <sup>ab</sup>	14.9 <sup>a</sup>	14.7 <sup>ab</sup>	14.9 <sup>ab</sup>	14.2 <sup>c</sup>	0.12	0.084	0.199	0.002	
Shoulder yield % <sup>2</sup>	16.2 <sup>d</sup>	16.6 <sup>abcd</sup>	16.5 <sup>bcd</sup>	16.2 <sup>cd</sup>	16.4 <sup>bcd</sup>	16.3 <sup>cd</sup>	17.0 <sup>a</sup>	16.8 <sup>ab</sup>	16.7 <sup>abc</sup>	16.4 <sup>bcd</sup>	0.16	0.020	0.024	0.454	
Total yield % <sup>2</sup>	53.1 <sup>ab</sup>	52.9 <sup>ab</sup>	52.3 <sup>b</sup>	53.1 <sup>ab</sup>	53.8 <sup>a</sup>	52.9 <sup>ab</sup>	52.9 <sup>ab</sup>	52.4 <sup>b</sup>	52.9 <sup>ab</sup>	51.2 <sup>c</sup>	0.31	0.152	0.009	0.002	

<sup>a,b,c,d,e,f</sup> Different letters within the same row denote significant difference between means.

<sup>1</sup>IMF adjusted to an equal carcass weight (kg)

<sup>2</sup>Estimated by VIA Scan

<sup>3</sup> Lambs grazed on Pasture for D<sub>1</sub> – D<sub>35</sub>, then transferred to Chicory or Raphanobrassica for D<sub>35</sub> – D<sub>67</sub>

**Table 3: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 35 or 67 days.**

	35 Days on Treatment (Slaughter 1)					67 Days on Treatment (Slaughter 2)					P-values			
	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph	SEM	Trt	Day	Trt x Day
Ultimate pH	5.64 <sup>a</sup>	5.58 <sup>cd</sup>	5.64 <sup>a</sup>	5.67 <sup>a</sup>	5.67 <sup>a</sup>	5.56 <sup>d</sup>	5.58 <sup>bcd</sup>	5.63 <sup>abc</sup>	5.56 <sup>d</sup>	5.64 <sup>ab</sup>	0.019	0.011	0.001	0.039
Lightness (L*)	35.40 <sup>b</sup>	36.90 <sup>a</sup>	35.49 <sup>b</sup>	35.54 <sup>b</sup>	35.61 <sup>b</sup>	35.43 <sup>b</sup>	35.51 <sup>b</sup>	35.23 <sup>bc</sup>	35.26 <sup>bc</sup>	34.67 <sup>c</sup>	0.229	0.002	0.001	0.036
Redness (a*)	15.43	15.42	15.21	15.29	15.28	15.67	15.54	15.27	15.61	15.31	0.258	0.726	0.365	0.975
Yellowness (b*)	6.90 <sup>ab</sup>	7.23 <sup>ab</sup>	6.79 <sup>ab</sup>	6.64 <sup>b</sup>	6.80 <sup>ab</sup>	7.38 <sup>a</sup>	7.22 <sup>ab</sup>	7.22 <sup>ab</sup>	7.16 <sup>ab</sup>	6.93 <sup>ab</sup>	0.206	0.373	0.029	0.630
Work done (kgF)	11.63 <sup>cd</sup>	10.94 <sup>d</sup>	11.45 <sup>cd</sup>	11.76 <sup>c</sup>	11.53 <sup>cd</sup>	15.14 <sup>ab</sup>	14.58 <sup>b</sup>	15.60 <sup>a</sup>	14.71 <sup>b</sup>	15.08 <sup>ab</sup>	0.245	0.055	<0.001	0.235
Peak force (kgF)	2.52 <sup>c</sup>	2.42 <sup>c</sup>	2.45 <sup>c</sup>	2.60 <sup>c</sup>	2.54 <sup>c</sup>	3.11 <sup>ab</sup>	2.96 <sup>b</sup>	3.24 <sup>a</sup>	3.14 <sup>ab</sup>	3.09 <sup>ab</sup>	0.061	0.077	<0.001	0.228
Drip loss (%)	2.63 <sup>bc</sup>	2.32 <sup>bc</sup>	2.13 <sup>c</sup>	2.32 <sup>bc</sup>	2.16 <sup>c</sup>	3.58 <sup>a</sup>	3.17 <sup>ab</sup>	3.52 <sup>a</sup>	3.68 <sup>a</sup>	3.09 <sup>ab</sup>	0.292	0.492	<0.001	0.809
Cook loss (%)	31.31	31.67	31.76	31.74	31.94	31.58	31.20	31.65	31.94	31.26	0.293	0.602	0.406	0.437

<sup>a,b,c,d,e</sup> Different letters within the same row denote significant difference between means.

**Table 6.4: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed five forage treatments. The means were statistically analysed with pH as a covariate.**

	35 Days on Treatment (Slaughter 1)					67 Days on Treatment (Slaughter 2)					SEM	P-values			
	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph		Trt	Day	Trt x Day	Sig of pH CoV
Ultimate pH	5.64 <sup>a</sup>	5.58 <sup>cd</sup>	5.64 <sup>a</sup>	5.67 <sup>a</sup>	5.67 <sup>a</sup>	5.56 <sup>d</sup>	5.58 <sup>bcd</sup>	5.63 <sup>abc</sup>	5.56 <sup>d</sup>	5.64 <sup>ab</sup>	0.019	0.011	0.001	0.039	
Lightness ( <i>L</i> *)	35.52 <sup>bcd</sup>	36.71 <sup>a</sup>	35.61 <sup>bcd</sup>	35.82 <sup>bc</sup>	35.88 <sup>b</sup>	35.15 <sup>cde</sup>	35.34 <sup>bcd</sup>	35.29 <sup>bcd</sup>	34.95 <sup>de</sup>	34.77 <sup>e</sup>	0.241	0.004	<0.001	0.108 0.070	
Redness ( <i>a</i> *)	15.68 <sup>ab</sup>	15.02 <sup>cd</sup>	15.48 <sup>abcd</sup>	15.86 <sup>a</sup>	15.84 <sup>a</sup>	15.09 <sup>cd</sup>	15.18 <sup>bcd</sup>	15.39 <sup>abcd</sup>	14.98 <sup>d</sup>	15.53 <sup>abc</sup>	0.188	0.675	0.174	0.180 <0.001	
Yellowness ( <i>b</i> *)	7.10 <sup>a</sup>	6.91 <sup>ab</sup>	7.00 <sup>ab</sup>	7.10 <sup>a</sup>	7.25 <sup>a</sup>	6.92 <sup>ab</sup>	6.92 <sup>ab</sup>	7.32 <sup>a</sup>	6.65 <sup>b</sup>	7.11 <sup>a</sup>	0.149	0.428	0.954	0.205 <0.001	
Work done (kgF)	11.60 <sup>c</sup>	10.99 <sup>c</sup>	11.42 <sup>c</sup>	11.69 <sup>c</sup>	11.46 <sup>c</sup>	15.21 <sup>ab</sup>	14.62 <sup>b</sup>	15.59 <sup>a</sup>	14.78 <sup>ab</sup>	15.06 <sup>ab</sup>	0.284	<0.001	<0.001	0.484 0.698	
Peak force (kgF)	2.54 <sup>cd</sup>	2.39 <sup>d</sup>	2.47 <sup>cd</sup>	2.65 <sup>c</sup>	2.59 <sup>cd</sup>	3.06 <sup>ab</sup>	2.93 <sup>b</sup>	3.25 <sup>a</sup>	3.09 <sup>ab</sup>	3.11 <sup>ab</sup>	0.069	<0.001	<0.001	0.159 0.265	
Drip loss (%)	2.70 <sup>abc</sup>	2.22 <sup>c</sup>	2.20 <sup>c</sup>	2.47 <sup>bc</sup>	2.31 <sup>c</sup>	3.43 <sup>ab</sup>	3.07 <sup>abc</sup>	3.55 <sup>a</sup>	3.51 <sup>a</sup>	3.15 <sup>abc</sup>	0.334	0.318	<0.001	0.848 0.448	
Cook loss (%)	31.48 <sup>abcd</sup>	31.39 <sup>bcd</sup>	31.95 <sup>abc</sup>	32.14 <sup>ab</sup>	32.33 <sup>a</sup>	31.18 <sup>cd</sup>	30.94 <sup>d</sup>	31.73 <sup>abcd</sup>	31.50 <sup>abcd</sup>	31.42 <sup>bcd</sup>	0.299	0.283	0.029	0.703 0.036	

<sup>a,b,c,d,e</sup> Different letters within the same row denote significant difference between means.

### 6.3.3 Fatty acid composition of muscle

There were no forage treatment effects on most of the fatty acids apart from the n-6 PUFA. Lambs fed Chicory for 35 days had greater levels of n-6 PUFA than the other 35-day treatment lambs (Table 6.5;  $p < 0.05$ ). There was also a day by treatment effect for the n-6 PUFA with lambs fed Raphanobrassica for 67 days had lower n-6 PUFA than PRG/WC fed lambs or PRG/Chicory fed lambs after 67 days ( $p < 0.05$ ).

The sum of fatty acids, levels of saturated fatty acids and monounsaturated fatty acids were greater for lambs grazed for 67 days compared to lambs that had grazed these forages for 35 days ( $p < 0.001$ ). Meat from lambs fed PRG/WC and lambs that started on PRG/WC and transferred to either Chicory (PRG/Chic) or Raphanobrassica (PRG/Raph) on D<sub>35</sub> for the final 32 days of grazing had greater levels of SFA, MUFA, PUFA, ALA, n-6 PUFA and n-3 PUFA but lower EPA+DHA and LC n-3 PUFA after 67 days grazing compared to 35 days grazing ( $p < 0.01$ ). Meat from lambs fed Chicory for 67 days had lower levels of EPA + DHA and long chain n-3 PUFA compared the meat from lambs fed Chicory for only 35 days ( $p < 0.05$ ). Similarly, meat from lambs that grazed PRG/WC for the first 35 days then transferred to Chicory (PRG/Chic) had lower levels of long chain n-3 PUFA after transferring to Chicory ( $p < 0.001$ ). Chicory fed lambs had the highest PUFA:SFA ratio after 35 days, but there was no difference to lambs initially fed PRG/WC and then transferred to Chicory ( $p < 0.05$ ).

The IMF was a significant covariate in the analysis of PUFA, C18:3 n-3 and n-6 PUFA, but not for any other fatty acid measures (Table 6.6;  $p < 0.05$ ). As with the unadjusted fatty acid results, there were no treatment differences for any of the fatty acid measures except for n-6 PUFA ( $p > 0.05$ ). The meat from lambs fed Chicory and PRG/Raph had greater levels of SFA and MUFA after 67 days compared to 35 days ( $p = 0.008$ ). EPA + DHA levels did not change over time for PRG/WC, Chicory, Raphanobrassica and PRG/Raph fed lambs, but the meat from PRG/Chic fed lambs levels were lower for EPA + DHA after 67 days compared to 35 days ( $p = 0.049$ ). A similar trend was evident with LC n-3 PUFA, except levels were lower in the meat from Chicory and PRG/Chic fed lambs after 67 days compared to 35 days ( $p < 0.05$ ).

**Table 6.5: Fatty acid content (mg/100g raw meat) of the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 35 or 67 days**

	35 Days on Treatment					67 Days on Treatment					SEM	P-values		
	PRG/WC	Chicory	Raphanobrassica	PRG/Chic	PRG/Raph	PRG/WC	Chicory	Raphanobrassica	PRG/Chic	PRG/Raph		Trt	Day	Trt x Day
Sum of FA	2342.40 <sup>bcd</sup>	2157.45 <sup>d</sup>	2359.95 <sup>bcd</sup>	2256.18 <sup>cd</sup>	2102.61 <sup>d</sup>	2668.04 <sup>ab</sup>	2726.91 <sup>a</sup>	2671.02 <sup>ab</sup>	2559.12 <sup>abc</sup>	2857.92 <sup>a</sup>	112.444	0.861	<0.001	0.213
Unreported FA	110.48 <sup>ab</sup>	97.64 <sup>b</sup>	104.56 <sup>ab</sup>	102.24 <sup>ab</sup>	99.60 <sup>ab</sup>	105.29 <sup>ab</sup>	111.04 <sup>ab</sup>	111.12 <sup>ab</sup>	101.82 <sup>ab</sup>	114.76 <sup>a</sup>	5.255	0.747	0.093	0.280
BCFA	31.32 <sup>ab</sup>	26.14 <sup>b</sup>	28.26 <sup>ab</sup>	29.14 <sup>ab</sup>	27.46 <sup>ab</sup>	30.55 <sup>ab</sup>	32.19 <sup>ab</sup>	30.14 <sup>ab</sup>	28.29 <sup>ab</sup>	33.15 <sup>a</sup>	2.135	0.825	0.092	0.332
SFA	1061.91 <sup>bcd</sup>	963.10 <sup>d</sup>	1052.80 <sup>bcd</sup>	1025.94 <sup>cd</sup>	936.44 <sup>d</sup>	1196.29 <sup>ab</sup>	1240.40 <sup>a</sup>	1195.67 <sup>ab</sup>	1146.53 <sup>abc</sup>	1312.26 <sup>a</sup>	56.521	0.928	<0.001	0.143
MUFA	943.75 <sup>cd</sup>	854.26 <sup>d</sup>	977.79 <sup>bcd</sup>	895.93 <sup>d</sup>	846.26 <sup>d</sup>	1115.25 <sup>ab</sup>	1135.35 <sup>a</sup>	1130.38 <sup>a</sup>	1059.97 <sup>abc</sup>	1186.34 <sup>a</sup>	51.292	0.622	<0.001	0.294
PUFA	226.26 <sup>cde</sup>	242.45 <sup>abc</sup>	224.79 <sup>de</sup>	232.07 <sup>bcde</sup>	220.31 <sup>e</sup>	251.21 <sup>a</sup>	240.13 <sup>abcd</sup>	233.86 <sup>abcde</sup>	250.80 <sup>a</sup>	244.55 <sup>ab</sup>	5.843	0.181	<0.001	0.145
EPA + DHA	28.61 <sup>abcd</sup>	29.88 <sup>ab</sup>	29.36 <sup>ab</sup>	30.26 <sup>a</sup>	28.90 <sup>abc</sup>	28.48 <sup>abcd</sup>	27.11 <sup>cd</sup>	28.16 <sup>bcd</sup>	26.79 <sup>d</sup>	28.30 <sup>abcd</sup>	0.706	0.996	0.002	0.131
C18:3 n-3 (ALA)	46.7 <sup>de</sup>	55.2 <sup>bcd</sup>	50.6 <sup>cde</sup>	48.2 <sup>de</sup>	45.0 <sup>e</sup>	63.0 <sup>ab</sup>	59.8 <sup>abc</sup>	53.9 <sup>bcde</sup>	64.9 <sup>a</sup>	60.5 <sup>ab</sup>	3.181	0.411	<0.001	0.109
n-3 PUFA	96.51 <sup>cd</sup>	106.80 <sup>abc</sup>	101.09 <sup>abcd</sup>	100.47 <sup>bcd</sup>	94.97 <sup>d</sup>	111.56 <sup>a</sup>	106.85 <sup>abc</sup>	102.31 <sup>abcd</sup>	111.09 <sup>a</sup>	108.90 <sup>ab</sup>	3.530	0.523	0.002	0.135
n-6 PUFA	93.82 <sup>c</sup>	108.42 <sup>ab</sup>	94.52 <sup>c</sup>	100.94 <sup>bc</sup>	94.36 <sup>c</sup>	112.59 <sup>a</sup>	104.69 <sup>ab</sup>	101.33 <sup>bc</sup>	113.48 <sup>a</sup>	106.66 <sup>ab</sup>	2.997	0.029	<0.001	0.018
LC n-3 PUFA	49.82 <sup>abc</sup>	51.65 <sup>a</sup>	50.53 <sup>ab</sup>	52.27 <sup>a</sup>	49.96 <sup>abc</sup>	48.53 <sup>bcd</sup>	47.01 <sup>cd</sup>	48.36 <sup>bcd</sup>	46.15 <sup>d</sup>	48.45 <sup>bcd</sup>	1.012	0.999	<0.001	0.107
PUFA:SFA	0.22 <sup>bcde</sup>	0.25 <sup>a</sup>	0.22 <sup>bcde</sup>	0.23 <sup>abc</sup>	0.24 <sup>ab</sup>	0.22 <sup>bcde</sup>	0.20 <sup>de</sup>	0.21 <sup>cde</sup>	0.22 <sup>abcd</sup>	0.19 <sup>e</sup>	0.010	0.603	0.001	0.039
n-6:n-3	0.98	1.02	0.94	1.01	1.00	1.01	0.98	0.99	1.02	0.98	0.017	0.105	0.343	0.081

a, b, c, d, e Different letters within the same row denote significant difference between means. <sup>1</sup>BCFA =  $\sum$  iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>2</sup>SFA =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>3</sup>MUFA =  $\sum$  C14:1, C16:1, C17:1 C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11. <sup>4</sup>PUFA =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3, C18:2 *cis*-9, *trans*-11. <sup>5</sup>EPA + DHA =  $\sum$  C20:5n-3, C22:6n-3. <sup>6</sup>n-3 PUFA =  $\sum$  C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3. <sup>7</sup>n-6 PUFA =  $\sum$  C18:2n-6, C20:4n-6. <sup>8</sup>LC n-3 PUFA =  $\sum$  C20:5n-3, C22:5n-3, C22:6n-3.

**Table 6.6: Fatty acid content (mg/100g fresh meat) of the Longissimus lumborum (loin) adjusted for IMF % from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 35 or 67 days**

	35 days on treatment					67 days on treatment					SEM	P-values			
	PRG/WC	Chicory	Raphanobrassica	PRG/Chic	PRG/Raph	PRG/WC	Chicory	Raphanobrassica	PRG/Chic	PRG/Raph		Trt	Day	Trt x Day	IMF CoV
Sum of FA	2400.59 <sup>bcd</sup>	2195.53 <sup>d</sup>	2360.15 <sup>bcd</sup>	2307.49 <sup>cd</sup>	2175.09 <sup>d</sup>	2607.82 <sup>abc</sup>	2682.26 <sup>ab</sup>	2675.23 <sup>abc</sup>	2512.84 <sup>abcd</sup>	2784.61 <sup>a</sup>	123.97	0.855	0.004	0.336	0.321
Unreported FA	111.82	98.53	104.56	103.42	101.28	103.90	110.01	111.21	100.74	113.07	5.926	0.764	0.366	0.296	0.627
BCFA	31.61	26.33	28.26	29.39	27.82	30.26	31.97	30.16	28.06	32.79	2.420	0.845	0.344	0.366	0.800
SFA	1091.87 <sup>abcd</sup>	982.71 <sup>cd</sup>	1052.90 <sup>bcd</sup>	1052.37 <sup>bcd</sup>	973.77 <sup>d</sup>	1165.28 <sup>abc</sup>	1217.40 <sup>ab</sup>	1197.83 <sup>ab</sup>	1122.70 <sup>abcd</sup>	1274.51 <sup>a</sup>	62.221	0.930	0.008	0.224	0.309
MUFA	964.43 <sup>bcd</sup>	867.79 <sup>d</sup>	977.86 <sup>bcd</sup>	914.17 <sup>cd</sup>	872.02 <sup>d</sup>	1093.85 <sup>ab</sup>	1119.48 <sup>ab</sup>	1131.87 <sup>ab</sup>	1043.53 <sup>abc</sup>	1160.29 <sup>a</sup>	57.229	0.609	0.001	0.444	0.442
PUFA	232.46 <sup>abc</sup>	246.50 <sup>a</sup>	224.82 <sup>c</sup>	237.53 <sup>abc</sup>	228.03 <sup>bc</sup>	244.79 <sup>ab</sup>	235.37 <sup>abc</sup>	234.31 <sup>abc</sup>	245.87 <sup>a</sup>	236.75 <sup>abc</sup>	5.774	0.125	0.278	0.212	0.032
EPA + DHA	28.18 <sup>abc</sup>	29.60 <sup>ab</sup>	29.36 <sup>abc</sup>	29.88 <sup>a</sup>	28.36 <sup>abc</sup>	28.92 <sup>abc</sup>	27.44 <sup>bc</sup>	28.13 <sup>abc</sup>	27.13 <sup>c</sup>	28.84 <sup>abc</sup>	0.769	0.997	0.049	0.096	0.238
C18:3 n-3 (ALA)	49.94 <sup>bc</sup>	57.27 <sup>abc</sup>	50.57 <sup>bc</sup>	51.06 <sup>bc</sup>	49.05 <sup>c</sup>	59.67 <sup>ab</sup>	57.35 <sup>abc</sup>	54.18 <sup>abc</sup>	62.36 <sup>a</sup>	56.37 <sup>abc</sup>	3.182	0.355	0.055	0.360	0.040
n-3 PUFA	99.16	108.54	101.09	102.81	98.27	108.82	104.82	102.50	108.99	105.57	3.759	0.519	0.391	0.385	0.144
n-6 PUFA	96.77 <sup>cd</sup>	110.35 <sup>ab</sup>	94.53 <sup>d</sup>	103.54 <sup>abc</sup>	98.03 <sup>cd</sup>	109.54 <sup>ab</sup>	102.43 <sup>bcd</sup>	101.54 <sup>bcd</sup>	111.14 <sup>a</sup>	102.95 <sup>abcd</sup>	3.028	0.018	0.080	0.019	0.049
LC n-3 PUFA	49.22 <sup>abcd</sup>	51.26 <sup>ab</sup>	50.52 <sup>abc</sup>	51.75 <sup>a</sup>	49.22 <sup>abcd</sup>	49.15 <sup>abcd</sup>	47.47 <sup>cd</sup>	48.32 <sup>bcd</sup>	46.62 <sup>d</sup>	49.20 <sup>abcd</sup>	1.106	0.998	0.009	0.086	0.257

a, b, c, d, e Different letters within the same row denote significant difference between means. <sup>1</sup>BCFA =  $\sum$  iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>2</sup>SFA =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>3</sup>MUFA =  $\sum$  C14:1, C16:1, C17:1, C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11. <sup>4</sup>PUFA =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3, C18:2 *cis*-9, *trans*-11. <sup>5</sup>EPA + DHA =  $\sum$  C20:5n-3, C22:6n-3. <sup>6</sup>n-3 PUFA =  $\sum$  C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3. <sup>7</sup>n-6 PUFA =  $\sum$  C18:2n-6, C20:4n-6. <sup>8</sup>LC n-3 PUFA =  $\sum$  C20:5n-3, C22:5n-3, C22:6n-3.

#### *6.3.4 Fatty acid composition of forage*

Raphanobrassica had the lowest concentration of fatty acids ( $p < 0.001$ ; Table 6.7). PRG/WC had a greater saturated fatty acid (SFA) concentration than both Chicory and Raphanobrassica across both sampling dates ( $p < 0.001$ ). The concentration of SFA in Chicory was greater at D<sub>55</sub> than D<sub>17</sub> ( $p < 0.001$ ). Polyunsaturated fatty acid (PUFA) levels were similar in PRG/WC and Chicory on D<sub>17</sub> but lower in PRG/WC at D<sub>55</sub> ( $p < 0.001$ ). Monounsaturated fatty acid (MUFA) levels were lowest in Chicory on D<sub>17</sub> but were greater at D<sub>55</sub> in both Chicory and PRG/WC, where Raphanobrassica remained the same ( $p < 0.001$ ). Levels of n-3 PUFA were similar for PRG/WC and Chicory on D<sub>17</sub> but were lower at D<sub>55</sub> compared to D<sub>17</sub> in the PRG/WC ( $p < 0.001$ ). The n-3 PUFA in Raphanobrassica was lower than the other forages and remained the same over the two sampling periods. Crossover Chicory (PRG/Chic) had lower n-3 PUFA than non-crossover Chicory ( $p < 0.001$ ). Chicory had the highest n-6 PUFA across the sampling dates, and all forages remained similar over time ( $p < 0.001$ ). Like with n-3 PUFA, crossover Chicory had less n-6 PUFA than Chicory ( $p < 0.001$ ).

**Table 6.7: Fatty acid content (mg/g dry weight) of forage (PRG/WC, Chicory and Raphanobrassica) collected on 3 February 2020 (D<sub>17</sub>) and 12 March 2020 (D<sub>55</sub>). Farmlet replicates (3) provided replication at each sampling date.**

	3/02/2020 (D <sub>17</sub> )					12/03/2020 (D <sub>55</sub> )					SEM	P-value (Date x Trt)
	PRG/WC	Chicory	Raphano- brassica	PRG/Chic (PRG) <sup>1</sup>	PRG/Raph (PRG) <sup>1</sup>	PRG	Chicory	Raphano- brassica	PRG/Chic (Chicory) <sup>1</sup>	PRG/Raph (Raphano- brassica) <sup>1</sup>		
Sum of FA	25.80 <sup>ab</sup>	24.73 <sup>ab</sup>	11.13 <sup>d</sup>	24.55 <sup>ab</sup>	26.68 <sup>a</sup>	22.41 <sup>bc</sup>	25.43 <sup>ab</sup>	9.79 <sup>d</sup>	19.84 <sup>c</sup>	8.70 <sup>d</sup>	1.19	<0.001
SFA <sup>2</sup>	8.53 <sup>a</sup>	5.97 <sup>d</sup>	4.43 <sup>e</sup>	8.15 <sup>ab</sup>	8.20 <sup>ab</sup>	8.67 <sup>a</sup>	7.32 <sup>bc</sup>	4.28 <sup>e</sup>	6.83 <sup>cd</sup>	3.55 <sup>e</sup>	0.34	<0.001
PUFA <sup>3</sup>	15.69 <sup>ab</sup>	18.02 <sup>a</sup>	5.35 <sup>e</sup>	14.59 <sup>bc</sup>	16.89 <sup>ab</sup>	11.03 <sup>d</sup>	16.54 <sup>ab</sup>	4.43 <sup>e</sup>	11.86 <sup>cd</sup>	4.13 <sup>e</sup>	1.04	<0.001
MUFA <sup>4</sup>	1.58 <sup>bc</sup>	0.73 <sup>e</sup>	1.35 <sup>cd</sup>	1.81 <sup>b</sup>	1.60 <sup>bc</sup>	2.71 <sup>a</sup>	1.57 <sup>bc</sup>	1.08 <sup>de</sup>	1.15 <sup>d</sup>	1.02 <sup>de</sup>	0.12	<0.001
n-3 PUFA <sup>5</sup>	12.39 <sup>ab</sup>	13.67 <sup>a</sup>	3.86 <sup>d</sup>	11.16 <sup>b</sup>	13.43 <sup>ab</sup>	7.25 <sup>c</sup>	11.48 <sup>ab</sup>	3.08 <sup>d</sup>	8.43 <sup>c</sup>	2.85 <sup>d</sup>	0.81	<0.001
n-6 PUFA <sup>6</sup>	3.30 <sup>c</sup>	4.35 <sup>ab</sup>	1.49 <sup>d</sup>	3.42 <sup>c</sup>	3.46 <sup>c</sup>	3.78 <sup>bc</sup>	5.06 <sup>a</sup>	1.34 <sup>d</sup>	3.42 <sup>c</sup>	1.28 <sup>d</sup>	0.26	<0.001

<sup>a, b, c, d, e</sup> Different letters within the same row denote significant difference between means. <sup>1</sup> Forage in brackets is the forage sampled at each sampling date, based on which forage the lambs were grazing at the time <sup>2</sup>Saturated fatty acids (SFA) =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, C24:0. <sup>3</sup>Polyunsaturated fatty acids (PUFA) =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3. <sup>4</sup>Monounsaturated fatty acids (MUFA) =  $\sum$  C14:1, C16:1, C17:1, C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11, C20:1. <sup>5</sup>n-3 PUFA = C18:3 n3. <sup>6</sup>n-6 PUFA = C18:2n-6

### 6.3.5 Volatile compounds

#### Acids

The top three most abundant volatile acids were acetic acid, pentanoic acid and hexanoic acid. Meat from lambs that had grazed for 67 days had a greater relative abundance of hexanoic acid in the headspace than meat from lambs that had grazed for 35 days (Table 6.8;  $p=0.042$ ). Meat from only the PRG/WC-fed lambs was relatively more abundant for 2-methyl-propanoic acid after 67 days compared to 35 days, but not for meat from lambs on other treatments ( $p=0.021$ ).

#### Alcohols

Relative abundance of 1-pentenol, 1-penten-3-ol and Z-2-penten-1-ol in the headspace of lamb meat was different between treatments (Table 6.8;  $p<0.05$ ). More abundant 1-penten-3ol was observed from the meat of lambs fed Chicory for 35 days compared to lambs fed PRG/WC, PRG/Chic and PRG/Raph for 35 days, but not different to lambs fed Raphanobrassica for 35 days (Table 6;  $p=0.026$ ). 1-pentenol was relatively more abundant from the meat of lambs fed Chicory for either 35 or 67 days than lambs fed Raphanobrassica for 35 or 67 days and lambs fed PRG/WC for 35 days ( $p=0.001$ ). For the meat obtained from lambs after 35 days of grazing the relative abundance of 1-penten-3-ol of meat from Chicory fed lambs was greater than PRG/WC -fed ( $p=0.026$ ). These three alcohols increased in relative abundance from the meat after 67 days of grazing ( $p<0.05$ ). Raphanobrassica fed lambs were the exception, with relative abundance of 1-penten-3-ol decreasing in the headspace of the meat from lambs that had grazed Raphanobrassica for 67 days compared to 35 days. ( $p=0.011$ ). The 1-octen-3-ol and 1-propanol also increased in abundance from the meat of the lambs at 67 days grazing compared to 35 days grazing ( $p<0.05$ ).

#### Aldehydes

Of all the aldehydes hexanal and heptanal were present in the greatest abundance in the headspace of the meat from lambs but the abundance of these volatiles in the meat was similar for lambs fed the different forage treatments (Table 6.8;  $p>0.05$ ). Relative abundance of pentanal in lambs fed Chicory for 67 days was greater than lambs fed Raphanobrassica for 67 days and lambs fed PRG/WC or Raphanobrassica for 35 days ( $p=0.047$ ). Pentanal, hexanal and propanal abundance increased while 2-methylbutanal and 3-methylbutanal abundance decreased in the headspace of meat of lambs grazing the forages for 67 days compared to 35 days ( $p<0.05$ ). The abundance of 3-methylbutanal in lambs fed PRG/Chic shifted from the greatest abundance after 35 days to the least after shifting to Chicory in the second phase and slaughtering at 67 days in the experiment ( $p=0.022$ ). Within the lambs that had been grazing for 35 days, the meat from Chicory fed lambs had the lowest relative abundance of nonanal, but after 67 days of grazing, the meat from Chicory fed lambs had greater relative abundance than Raphanobrassica and PRG/Chic fed lambs ( $p=0.009$ ).

### **Ketones**

Acetone was more abundant in the headspace of meat from lambs fed Chicory for 35 days than lambs fed PRG/WC or Raphanobrassica for 35 days (Table 6.8;  $p=0.03$ ). Relative abundance of acetone in lambs fed PRG/WC and Raphanobrassica increased over time, where abundance in Chicory fed lambs decreased and as a result had a lower abundance than lambs fed PRG/WC for 67 days ( $p<0.001$ ). The abundance of butyrolactone decreased ( $p<0.001$ ) and 2,3-pentanedione increased in the meat from the lambs that had grazed for 67 days compared to 35 days ( $p=0.003$ ).

### **Hydrocarbons**

1-octene was present in relatively greater abundance from the meat of lambs fed PRG/WC compared to other forage diets (Table 6.8;  $p=0.006$ ). Switching from a PRG/WC diet to chicory was associated with lower abundance of 1-octene from the meat of lambs ( $p=0.001$ ). Similarly, octane was present in lower abundance in lambs fed Chicory for 35 days and lambs fed PRG/Chic for 67 days than other treatment groups, but no different to lambs fed Raphanobrassica or PRG/Raph for 67 days ( $p=0.026$ ). Relative abundance of octane and 2 and 3-octene was lower for meat from lambs grazed for 67 days compared to 35 days ( $p<0.05$ ). Within the 35-day group of lambs, lambs fed Chicory had a relatively lower abundance of toluene than other treatments, however this effect was less evident in the 67-day lambs where they only had a lower relative abundance than Raphanobrassica and PRG/Raph fed lambs ( $p<0.001$ ). Relative abundance of toluene in meat from lambs fed PRG/WC in the first 35 days of the study (PRG/WC, PRG/Chic and PRG/Raph) was greater in abundance than the lambs fed PRG/WC for 67 days ( $p<0.001$ ).

### **Sulphur Compounds**

Dimethyl sulfide was less abundant in the meat of lambs fed PRG/WC than the meat from lambs fed Chicory and Raphanobrassica for 35 days (Table 6.8;  $p=0.002$ ). In the meat of PRG/WC fed lambs the abundance of dimethyl sulfide was greater after 67 days of grazing compared to 35 days grazing ( $p<0.001$ ). Lambs fed Raphanobrassica for 35 days had a greater relative abundance of dimethyl sulfone than other treatments ( $p=0.010$ ) and abundance of this volatile decreased in the meat of lambs that had grazed for 67 days ( $p<0.001$ ).



**Table 6.8: Relative abundance of volatile compounds in the headspace of cooked lamb loin from lambs finished on Pasture, Chicory or Raphanobrassica for 35 or 67 days. Values presented are log<sub>10</sub> transformed.**

Treatment	Slaughter 1					Slaughter 2					P-values				
	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph	PRG/WC	Chicory	Raphano-brassica	PRG/Chic	PRG/Raph	Approx SEM	LSD / LSR 5%	Trt	Day	Trt x Slt
<b>Acids</b>															
Acetic acid	0.085	0.100	0.117	0.094	0.109	0.108	0.086	0.088	0.102	0.089	0.010	1.34	0.932	0.337	0.081
2-Methyl-Propanoic acid	0.021 <sup>c</sup>	0.029 <sup>ab</sup>	0.028 <sup>ab</sup>	0.026 <sup>bc</sup>	0.026 <sup>abc</sup>	0.034 <sup>a</sup>	0.027 <sup>ab</sup>	0.028 <sup>ab</sup>	0.028 <sup>ab</sup>	0.024 <sup>bc</sup>	0.003	1.31	0.732	0.142	0.021
Butanoic acid	0.036	0.043	0.042	0.038	0.042	0.042	0.039	0.038	0.036	0.035	0.005	1.41	0.925	0.463	0.660
Pentanoic acid	0.040	0.037	0.040	0.039	0.040	0.049	0.047	0.039	0.040	0.042	0.005	1.36	0.788	0.153	0.709
Hexanoic acid	0.058 <sup>b</sup>	0.058 <sup>b</sup>	0.060 <sup>ab</sup>	0.063 <sup>ab</sup>	0.058 <sup>ab</sup>	0.077 <sup>ab</sup>	0.079 <sup>a</sup>	0.061 <sup>ab</sup>	0.064 <sup>ab</sup>	0.064 <sup>ab</sup>	0.007	1.36	0.805	0.042	0.454
Heptanoic acid	0.027	0.024	0.028	0.026	0.028	0.034	0.032	0.024	0.027	0.029	0.003	1.33	0.565	0.178	0.223
<b>Alcohols</b>															
1-Butanol	0.056 <sup>c</sup>	0.074 <sup>abc</sup>	0.064 <sup>bc</sup>	0.076 <sup>ab</sup>	0.070 <sup>abc</sup>	0.080 <sup>ab</sup>	0.089 <sup>a</sup>	0.082 <sup>ab</sup>	0.088 <sup>a</sup>	0.085 <sup>ab</sup>	0.008	1.33	0.300	0.001	0.873
1-Penten-3-ol	0.420 <sup>bc</sup>	0.628 <sup>a</sup>	0.549 <sup>ab</sup>	0.457 <sup>bc</sup>	0.375 <sup>c</sup>	0.635 <sup>a</sup>	0.702 <sup>a</sup>	0.454 <sup>bc</sup>	0.557 <sup>ab</sup>	0.630 <sup>a</sup>	0.058	1.35	0.026	0.002	0.011
1-Pentanol	0.604 <sup>bc</sup>	0.866 <sup>a</sup>	0.545 <sup>c</sup>	0.689 <sup>abc</sup>	0.549 <sup>c</sup>	0.805 <sup>ab</sup>	0.909 <sup>a</sup>	0.610 <sup>bc</sup>	0.713 <sup>abc</sup>	0.770 <sup>ab</sup>	0.073	1.33	0.001	0.013	0.450
Z-2-Penten-1-ol	0.036 <sup>cd</sup>	0.054 <sup>ab</sup>	0.046 <sup>abc</sup>	0.040 <sup>bcd</sup>	0.033 <sup>d</sup>	0.055 <sup>a</sup>	0.062 <sup>a</sup>	0.040 <sup>cd</sup>	0.047 <sup>abc</sup>	0.058 <sup>a</sup>	0.005	1.36	0.028	0.002	0.017
1-Hexanol	0.117	0.097	0.100	0.110	0.106	0.099	0.138	0.086	0.086	0.108	0.013	1.40	0.384	0.596	0.104
1-Octen-3-ol	0.103 <sup>bc</sup>	0.124 <sup>abc</sup>	0.104 <sup>bc</sup>	0.118 <sup>abc</sup>	0.093 <sup>c</sup>	0.132 <sup>ab</sup>	0.161 <sup>a</sup>	0.099 <sup>bc</sup>	0.113 <sup>bc</sup>	0.133 <sup>ab</sup>	0.014	1.39	0.085	0.045	0.281
1-Heptanol	0.061 <sup>abc</sup>	0.054 <sup>bc</sup>	0.056 <sup>bc</sup>	0.061 <sup>abc</sup>	0.055 <sup>bc</sup>	0.058 <sup>bc</sup>	0.084 <sup>a</sup>	0.052 <sup>bc</sup>	0.048 <sup>c</sup>	0.071 <sup>ab</sup>	0.007	1.41	0.307	0.394	0.047
1-Octanol	0.050 <sup>abc</sup>	0.037 <sup>c</sup>	0.042 <sup>bc</sup>	0.051 <sup>abc</sup>	0.046 <sup>bc</sup>	0.046 <sup>abc</sup>	0.063 <sup>a</sup>	0.038 <sup>bc</sup>	0.038 <sup>bc</sup>	0.051 <sup>ab</sup>	0.005	1.38	0.301	0.675	0.006
E-2-Octen-1-ol	0.013 <sup>b</sup>	0.015 <sup>ab</sup>	0.013 <sup>b</sup>	0.015 <sup>ab</sup>	0.012 <sup>b</sup>	0.016 <sup>ab</sup>	0.020 <sup>a</sup>	0.012 <sup>b</sup>	0.013 <sup>b</sup>	0.016 <sup>ab</sup>	0.002	1.34	0.035	0.076	0.212
Isopropyl Alcohol	0.029 <sup>c</sup>	0.047 <sup>a</sup>	0.030 <sup>bc</sup>	0.037 <sup>ab</sup>	0.033 <sup>bc</sup>	0.036 <sup>bc</sup>	0.030 <sup>bc</sup>	0.032 <sup>bc</sup>	0.034 <sup>bc</sup>	0.031 <sup>bc</sup>	0.003	1.26	0.092	0.271	0.003
Ethanol	0.049	0.073	0.114	0.084	0.068	0.071	0.044	0.066	0.086	0.056	0.018	2.03	0.264	0.275	0.341
1-Propanol	0.027 <sup>d</sup>	0.037 <sup>abc</sup>	0.032 <sup>cd</sup>	0.038 <sup>abc</sup>	0.032 <sup>bcd</sup>	0.039 <sup>abc</sup>	0.042 <sup>a</sup>	0.036 <sup>abc</sup>	0.039 <sup>abc</sup>	0.042 <sup>ab</sup>	0.004	1.32	0.226	0.003	0.444
3-Methyl-1-butanol	0.009	0.006	0.009	0.009	0.009	0.009	0.008	0.007	0.008	0.008	0.001	1.45	0.636	0.857	0.248

1-(2-Methoxy-1-methyl)-2-propanol	0.006	0.007	0.008	0.007	0.008	0.010	0.008	0.008	0.008	0.006	0.001	1.66	0.965	0.410	0.330	
1-(2-Methoxypropoxy)-2-propanol	0.008	0.012	0.011	0.010	0.012	0.015	0.010	0.013	0.012	0.007	0.002	1.86	0.844	0.512	0.153	
2-(2-Ethoxyethoxy) Ethanol	0.018	0.020	0.021	0.019	0.020	0.022	0.020	0.020	0.019	0.018	0.001	1.23	0.938	0.649	0.343	
<b>Aldehydes</b>																
2-Methylbutanal	0.036 <sup>ab</sup>	0.027 <sup>bc</sup>	0.029 <sup>abc</sup>	0.039 <sup>a</sup>	0.030 <sup>abc</sup>	0.028 <sup>bc</sup>	0.026 <sup>cd</sup>	0.023 <sup>cd</sup>	0.019 <sup>d</sup>	0.026 <sup>cd</sup>	0.003	1.37	0.437	<0.001	0.046	
3-Methylbutanal	0.092 <sup>ab</sup>	0.088 <sup>b</sup>	0.071 <sup>bc</sup>	0.121 <sup>a</sup>	0.079 <sup>bc</sup>	0.075 <sup>bc</sup>	0.081 <sup>bc</sup>	0.072 <sup>bc</sup>	0.061 <sup>c</sup>	0.074 <sup>bc</sup>	0.009	1.38	0.460	0.006	0.022	
Pentanal	0.535 <sup>de</sup>	0.694 <sup>abcd</sup>	0.546 <sup>cde</sup>	0.593 <sup>bcde</sup>	0.488 <sup>e</sup>	0.735 <sup>abc</sup>	0.868 <sup>a</sup>	0.576 <sup>bcde</sup>	0.681 <sup>abcd</sup>	0.750 <sup>ab</sup>	0.070	1.35	0.047	0.001	0.452	
Hexanal	3.671 <sup>b</sup>	4.027 <sup>b</sup>	3.470 <sup>b</sup>	4.083 <sup>b</sup>	3.564 <sup>b</sup>	4.973 <sup>ab</sup>	6.459 <sup>a</sup>	3.689 <sup>b</sup>	4.685 <sup>ab</sup>	5.172 <sup>ab</sup>	0.627	1.49	0.193	0.003	0.597	
Heptanal	1.158	0.944	1.021	1.179	1.168	1.023	1.396	0.947	0.932	1.104	0.119	1.36	0.615	0.775	0.052	
Z-4-Heptenal	0.092	0.088	0.080	0.102	0.095	0.091	0.121	0.080	0.080	0.099	0.009	1.33	0.154	0.763	0.118	
Octanal	0.251 <sup>ab</sup>	0.206 <sup>b</sup>	0.212 <sup>b</sup>	0.250 <sup>ab</sup>	0.232 <sup>ab</sup>	0.224 <sup>b</sup>	0.316 <sup>a</sup>	0.204 <sup>b</sup>	0.198 <sup>b</sup>	0.272 <sup>ab</sup>	0.028	1.39	0.382	0.581	0.048	
Nonanal	0.611 <sup>abc</sup>	0.474 <sup>d</sup>	0.532 <sup>bcd</sup>	0.642 <sup>ab</sup>	0.610 <sup>abc</sup>	0.553 <sup>abcd</sup>	0.681 <sup>a</sup>	0.498 <sup>cd</sup>	0.487 <sup>cd</sup>	0.598 <sup>abcd</sup>	0.050	1.28	0.468	0.719	0.009	
E-2-Nonenal	0.020	0.017	0.017	0.020	0.023	0.020	0.024	0.017	0.019	0.019	0.002	1.35	0.425	0.736	0.083	
Propanal	0.114 <sup>cd</sup>	0.146 <sup>bcd</sup>	0.124 <sup>cd</sup>	0.119 <sup>cd</sup>	0.109 <sup>d</sup>	0.168 <sup>abc</sup>	0.228 <sup>a</sup>	0.129 <sup>bcd</sup>	0.162 <sup>abc</sup>	0.187 <sup>ab</sup>	0.021	1.48	0.119	<0.001	0.448	
Dodecanal	0.014	0.015	0.013	0.015	0.014	0.015	0.018	0.014	0.014	0.016	0.001	1.24	0.323	0.168	0.644	
Benzaldehyde	0.024	0.025	0.024	0.026	0.022	0.026	0.025	0.022	0.023	0.026	0.002	1.20	0.550	0.971	0.175	
<b>Ketones</b>																
Acetone	0.578 <sup>bc</sup>	0.831 <sup>a</sup>	0.496 <sup>c</sup>	0.689 <sup>ab</sup>	0.685 <sup>ab</sup>	0.785 <sup>a</sup>	0.644 <sup>b</sup>	0.700 <sup>ab</sup>	0.698 <sup>ab</sup>	0.610 <sup>b</sup>	0.046	1.21	0.030	0.183	<0.001	
Butyrolactone	0.092 <sup>a</sup>	0.102 <sup>a</sup>	0.092 <sup>a</sup>	0.098 <sup>a</sup>	0.095 <sup>a</sup>	0.083 <sup>ab</sup>	0.072 <sup>b</sup>	0.070 <sup>b</sup>	0.071 <sup>b</sup>	0.073 <sup>b</sup>	0.006	1.23	0.818	<0.001	0.474	
Acetoin	0.237 <sup>a</sup>	0.047 <sup>b</sup>	0.193 <sup>a</sup>	0.219 <sup>a</sup>	0.221 <sup>a</sup>	0.128 <sup>ab</sup>	0.173 <sup>a</sup>	0.269 <sup>a</sup>	0.121 <sup>ab</sup>	0.112 <sup>ab</sup>	0.062	2.74	0.143	0.820	0.025	
6-Methyl-5-Hepten-2-one	0.009	0.007	0.010	0.009	0.010	0.009	0.008	0.007	0.008	0.008	0.001	1.33	0.210	0.247	0.154	
2,3-Pentanedione	0.038 <sup>cd</sup>	0.049 <sup>bcd</sup>	0.043 <sup>bcd</sup>	0.041 <sup>bcd</sup>	0.036 <sup>d</sup>	0.057 <sup>abc</sup>	0.079 <sup>a</sup>	0.040 <sup>bcd</sup>	0.050 <sup>abcd</sup>	0.064 <sup>ab</sup>	0.008	1.59	0.161	0.003	0.320	
4-Methyl-3-penten-2-one	0.006	0.010	0.009	0.011	0.009	0.007	0.008	0.009	0.011	0.008	0.002	2.21	0.448	0.874	0.993	
4-Hydroxy-4-methyl-2-pentanone	0.008	0.013	0.013	0.013	0.011	0.011	0.010	0.011	0.011	0.009	0.002	1.59	0.583	0.349	0.507	

<b>Hydrocarbons</b>															
3-Ethyl-2-methylpentane	0.007	0.002	0.004	0.004	0.005	0.003	0.004	0.001	0.002	0.002	0.002	3.80	0.715	0.052	0.401
Octane	0.192 <sup>a</sup>	0.104 <sup>d</sup>	0.146 <sup>abc</sup>	0.184 <sup>ab</sup>	0.165 <sup>ab</sup>	0.148 <sup>abc</sup>	0.143 <sup>abc</sup>	0.111 <sup>cd</sup>	0.105 <sup>d</sup>	0.139 <sup>bcd</sup>	0.016	1.36	0.026	0.006	0.003
2-Octene	0.025 <sup>a</sup>	0.009 <sup>cd</sup>	0.019 <sup>ab</sup>	0.028 <sup>a</sup>	0.025 <sup>a</sup>	0.013 <sup>bc</sup>	0.013 <sup>bc</sup>	0.008 <sup>cd</sup>	0.007 <sup>d</sup>	0.011 <sup>bcd</sup>	0.003	1.85	0.133	<0.001	0.003
1-Octene	0.190 <sup>a</sup>	0.066 <sup>c</sup>	0.140 <sup>ab</sup>	0.155 <sup>a</sup>	0.131 <sup>ab</sup>	0.144 <sup>a</sup>	0.126 <sup>ab</sup>	0.067 <sup>c</sup>	0.088 <sup>bc</sup>	0.128 <sup>ab</sup>	0.021	1.63	0.006	0.084	0.001
3-Octene	0.008 <sup>a</sup>	0.001 <sup>d</sup>	0.005 <sup>a</sup>	0.009 <sup>a</sup>	0.006 <sup>a</sup>	0.003 <sup>abc</sup>	0.003 <sup>ab</sup>	0.001 <sup>bcd</sup>	0.001 <sup>cd</sup>	0.002 <sup>abcd</sup>	0.002	3.66	0.130	0.004	0.002
Decane	0.006	0.007	0.006	0.007	0.007	0.007	0.004	0.012	0.006	0.006	0.002	2.24	0.551	0.978	0.285
α-Pinene	0.006 <sup>ab</sup>	0.005 <sup>b</sup>	0.009 <sup>a</sup>	0.007 <sup>ab</sup>	0.008 <sup>ab</sup>	0.009 <sup>a</sup>	0.007 <sup>ab</sup>	0.005 <sup>b</sup>	0.008 <sup>ab</sup>	0.005 <sup>ab</sup>	0.001	1.78	0.663	0.925	0.036
Limonene	0.010 <sup>c</sup>	0.017 <sup>abc</sup>	0.025 <sup>ab</sup>	0.015 <sup>bc</sup>	0.026 <sup>ab</sup>	0.026 <sup>ab</sup>	0.009 <sup>c</sup>	0.019 <sup>abc</sup>	0.034 <sup>a</sup>	0.011 <sup>c</sup>	0.005	2.18	0.183	0.930	0.002
Toluene	0.044 <sup>ab</sup>	0.011 <sup>d</sup>	0.027 <sup>bc</sup>	0.058 <sup>a</sup>	0.061 <sup>a</sup>	0.021 <sup>c</sup>	0.018 <sup>cd</sup>	0.041 <sup>ab</sup>	0.019 <sup>cd</sup>	0.041 <sup>b</sup>	0.007	1.79	<0.001	0.032	<0.001
													1		
<b>Sulphur compounds</b>															
Carbon disulfide	0.059 <sup>abc</sup>	0.021 <sup>d</sup>	0.125 <sup>a</sup>	0.034 <sup>cd</sup>	0.043 <sup>bcd</sup>	0.059 <sup>abc</sup>	0.077 <sup>ab</sup>	0.048 <sup>bc</sup>	0.046 <sup>bcd</sup>	0.111 <sup>a</sup>	0.018	2.24	0.060	0.079	0.002
Dimethyl sulfide	0.073 <sup>c</sup>	0.184 <sup>a</sup>	0.185 <sup>a</sup>	0.101 <sup>b</sup>	0.134 <sup>ab</sup>	0.167 <sup>a</sup>	0.151 <sup>a</sup>	0.146 <sup>a</sup>	0.154 <sup>a</sup>	0.142 <sup>a</sup>	0.017	1.39	0.002	0.021	<0.001
Dimethyl sulfone	0.016 <sup>bc</sup>	0.013 <sup>cd</sup>	0.036 <sup>a</sup>	0.019 <sup>bc</sup>	0.022 <sup>b</sup>	0.010 <sup>de</sup>	0.007 <sup>e</sup>	0.008 <sup>e</sup>	0.007 <sup>e</sup>	0.008 <sup>e</sup>	0.002	1.56	0.010	<0.001	0.018
<b>Others</b>															
N, N-Dibutyl-formamide	0.016	0.015	0.014	0.017	0.015	0.019	0.017	0.015	0.017	0.015	0.002	1.40	0.553	0.359	0.959
Ethyl Acetate	0.093	0.095	0.091	0.112	0.091	0.089	0.084	0.091	0.087	0.097	0.006	1.19	0.521	0.075	0.107
Trichloromethane	0.056	0.027	0.035	0.059	0.039	0.075	0.050	0.028	0.032	0.063	0.016	2.60	0.267	0.588	0.332
Triacetin	0.006	0.006	0.008	0.006	0.007	0.010	0.007	0.007	0.009	0.006	0.001	1.73	0.585	0.300	0.271

a, b, c, d, e Different letters within the same row denote significant difference between mean

### Stepwise discriminant analysis

To visualise differences in volatile profiles amongst the treatments, a stepwise discriminant analysis plot is presented in Figure 6.2. The stepwise discriminant analysis showed that of the 57 volatile compounds detected in the headspace of the loin muscle samples, 10 compounds were retained in the analysis due to being unique to the treatments. These were dimethyl sulfone, toluene, dimethyl sulfide, acetone, limonene, Z-2-penten-1-ol, 1-octen-3-ol, 1-hexanol, butyrolactone and 1-octene. The canonical variate analysis (CVA) applied to the 10 volatiles gave 8 canonical variables, with the first two accounting for 71% of the total variability. The first canonical variable (Scores [1]; Figure 6.2) separated the two time periods, with the three treatments fed pasture for 35 days (G1, Y1, R1) having a unique volatile profiles from all treatments after 67 days feeding. The second variable (Scores [2]) separated lambs fed Raphanobrassica for 35 days (O1) and lambs fed Chicory for 35 days (B1) from the other treatments. Within the two time periods, there was separation for the 35 day grazing period but not the 67 day grazing period.

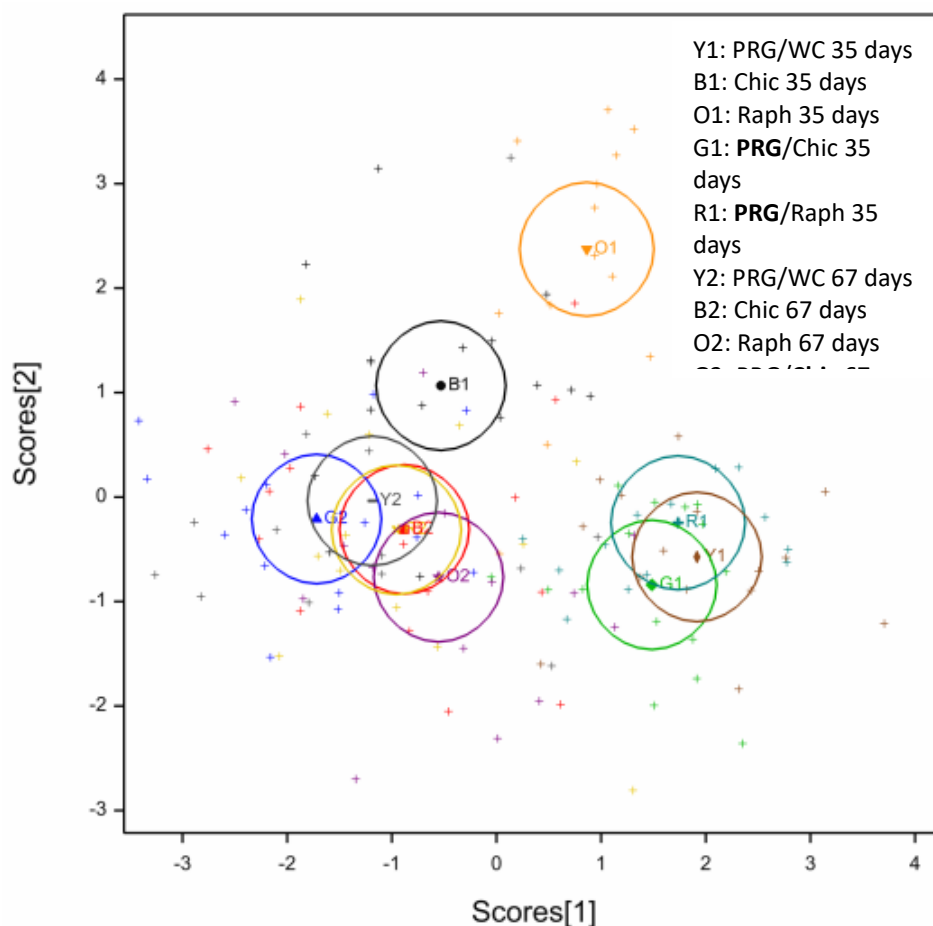


Figure 6.2: Stepwise discriminant analysis of volatile compounds in the headspace of cooked *Longissimus lumborum* muscle (loin) from lambs finished on PRG/WC, Chicory (Chic) or Raphanobrassica (Raph) for 35 or 67 days in Study 2. Regarding the crossover treatments (PRG/Chic and PRG/Raph) the forage in bold indicates which forage type the lambs were grazing at time of slaughter.

## 6.4 Discussion

The objective of the current study was to evaluate the effect of grazing lambs on PRG/WC, Chicory or Raphanobrassica for 35 or 67 days on lamb carcass characteristics, meat quality, fatty acid composition and volatile compounds. Forage type and length of time grazing influenced carcass characteristics (final live weight, carcass weight, dressing out percentage and IMF%), some objective measures of meat quality (pH, colour, peak shear force & water holding capacity), fatty acid composition and relative abundance of volatile compounds.

### 6.4.1 Carcass measures

Lambs that had grazed their treatments for 67 days had greater final live weight, carcass weight, dressing out percentage, intramuscular fat and Viascan-GR than lambs that had grazed for 35 days. The lambs were 32 days older at slaughter 2 and this additional time grazing allowed for further growth and fat deposition. Compared to muscle, fat is a later developing tissue (McPhee et al., 2008) and within the fat depots, intramuscular fat is the last to be deposited (Kempster, 1981). Thus, as an animal grows closer to its mature weight, the proportion of fat increases and increased fat deposition has also been linked with heavier carcass weights (Schreurs and Kenyon, 2017) so, greater subcutaneous fat depths and higher IMF values are seen in animals that are older or heavier at slaughter.

Within the two slaughters, lambs fed Chicory had the highest final live weight and carcass weight which aligns with the results of the first study of this thesis (Chapters 3 and 4) and with previous research that shows the high feeding value of Chicory over summer (Li & Kemp, 2005). Final live weight of PRG/WC and Raphanobrassica fed lambs were similar across both slaughters however, Raphanobrassica fed lambs had a greater carcass weight. Feeding Chicory or Raphanobrassica for a short duration (Chicory and Raphanobrassica at slaughter 1 and PRG/Chic and PRG/Raph at slaughter 2) did not increase final liveweight but did increase carcass weight. The exception was lambs that had switched from PRG/WC to Raphanobrassica at D<sub>35</sub>, however these lambs were disadvantaged by being lighter at time of crossover compared to the other lambs grazed on PRG/WC in the first 35 days (Chapter 5).

The increased carcass weights of lambs fed Chicory and Raphanobrassica can partially be attributed to the increased dressing out percentages. Dressing out percentage can be influenced by a number of factors, including liveweight, carcass fat level, breed, diet and time off feed (Litherland et al., 2010). Given final live weight was similar, breed and time off feed were the same, the difference between PRG/WC and Chicory and Raphanobrassica was likely due to the increased fat deposition (ViaScan-GR) and diet. The effect of diet was discussed in study 1 (Chapter 4), but it is interesting to note that the

increase in dressing out percentage when lambs were fed Chicory or Raphanobrassica was evident after 35 days grazing (slaughter 1) and 32 days grazing (crossover treatments at slaughter 2) which are shorter grazing durations than the 64 days used in the first study (Chapter 4). The benefit of this is that lambs grazing alternative forages during summer for short grazing durations (32-35 days) can result in lambs that will yield greater carcass weights at a given liveweight which increases profitability of lamb finishing operations.

Differences in the meat yield measures estimated by VIAScan were evident across the two slaughter dates, with total yield, leg yield and loin yield decreasing over time. This is likely a consequence of differences in fat that had been deposited in the carcass as evidenced by the GR and IMF values. Lean meat yield is a measure of how much muscle is in the carcass so, more fat in the carcass will lower the proportion that is muscle and give a lower lean meat yield percentage.

#### 6.4.2 Objective meat quality measures

All lamb meat had a pH of less than 5.8 which is the acceptable threshold for meat quality (Egan & Shay, 1988). Within the lambs slaughtered after 35 days grazing, meat from lambs fed Chicory had a lower pH than other forage treatments. When considering the lambs slaughtered after 67 days grazing, meat from Raphanobrassica fed lambs had a higher pH than other forage treatments. The pH of meat is an important determinant of quality as it directly affects other measures of quality such as meat colour, tenderness, water holding capacity and oxidation (Prache et al., 2022; Savell et al., 2005). Because there were treatment effects on pH, this was included as a covariate for other measures of meat quality to look at the effects of the treatment independent of pH. Differences in pH are often associated with pre-slaughter stressors, or low energy intake causing glycogen stores to be depleted in the muscle (Pethick & Rowe, 1996). The lower pH in the meat from Chicory fed lambs after 35 days could be explained by its high nutritive value and potentially higher animal intakes giving a greater energy intake to allow for greater glycogen stores. The higher pH in the meat from Raphanobrassica fed lambs after 67 days grazing is more difficult to explain given the animal performance of these lambs was greater than on PRG/WC and this difference was not observed in study 1 (Chapter 4). This indicates an investigation into the end products of digestion and metabolism may be needed to fully understand.

Meat from lambs grazed for 35 days was lighter colour than lambs grazed for 67 days, and meat from lambs fed Chicory for 35 days was lighter colour than all other forage treatments. The lighter colour meat from lambs fed Chicory for 35 days is difficult to explain as there was no difference in IMF% between forage treatments and this result was not measured with either Chicory treatment in the second slaughter or in study 1 (Chapter 4). High levels of IMF in meat can increase lightness values when measured objectively due to the dilution of muscle fibres (Warner et al., 2010). There were no

treatment or day effects on redness or yellowness values. Thresholds for acceptability of meat colour by consumers were suggested by Khliji et al (2010), with values for lightness ( $L^*$ ) below 34 and redness ( $a^*$ ) below 9.5 considered dark and unacceptable to average consumers. Lightness and redness values measured in this study were above these thresholds for all forage treatments, suggesting that they would be deemed acceptable by consumers. There are usually minimal differences in meat colour between forage diets (De Brito et al., 2016; Ye, Schreurs, et al., 2020a). It is more likely that forage diet would influence fat colour due to deposition of carotenoid pigments from plants however this was not measured in this study (Priolo et al., 2001).

Following flavour, tenderness is the next determinant of eating quality for lamb, directly influencing consumer satisfaction and repurchase (Prache et al., 2022). Small differences in shear force measures were found in this study, with meat from lambs grazed for 67 days having higher work done and peak force values than meat from lambs grazed for 35 days. These lambs were older and heavier at slaughter, so this increase in shear force can likely be explained by the decrease in collagen solubility that occurs as animals age (Hopkins et al., 2013; Purchas et al., 2002; Young et al., 1993). As lambs age the proportion of fat in the carcass increases, including deposition of IMF which was also seen in the results of this study (M. McPhee et al., 2008). Increasing IMF can positively influence tenderness so long as the increase in IMF outweighs the associated reduction in collagen solubility (Hopkins et al., 2006) however the increase in IMF in this study was not sufficient to offset this and shear force values increased as a result. Within the lambs grazed for 67 days, meat from lambs grazing Chicory had lower shear force values than lambs fed Raphanobrassica, with no differences observed with the crossover treatments where the lambs had only been grazing Chicory or Raphanobrassica for the last 32 days of the study. Despite the increase in shear force values in the meat of lambs from the second slaughter, peak force values were low for all treatments, well below the threshold of 40 N (4.08 kgF) proposed by Hopkins et al. (2006) for Australian consumers perception of “good every day” lamb. Hopkins et al., (2006) also proposed a conservative shear force target of 27 N (2.75 kgF) to achieve a failure rate of no more than 10% for lamb loin. Peak force from all forage treatments after 35 days grazing in this study were below this conservative target.

Water holding capacity is a predictor of overall liking of meat as it indicates whether muscles are likely to lose water during refrigeration, storage and cooking, which can be viewed negatively by consumers (Hopkins et al., 2006). While there was no effect of treatment on drip loss, days grazing did have an effect with meat from lambs grazed for 67 days having higher drip loss than meat from lambs grazed for 35 days. These lambs had higher carcass weights than the lambs from slaughter 1 and lower water holding capacity has been attributed to lambs that are heavier at slaughter (Vergara et al., 1999). The same effect was not observed when considering cook loss, with days grazing having an effect, but less

cook loss was measured from meat from lambs grazed for 67 days. Values for both drip loss and cook loss were similar to previously reported values of meat from lambs (Ye, Schreurs, et al., 2020) and to study 1 (Chapter 4). Post slaughter treatments such as chilling and ageing heavily influence water holding capacity and the heavier carcasses from slaughter 2 are likely to have chilled more slowly however this was not measured directly.

### 6.4.3 Fatty acid composition

Fatty acid composition was similar between forage treatments with differences only measured in levels of n-6 PUFA. Chicory had the highest amount of n-6 PUFA in the forage samples, and this translated into the meat of lambs fed Chicory. Excessive intakes of n-6 PUFA are commonly found in modern Western diets and are associated with a number of diseases, including cardiovascular disease, cancers, inflammatory and autoimmune diseases (Simopoulos, 2008). However the increase in n-6 PUFA in the meat from lambs fed Chicory was not sufficient to alter the n6:n3, which was not different between treatments and all treatments were below 1.1, which is similar to the ratios of lamb meat obtained from grazed forage production systems (De Brito et al., 2017; Ye, Eyres, et al., 2020) and to study 1 (Chapter 4).

The different grazing durations had a much larger effect on fatty acid composition than did the forages themselves, with grazing duration effects across all the fatty acid measures except branched chain fatty acids and n6:n3 ratio. The addition of an IMF covariate did remove some of the grazing duration effects but they were still evident for the sum of fatty acids, saturated fatty acids, monounsaturated fatty acids, EPA + DHA, n-6 PUFA, long chain n3-PUFA and PUFA:SFA. Lambs that had grazed their forage treatments for 67 days had a fatty acid profile that was more saturated. This was particularly evident in Chicory fed lambs, where lambs fed Chicory for 67 days or fed Pasture for 35 days then switched to Chicory for 32 days (PRG/Chic) had lower levels of EPA + DHA and long chain n-3 PUFA than those same treatments after 35 days grazing. A negative association between PUFA proportion and total lipid content has been reported in numerous studies (Salvatori et al., 2004). As animals age, the PUFA proportion in meat decreases due to the relative increase in neutral lipids (Warren et al., 2008). Chicory fed lambs had the greatest carcass weight and VIA-Scan GR, with lambs fed Chicory for 67 days weighing an average of 24.7 kg and had a GR of 13.1. Chicory fed lambs had a carcass with more fat than the other treatments, so the reduction in long chain unsaturated fatty acids is expected as a consequence of greater carcass fat. The average carcass weight for New Zealand lamb is 19.0 kg (Beef and Lamb, 2023) so in a commercial system the Chicory fed lambs would likely have been slaughtered earlier rather than working to set grazing durations as was the case in this research.

PUFA and the ALA concentration in the forage samples was greatest in PRG/WC and Chicory and lowest in Raphanobrassica on D<sub>17</sub>. By D<sub>55</sub> levels in Pasture had decreased and were lower than Chicory but still

higher than Raphanobrassica. The ALA concentration in forage is an important consideration as it is a precursor of EPA + DHA (Kitessa et al., 2010) which are the fatty acids with the most benefits to human health (McAfee et al., 2010). Unlike in study 1 (Chapter 4), the differing levels of PUFA and ALA in the forage samples in the current study were not reflected in the meat samples, where there were no differences between treatments for either PUFA, ALA or EPA + DHA.

Levels of PUFA and ALA were lower in Raphanobrassica in the current study compared to study 1 (Chapter 4). Levels of ALA vary in forages depending on season and state of maturity, thus grazing management and environmental conditions can affect the amount of ALA delivered to the grazing animal (Boufaïed et al., 2003; Elgersma et al., 2003). Greatest concentrations are found in the leaf and lowest in the stem. The improved grazing management of Raphanobrassica in this study to reduce stem production should have increased ALA levels compared to study 1 (Chapter 4), so the reduced levels measured are difficult to explain (Boufaïed et al., 2003). Chicory and Pasture had similar levels of ALA to Chapter 4 and previous research (Alvarenga et al., 2015; Boufaïed et al., 2003).

The human health benefits attributed to consumption of meat lipids are primarily from long chain n-3 PUFA, particularly EPA + DHA (Russell & Bürgin-Maunders, 2012). In the current study, meat from lambs fed PRG/WC, Chicory or Raphanobrassica provided 27 to 30 mg EPA + DHA per 100g muscle with no differences evident between forage treatments. In New Zealand and Australia, a food can legally be claimed to be a source of omega-3 fatty acids if EPA + DHA is greater than 30 mg per serving of food (FSANZ, 2012). Based on a serving size of 135 g of meat, a lamb with EPA + DHA of 23 mg/100g muscle will meet this Australian and New Zealand standard (Ponnampalam, Butler, Jacob, et al., 2014), with all forage treatments meeting this source requirement. To be considered a "good source" a food requires 44 mg/100g muscle, which no forage treatment was able to achieve in this study. Similarly, no forage treatment met the European standards required to achieve a "source" or "good source" of omega-3 fatty acids at 40 and 80 mg/100g muscle, respectively. The EPA + DHA levels in this study were similar to research with lambs of similar maturity grazing a range of forages in Australia (De Brito et al., 2017; Ponnampalam, Butler, Jacob, et al., 2014). When comparing to a grazed forage study under New Zealand conditions, results in this study were lower than 6-8 month old lambs, and similar to 12 month old lambs (Ye, Eyres, et al., 2020). Levels were also lower in the current study than in study 1, which were similar to the 6-8 month lambs in the Ye, Eyres et al (2020) study, potentially due to the lambs in the current study being taken to higher carcass weights, and thus more similar to a 12 month lamb.

The n6:n3 ratio is usually highly influenced by the diet of an animal, unlike the PUFA:SFA ratio (Bas & Morand-Fehr, 2000). However in the current study, the n6:n3 ratio was not influenced by forage treatment. PUFA:SFA was similar between forage treatments but was lower in lambs grazed for 67 days

compared to those grazed for 35 days. This can be explained by the lambs depositing more saturated fat as they get older, due to depositing more adipose tissue. All treatments resulted in meat with a PUFA:SFA ratio below the recommended value of 0.45 (Department of Health, 1994).

#### 6.4.4 Volatile compounds

Two sulphur compounds, dimethyl sulfide and dimethyl sulfone, were identified in the stepwise analysis as being unique to the treatments. When considering the relative abundance of these volatiles in Table 6, both dimethyl sulfide and dimethyl sulfone were more abundant in meat from lambs fed Raphanobrassica for 35 days, but in the case of dimethyl sulfide abundance was not different to meat from lambs fed Chicory for 35 days. These differences were no longer detected after a longer feeding duration of 67 days. Sulphur compounds have been detected in samples of forage rape (*Brassica napus ssp. Biennis*) and were suggested to have originated from the enzymatic breakdown of plant secondary metabolites, such as S-methyl-L-cysteine-sulfoxide (Frank, Watkins, et al., 2016). In meat, presence of sulphur compounds is strongly diet dependant and is linked to a breakdown of the amino acids cysteine and methionine, compounds previously reported in cooked meat aroma (Frank, Watkins, et al., 2016; Young et al., 2003). Dimethyl sulfide typically is associated with sulfurous, onion, cabbage or cauliflower odours, and dimethyl sulfone has sulfurous or burnt odours (Pavan et al., 2021). Dimethyl sulfone has been linked to an unfavourable “milky” flavour in meat from pasture fed sheep (Young et al., 2003). In the study of Pavan et al., (2021), dimethyl sulfide was detected in greater abundance in chicory fed lambs compared grass fed lambs, which supports the findings of this study.

Alcohols, ketones and aldehydes are derived from oxidation of unsaturated fatty acids thus higher abundance is usually seen in meat with higher levels of PUFA (Young et al., 2003). Lipid volatiles are believed to contribute to desirable meat flavour, however increased levels of PUFAs and high levels of oxidation in phospholipids may negatively impact the palatability of cooked meat (Gkarane et al., 2018). These volatiles have high odour thresholds, which reduces their influence on flavour in lipid based foods (Gkarane et al., 2018). Three alcohols were retained in the stepwise discriminant analysis, those being Z-2-penten-1-ol, 1-octen-3-ol and 1-hexanol. When considering the relative abundance of these alcohols, Z-2-penten-1-ol was more abundant in lambs fed Chicory for 35 days compared to lambs fed PRG/WC. After 67 days grazing, Chicory fed lambs still had the greatest relative abundance, but only greater than lambs fed Raphanobrassica for 67 days. The volatile Z-2-penten-1-ol is associated with green and fruity flavours (Pavan et al., 2021). Greater relative abundance of this compound was detected in meat from 4-month-old, weaned lambs with carcass weights of 18.8 kg, compared to 6-8 month old lambs or 12 month old lambs which had carcass weights ranging from 16.7 to 18.1 kg and 19 to 19.5 kg respectively (Pavan et al., 2021). Of the 6-8 month old lambs, chicory fed lambs had higher Z-2-penten-1-ol than grass fed lambs so, like the study of Pavan et al (2021) this study has

shown Z-2-penten-1-ol to be an indicator of chicory feeding in meat from young lambs, even when taken to a heavier carcass weight. The 1-octen-3-ol was relatively more abundant in lambs fed Chicory for 67 days compared to lambs fed Raphanobrassica for 67 days, or lambs fed PRG/WC then Chicory (PRG/WC for 35 days, then Chicory for a further 32 days). The volatile 1-octen-3-ol arises from the oxidation of C18:2n-6 (Gkarane et al., 2018) and is typically described as having green, mushroom, earthy or oily odours (Pavan et al., 2021). In the current study, the greater n-6 PUFA in the chicory forage maybe resulting in greater abundance of 1-octen-3-ol from the meat of lambs fed chicory. However, this effect was not evident in the study of Pavan et al., (2021) where 1-octen-3-ol was more abundant in 4-month-old weaned lambs than 6-8 month lambs fed on red clover or grass, but not different to lambs fed chicory.

When considering 1-hexanol, relative abundance was greatest in lambs fed Chicory for 67 days, suggesting that 1-hexanol is a marker of a longer period of feeding chicory feeding. The volatile 1-hexanol has been associated with green, fruity, oily and fusel flavours (Pavan et al., 2021). Chicory feeding was also found to result in a greater abundance of 1-hexanol in the lamb meat from the study of Pavan et al., (2021). This volatile is negatively correlated with sensory scores from some consumers but positively correlated with sensory scores for others when a cluster analysis was undertaken, suggesting the influence of oxidation and the formation of 1-hexanol is not consistent across all consumers (Pavan et al., 2021). Based on the findings of the three alcohols retained in the discriminant analysis, they appear to all be linked to Chicory feeding. Given that these alcohol volatiles are linked to lipid oxidation, this aligns with the high PUFA levels in Chicory fed lamb in this study, particularly in the first grazing period of 35 days. This was also found in another recent study, where lambs that grazed chicory after weaning had higher levels of PUFA and higher abundance of compounds arising from lipid oxidation (Ye, Eyres, et al., 2020).

Acetone and butyrolacetone were the two ketones influential in the stepwise discriminant analysis. Lambs fed Chicory for 35 days had the greatest abundance of these two volatiles when compared to other treatments within the same feeding duration. After 67 days grazing, lambs fed PRG/WC had the greatest relative abundance of these volatiles. Whilst both these ketones are associated with lipid oxidation, acetone also has been linked with storage time, increasing with time in storage regardless of aging method (Li et al., 2021). The increase of acetone in the headspace of meat is also reported to be linked to microbial metabolism during storage (Senter et al., 2000). This volatile is linked to earthy odours, common in dry aged beef (Li et al., 2021). Potentially the difference in the ketones between forage treatments is an indicator of the potential for the treatments to induce or suppress lipid oxidation and microbial activity with aging but this would need specific investigation to clarify. Butyrolacetone has been identified in freshly slaughtered beef and is associated with sweet, pleasant

and creamy odours (Conte et al., 2021). In the study of Ye et al., (2020), acetone was less abundant in the headspace of meat from lambs fed chicory compared to lambs fed red clover, mixed pasture or perennial ryegrass, which is in contrast to the findings of the current study.

Three hydrocarbons were influential in the stepwise discriminant analysis: toluene, limonene and 1-octene. Hydrocarbons are non-lipid volatiles and are influenced by production system via fatty acid profile differences (Ye, Eyres, et al., 2020). Terpenes such as toluene and limonene originate directly from diet, and toluene is very often detected in lamb tissues (Sivadier et al., 2010). Terpene biosynthesis occurs exclusively in plants, it is used as a marker of pasture feeding as its presence infers a forage based diet (Vasta & Priolo, 2006). After 35 days grazing, meat from lambs fed PRG/WC had higher abundance of Toluene and PRG/WC fed lambs also had a greater abundance of 1-octene in the meat compared to meat from lamb fed Chicory or Raphanobrassica indicating the potential of these hydrocarbons as markers of a PRG/WC diet.

Aldehydes have been shown to play important roles in the flavour of beef, particularly during cooking (Mottram, 1998). Nonanal is a straight chain aldehyde, which is formed during lipid oxidation and used as an indicator of lipid oxidation in meat (Li et al., 2021). It is associated with green, fatty and sweet odours (Calkins & Hodgen, 2007). In beef, flavour liking score is correlated with nonanal (Li et al., 2021). In lamb, it has been weakly linked to off-flavours (Gkarane et al., 2018). The current study showed relative abundance increased with feeding Chicory, and the greater relative abundance in lambs fed Chicory for 67 days compared to 35 days suggests it is marker of length of time fed chicory. This is in agreement with other research, where chicory feeding was associated with higher relative abundance of nonanal than lambs fed perennial ryegrass (Ye, Eyres, et al., 2020). Frank, Watkins et al., (2016) found highest abundance in meat from lambs fed forage rape, and the lowest with lambs fed ryegrass but no differences were evident between lambs fed Raphanobrassica and lambs fed PRG/WC in the current study.

In the study of Ye, Eyres et al (2020) lambs fed on chicory, red clover or mixed pasture produced distinctive meat flavour due to a greater relative abundance of overall meat volatiles compared with lambs that grazed perennial ryegrass. Similarly, this study has found that the forage treatment, but more so the forage fed in interaction with the length of time grazing, creates a unique profile of volatiles that could discriminate the treatments. This study found 10 volatiles to be key for differentiating the forage grazed and length of time grazing. These volatiles were: dimethyl sulfone, toluene, dimethyl sulfide, acetone, limonene, Z-2-penten-1-ol, 1-octen-3-ol, 1-hexanol, butyrolactone and 1-octene.

## 6.5 Conclusion

Forage treatment and grazing duration influenced final live weight, carcass weight, dressing out percentage and V-GR, with the lambs being older, heavier and fatter after a 67 day grazing duration. Alternative forages to PRG/WC increased carcass weight, DO% and V-GR regardless of grazing duration. Meat quality and fatty acid composition was influenced by grazing duration, but effects of forage treatment were minimal. Showing similar trends to carcass composition results, the longer grazing duration resulted in heavier lambs that had higher shear force values, drip loss and had a fatty acid profile that was more saturated. Lamb meat from all forage treatments met thresholds for acceptable meat quality. Meat from all forage treatments also met source requirements for EPA + DHA and had PUFA:SFA ratios below the recommended value of 0.45. Whilst our expectation was that alternative forages would deliver meat with more beneficial fatty acids, newly sown tetraploid perennial ryegrass/white clover was used in this study which would have higher quality than older run-out pastures. The consistency of meat quality and fatty acid composition between forage treatments supports the use of a combination of high quality forages on farm to ensure a consistent end product that meets the expectations of consumers.

This study builds on others that have investigated the volatile profile of lamb meat has found that the forage treatment, but more so the forage fed in interaction with the length of time grazing, creates a unique profile of volatiles that could discriminate the treatments. In particular, Z-2-penten-1-ol, 1-octen-3-ol, 1-hexanol and nonanal were markers of chicory feeding, dimethyl sulphide a marker of Raphnobrassica feeding and toluene and 1-octene markers of PRG/WC feeding.

## Chapter 7

### Experiment 3: Influence of Chicory, Raphanobrassica or Perennial Ryegrass/White Clover Diet on sensory properties of *Longissimus thoracis* muscle (loin) of lambs



## 7.1 Introduction

Ninety-five percent of New Zealand sheep meat is exported, so ensuring consumer satisfaction across a range of key markets is crucial to drive repurchasing decisions and maintain value. In 2023, 378,515 tonnes of sheepmeat valued at \$3.9 billion was exported, with 27% of this destined for China, but the greatest price per tonne achieved in exports to the USA (Meat Industry Association, 2023).

There are multiple factors that drive consumer repurchasing decisions, such as price, visual assessment, sustainability, animal welfare factors and potential health benefits (Grunert et al., 2004; Henchion et al., 2014). Each factor has a different degree of importance to each consumer; however research suggests that consumers are not willing to compromise on eating quality for other benefits (Verbeke, 2006). Consumer segmentation and targeting different products to relevant markets is beneficial for increasing value, but ensuring high eating quality is crucial for the success of the New Zealand red meat industry (Craigie et al., 2017).

Eating quality of meat is a combination of meat tenderness, flavour and juiciness (Miller, 2020). Intramuscular fat (IMF) has been shown to have a positive effect on eating quality, with a recent New Zealand study reporting a positive influence on consumers overall liking of lamb. Intramuscular fat levels were grouped and ranged from 1.09% to 5.68% with liking increasing significantly as IMF% in the lamb reached 3%, achieving maximum scores at 4% (Realini et al., 2021). In contrast to beef, where tenderness is the most influential attribute on consumer liking, flavour is considered the most important attribute for lamb (Miller, 2020).

Study 2 (Chapter 6) found that feeding lambs different finishing diets resulted in meat that had unique volatile profiles, particularly after a 35 day grazing duration. In study 3, the hypothesis was that untrained consumers would identify differences in overall liking and flavour intensity between meat from lambs fed Perennial ryegrass white clover (PRG/WC), Chicory or Raphanobrassica. Studies 1 and 2 did not result in differences in objective measures of tenderness or water holding capacity so we did not expect the consumers to identify differences in tenderness or juiciness in the sensory panel.

To market high quality lamb that meets the expectations of discerning consumers, there needs to be an understanding of how animal diet affects eating quality attributes, particularly flavour. The aim of this chapter was to investigate the eating quality of meat from lambs that had been finished on PRG/WC, Chicory or Raphanobrassica by untrained consumers. Meat quality assessments and fatty acid composition were measured to help understand the findings of the sensory panel.

## 7.2 Materials and Methods

### 7.2.1 Experimental design and sample collection

The animal grazing component of this study was located at Kimihia Research Centre, 4km Northwest of Lincoln, Canterbury, New Zealand. The study ran for 102 days, from 23 December 2021 to 4 April 2022. The design involved 3 forage treatments: Established Perennial ryegrass/white clover pasture (PRG/WC), spring sown Chicory & spring sown Raphanobrassica. Seventy-two weaned Romney-cross, ewe lambs aged approximately 5 months were utilised for the trial (24 per treatment). Lambs were purchased from a single commercial farm to ensure sufficient lambs with the same breeding and management were available and represented a typical New Zealand lamb for finishing. Ewe lambs were utilised for this trial to ensure maximum potential for fat deposition and to eliminate any chance of ram taint affecting perceptions of consumers in the sensory panel. Lambs were tagged with electronic identification (EID) tags and weighed prior to being allocated to a treatment group resulting in an average starting liveweight of  $23.1 \pm 0.2$  kg. Lambs were rotationally grazed on each of the forages according to best practice grazing management throughout the grazing period, with lambs being shifted prior to reaching the desired post grazing residual of 1400 kgDM/ha (Morris & Kenyon, 2014). Unrestricted access to fresh water was always available.

The lambs were transported 150km for processing at the Alliance Smithfield Plant on 4 April 2022 and processed on 5 April 2022 after being held in lairage overnight. Carcasses were prepared following standard commercial dressing procedures for New Zealand export lamb. Each carcass was given an identification number that linked to the slaughter order and EID tag, allowing traceability of each individual lamb. Hot carcass weight (HCW) was recorded; the depth of tissue at the GR site (tissue depth 110 mm from the midline over the 12<sup>th</sup> rib) was obtained using the Alliance Group VIAscan® system (Hopkins et al., 2004).

The carcasses were chilled at -4°C for 12 hours then both the left and right bone-in short loin (*Longissimus lumborum*, LL) and rib loin (*Longissimus thoracis*, LT) were removed from each carcass and vacuum-packed with their respective carcass identification tag. The samples were then transported to the Massey University Pilot Plant and aged at 1°C for 21 days to mimic typical procedures for export lamb, followed by frozen storage at -30°C.

### 7.2.2 Loin meat quality, intramuscular fat and fatty acid analyses

The short loin (LL) was utilised for meat quality and fatty acid testing and the left and right rib loin (LT) was used for the consumer panel.

Short loin samples (LL) (n=72) were analysed for meat quality over a 6-week period. The samples were thawed at 1°C for 24 hours prior to analysis. The loin was boned out, fat cap removed and partitioned

into sections (Figure 4.1; Chapter 4) for each of the objective meat quality tests. Testing methods for objective meat quality (pH, meat colour, shear force, water holding capacity), intramuscular fat and fatty acid composition were fully described in Study 1 (Chapter 4).

### 7.2.3 Consumer sensory evaluation

One hundred and twenty-six untrained consumers were recruited in Palmerston North in July 2022 by Food Experience and Sensory Testing (FEAST) laboratory at Massey University to evaluate the eating quality of lamb samples from lambs that had grazed PRG/WC, Chicory or Raphanobrassica. Participants were selected according to the following criteria: age (18-65 years old), physiological state (not pregnant or lactating) and consumption profile (not allergic or intolerant to lamb, regularly consume red meat including lamb). Twelve sessions were run over 3 days, with 4 sessions per day. Twelve participants were booked into each session, with a minimum of 10 required to attend to reach the desired target of 120 consumers. Each consumer attended one session and were asked to rank overall liking, flavour, tenderness, and juiciness of lamb samples from lambs that had grazed on PRG/WC, Chicory or Raphanobrassica.

Two days prior to a session being run, vacuum packed bone-in rib loins (LT) were thawed at 4°C for 24 hours. One loin from each treatment was utilised for each of the 4 questions in a session (1 LT sample x 3 treatments x 4 questions = 12 loins total per session). Twenty-four hours prior to a session, the loins were boned out and any connective tissue removed before being repackaged into individual vacuum packs. The twelve loins were *sous vide* cooked at 58°C for 1 hour. After cooking, loins were refrigerated overnight.

On the day of a session, the loins were removed from the fridge 1.5 hours before cooking. Five minutes prior to cooking, the loins were removed from the vacuum pack, patted dry using paper towels and rested for 5 minutes. Thermocouples were inserted into the centre of each loin and the loins were subsequently grilled in a clamshell hot plate (Roband Aluminium Grill Station 8 Slice Smooth Plates WGSA815S, Nisbets, Auckland), pre-heated to 150°C for 2.5 minutes, to reach an internal temperature of 65°C (medium degree of doneness). Cooked loins were then rested for 5 minutes before each loin being cut into seven 1-cm-thick slices lengthways, followed by a cut in half cross ways using a cutting grid. The 14 samples per loin weighed approximately 4 grams each. Lamb samples were individually wrapped in aluminium foil pre-coded with 3-digit codes and kept in a sample warmer at 50°C before serving. Unique 3-digit codes were used for each question to prevent bias. Samples were served on pre heated ceramic dishes, with each panellist receiving 3 samples (1 per treatment) for each question. Each panellist received their samples in a different order according to a Williams square design. Cook times were staggered so that the rest time was the same for each question.

The panellists evaluated the samples in individual sensory booths with controlled conditions under white light. Participants were provided with filtered water and unsalted gluten-free crackers to cleanse their palate between each lamb sample. Each panellist was asked four questions, in each question they ranked 3 lamb samples for an attribute (overall liking, flavour intensity, tenderness and juiciness). Samples were ranked from 1-3, with one being the least (e.g least liked) and 3 being the most.

**Table 7.1: Questions asked to participants in sensory study**

Attribute	Score		
	1	2	3
Overall liking	Least liked	Intermediate	Most liked
Flavour intensity	Least flavour intensity	Intermediate	Most flavour intensity
Tenderness	Least tender	Intermediate	Most tender
Juiciness	Least juicy	Intermediate	Most juicy

#### 7.2.4 Statistical analysis

##### **Carcass characteristics, objective meat quality and fatty acid composition**

All data was tested for normality and outliers using Genstat 24.0 (VSN-International, 2024) before analysis.

Final live weight, carcass weight, dressing out percentage, V-GR and fatty acid composition were analysed using an analysis of variance (ANOVA) in Genstat 24.0 (VSN International, 2024). For the analysis of intramuscular fat, an analysis of covariance was used where carcass weight was included as the covariate.

Objective meat quality (pH, meat colour, shear force, water holding capacity) was analysed using an analysis of covariance. Muscle pH was included as a covariate in the model for all the meat quality characteristics.

There was no replication of the treatments, so we are not accounting for variation in forage plots. Differences among least square means were assessed according to Fisher's unprotected least significant difference test and were considered significant at a probability level of <0.05.

##### **Consumer sensory panel**

A total of 144 LT loins (4 questions x 3 treatments x 12 sessions) were evaluated by 126 consumers over 12 sessions.

To determine if significant differences existed in the ranking of the forage treatment for each of the 4 attributes considered (overall liking, flavour intensity, tenderness and juiciness), The data were analysed using a Friedman analysis in Microsoft Excel (version 16.0) as described in (Meilgaard et al., 1999) for randomized block analysis of rank data.

The Friedman's test is a nonparametric statistical technique used to investigate the sources of variation in a data set with rankings. This test allows for a global comparison across the samples. The rank sums of the samples were calculated and used to obtain Friedman's T-statistic which was compared with the critical value of  $\chi^2$ , at  $\alpha=0.05$ , with  $(t - 1)$  degrees of freedom, where  $t$  is the number of treatments. Where the Friedman test was significant, a multiple pairwise comparisons using Tukey's Honestly Significant Difference was performed to determine the significance of all pairwise comparisons.

## 7.3 Results

### 7.3.1 Carcass characteristics

Final liveweight, carcass weight and dressing out percentage was greatest for lambs fed Chicory, followed by lambs fed Raphanobrassica and then lambs fed PRG/WC ( $p < 0.001$ , Table 7.2). Intramuscular fat (IMF%) was greater in lambs fed Chicory than lambs fed Pasture ( $p < 0.05$ ), however this effect was no longer evident when carcass weight was included as a covariate in the statistical analysis ( $p > 0.05$ ). VIA Scan GR was greater for lambs fed Chicory and Raphanobrassica compared to lambs fed Pasture ( $p < 0.001$ ).

**Table 7.2: Mean values for hot carcass weight, final liveweight, dressing out percentages, intramuscular fat (IMF) and ViaScan-GR of lambs grazed on PRG/WC, Chicory or Raphanobrassica for 102 days**

	Treatment			SEM	P-value	
	PRG/WC	Chicory	Raphano- brassica		Treatment	HCW covariate
Final live weight (kg)	41.0 <sup>c</sup>	45.0 <sup>a</sup>	43.8 <sup>b</sup>	0.38	<0.001	
Hot carcass weight (kg)	17.1 <sup>c</sup>	21.2 <sup>a</sup>	19.4 <sup>b</sup>	0.21	<0.001	
Dressing out (%)	41.7 <sup>c</sup>	47.1 <sup>a</sup>	44.4 <sup>b</sup>	0.00	<0.001	
IMF (%)	3.0 <sup>b</sup>	3.8 <sup>a</sup>	3.4 <sup>ab</sup>	0.21	0.033	
IMF <sup>1</sup> (%)	3.4	3.5	3.4	0.33	0.942	0.148
V-GR <sup>2</sup>	7.0 <sup>b</sup>	11.5 <sup>a</sup>	11.1 <sup>a</sup>	0.46	<0.001	

<sup>a,b,c</sup> Different letters within the same row denote significant difference between means

<sup>1</sup>IMF adjusted to an equal carcass weight (kg)

<sup>2</sup>Estimated by ViaScan

### 7.3.2 Objective meat quality tests

There were no forage treatment effects on any of the meat quality measures ( $p > 0.05$ , Tables 7.3, 7.4). The pH covariate was significant for lightness, shear force work done, shear force peak force and cook loss ( $p < 0.05$ ).

**Table 3: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days.**

	Forage Treatment			SEM	P-value
	PRG/WC	Chicory	Raphanobrassica		
Ultimate pH	5.68	5.69	5.71	0.01	0.277
Lightness (L*)	34.61	35.35	34.35	0.31	0.061
Redness (a*)	15.77	15.96	15.28	0.25	0.154
Yellowness (b*)	6.59	6.65	6.09	0.18	0.064
Work done (kgF)	10.83	11.46	11.15	0.34	0.443
Peak force (kgF)	2.40	2.40	2.44	0.07	0.877
Drip loss (%)	2.24	2.35	2.57	0.19	0.463
Cook loss (%)	30.63	30.14	29.96	0.29	0.253

**Table 7.4: Mean values for objective meat quality tests on the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. The means were statistically analysed with pH as a covariate.**

	Forage Treatment			SEM	P-values	
	PRG/WC	Chicory	Raphanobrassica		Treatment	pH covariate
pH	5.68	5.69	5.71	0.01	0.277	-
Lightness (L*)	34.53	35.30	34.48	0.29	0.093	0.007
Redness (a*)	15.72	15.93	15.36	0.25	0.269	0.063
Yellowness (b*)	6.56	6.62	6.14	0.18	0.134	0.062
Work done (kgF)	10.92	11.52	10.99	0.33	0.366	0.003
Peak force (kgF)	2.42	2.41	2.42	0.07	0.991	0.037
Drip loss (%)	2.22	2.35	2.59	0.19	0.408	0.492
Cook loss (%)	30.54	30.07	30.10	0.28	0.406	0.001

### 7.3.3 Fatty acid composition

There were forage treatment effects on most of the fatty acids (FA) except for the sum of fatty acids, saturated fatty acids (SFA), monounsaturated fatty acids (MUFA) and EPA + DHA ( $p>0.05$ , Table 7.5). The meat from lambs fed Raphanobrassica had higher levels of branched chain fatty acids (BCFA) than meat from lambs fed Chicory ( $p<0.05$ ). Meat from lambs fed Chicory had greater levels of polyunsaturated fatty acids (PUFA), C18:3 n-3 (ALA), n-3 PUFA and n-6 PUFA than both meat from lambs fed PRG/WC and Raphanobrassica ( $p<0.001$ ). In the case of long chain n-3 PUFA, the meat from Chicory fed lambs had a higher concentration than meat from PRG/WC fed lambs but no different to the meat of Raphanobrassica fed lambs ( $p<0.05$ ). For the fatty acid ratios, meat from lambs fed PRG/WC and Raphanobrassica had lower ratios of n-6:n-3 compared to meat from Chicory fed lambs, which had a greater ratio of PUFA:SFA compared to the other treatments ( $p<0.001$ ).

**Table 7.5: Fatty acid content (mg/100g raw meat) of the Longissimus lumborum (loin) from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days.**

	Treatment			SEM	P-value
	PRG/WC	Chicory	Raphanobrassica		
Sum of FA	4030.12	4583.57	4496.87	179.86	0.075
Unreported FA	203.04 <sup>b</sup>	231.00 <sup>a</sup>	226.82 <sup>a</sup>	8.09	0.040
BCFA <sup>1</sup>	42.48 <sup>ab</sup>	37.78 <sup>b</sup>	46.92 <sup>a</sup>	1.97	0.010
SFA <sup>2</sup>	1802.81	2022.46	2036.69	82.31	0.091
MUFA <sup>3</sup>	1725.65	1903.80	1889.76	81.05	0.233
PUFA <sup>4</sup>	281.00 <sup>b</sup>	407.79 <sup>a</sup>	320.10 <sup>b</sup>	16.87	<0.001
EPA+DHA <sup>5</sup>	29.20 <sup>b</sup>	32.15 <sup>a</sup>	30.86 <sup>ab</sup>	0.89	0.070
C18:3 n-3	74.77 <sup>c</sup>	121.23 <sup>a</sup>	97.43 <sup>b</sup>	6.95	<0.001
n-3 PUFA <sup>6</sup>	125.66 <sup>c</sup>	177.41 <sup>a</sup>	151.03 <sup>b</sup>	7.91	<0.001
n-6 PUFA <sup>7</sup>	122.27 <sup>b</sup>	194.98 <sup>a</sup>	139.32 <sup>b</sup>	8.03	<0.001
LC n-3 PUFA <sup>8</sup>	50.89 <sup>b</sup>	56.18 <sup>a</sup>	53.59 <sup>ab</sup>	1.31	0.023
n-6:n-3	0.97 <sup>b</sup>	1.11 <sup>a</sup>	0.92 <sup>b</sup>	0.02	<0.001
PUFA:SFA	0.16 <sup>b</sup>	0.20 <sup>a</sup>	0.16 <sup>b</sup>	0.01	<0.001

<sup>a, b, c, d, e</sup> Different letters within the same row denote significant difference between means. <sup>1</sup>Branched chain fatty acids (BCFA) =  $\sum$  iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0, <sup>2</sup>Saturated fatty acids (SFA) =  $\sum$  C10:0, C12:0, C14:0, C15:0, C16:0, C17:0, C18:0, C20:0, C22:0, iso-C14:0, iso-C15:0, anteiso-C15:0, iso-C16:0, iso-C17:0, anteiso-C17:0. <sup>3</sup>Monounsaturated fatty acids (MUFA) =  $\sum$  C14:1, C16:1, C17:1 C18:1 *trans*-9, C18:1 *trans*-11, C18:1 *cis*-9, C18:1 *cis*-11. <sup>4</sup>Polyunsaturated fatty acids (PUFA) =  $\sum$  C18:2n-6, C20:4n-6, C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3, C18:2 *cis*-9, *trans*-11. <sup>5</sup>EPA + DHA =  $\sum$  C20:5n-3, C22:6n-3. <sup>6</sup>n-3 PUFA =  $\sum$  C18:3n-3, C20:5n-3, C22:5n-3, C22:6n-3. <sup>7</sup>n-6 PUFA =  $\sum$  C18:2n-6, C20:4n-6. <sup>8</sup>LC n-3 PUFA =  $\sum$  C20:5n-3, C22:5n-3, C22:6n-3.

### 7.3.4 Consumer sensory study

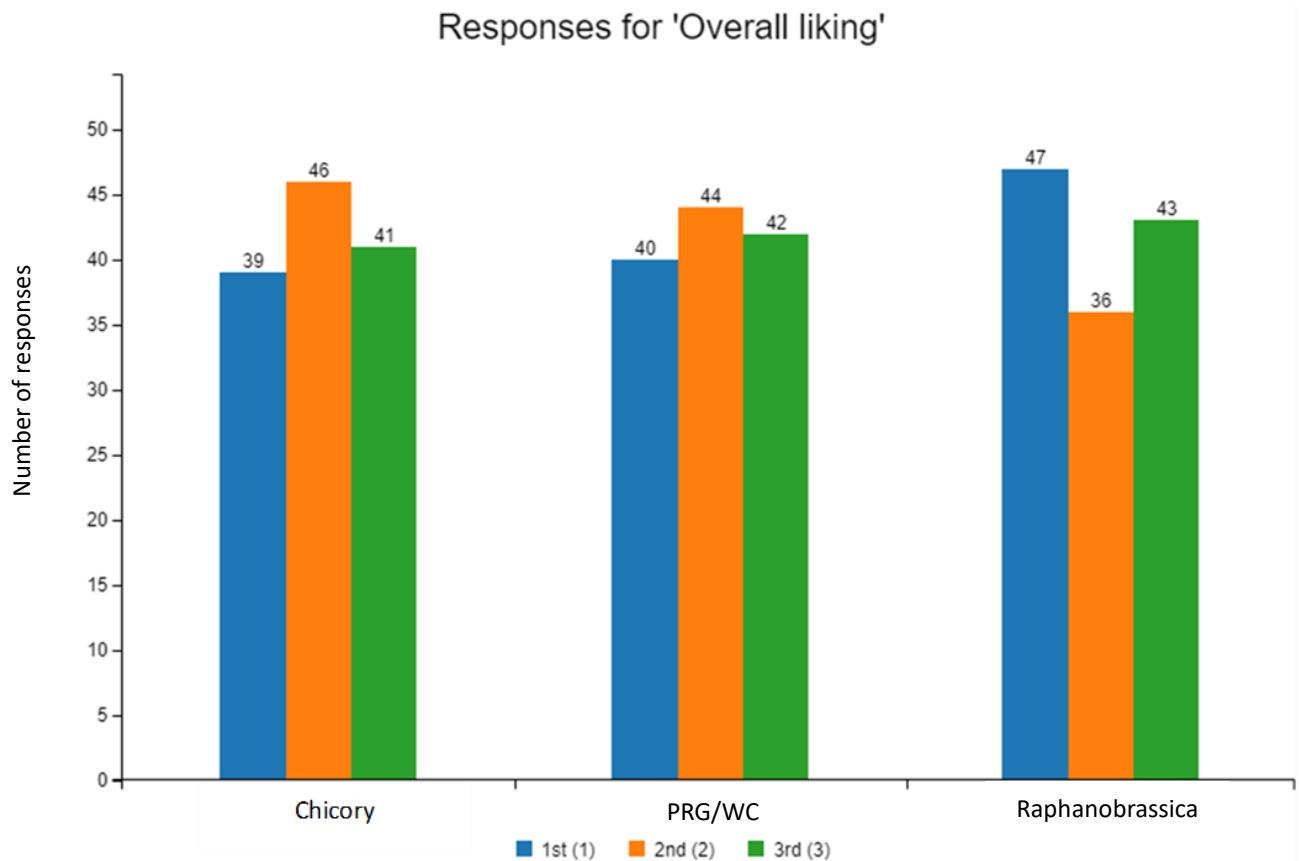
Consumer scores for liking, tenderness, flavour and juiciness were similar for the meat of lamb fed the three forage treatments ( $p > 0.05$ , Table 7.6). However, there was a tendency ( $p = 0.09$ ) for meat from lambs fed Chicory to be ranked as less tender than meat from lambs fed PRG/WC or Raphanobrassica.

**Table 7.6: Consumer ranking of four attributes for meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. Samples were ranked from 1 - 3, with 1 being the 'least' and 3 the 'most' of each attribute.**

	Treatment			P-value
	PRG/WC	Chicory	Raphanobrassica	
Overall liking	2.016 ± 0.810	2.016 ± 0.800	1.968 ± 0.848	0.909
Tenderness	2.063 ± 0.827	1.841 ± 0.833	2.095 ± 0.774	0.090
Flavour intensity	1.929 ± 0.792	1.960 ± 0.833	2.111 ± 0.822	0.302
Juiciness	1.992 ± 0.825	1.992 ± 0.825	2.016 ± 0.810	0.976

#### 7.3.4.1 Overall liking ranking

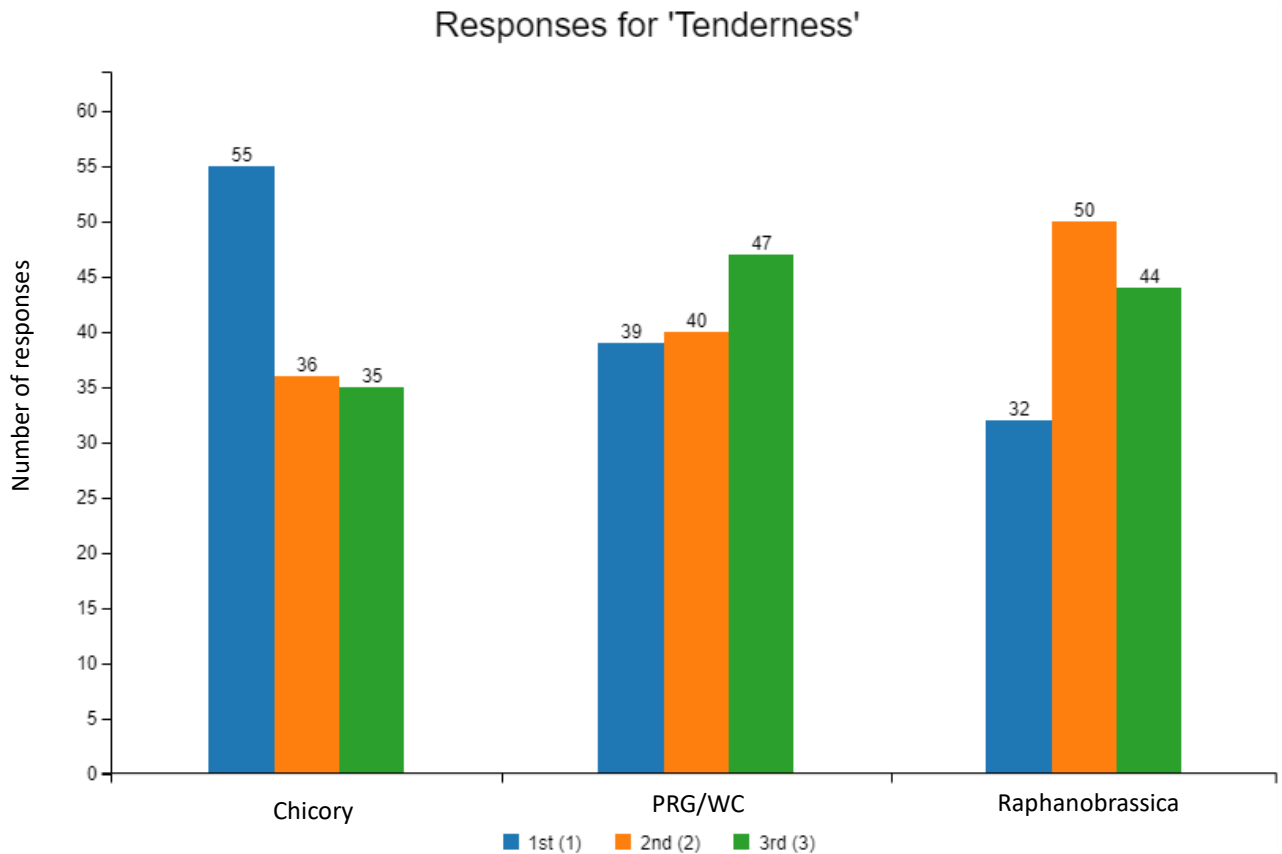
Consumers were dichotomous with their liking of the meat from lambs fed Raphanobrassica ranking either as the least liked or most liked, with fewer consumers ranking it intermediate to the other two treatments. For meat from lambs fed Chicory, consumers tended to rank the liking of these samples intermediate to meat from the other forage treatments, reflecting the opposite pattern to the rankings of the meat from Raphanobrassica. Meat from PRG/WC fed lambs tended to have the most even distribution of rank for overall liking (Figure 7.1).



**Figure 7.1: Consumer responses for Question 1: Overall liking of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least liked, a score of 3 = most liked.**

#### 7.3.4.2 Tenderness ranking

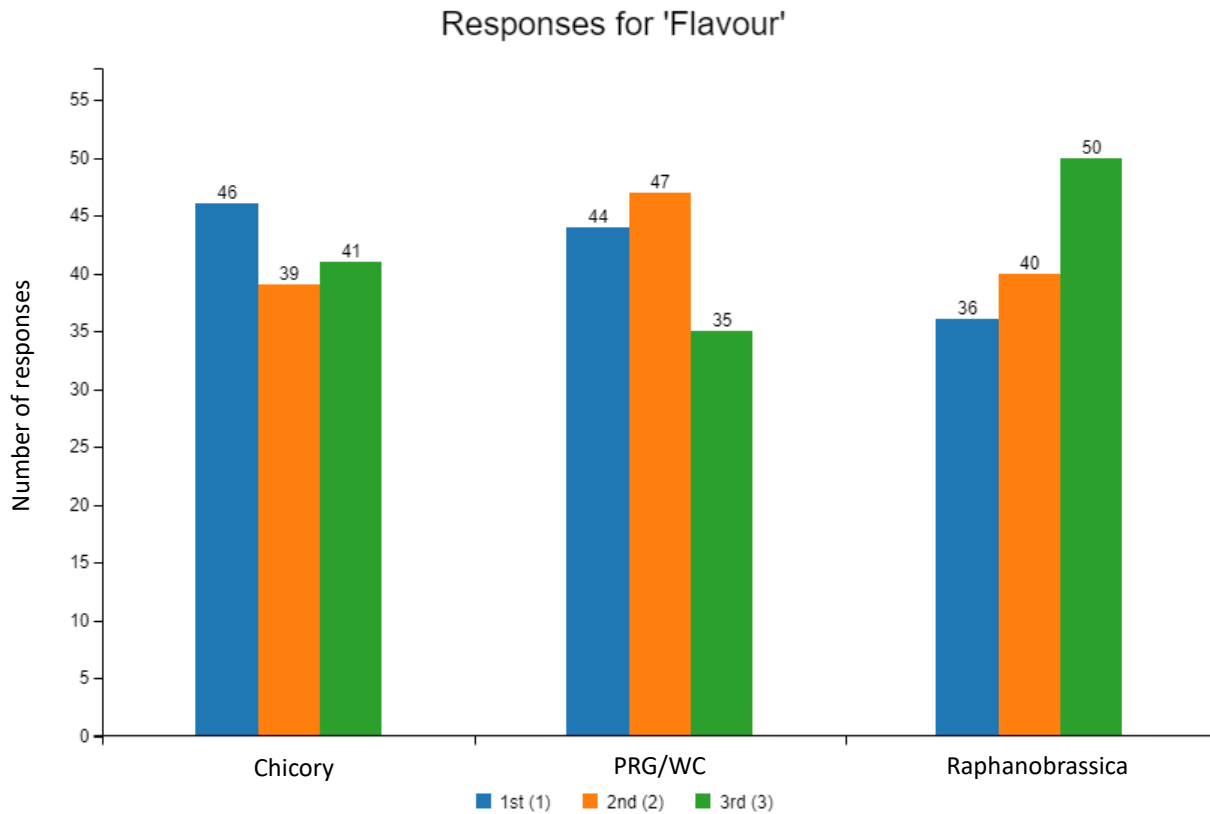
Tenderness was the one eating attribute where the results trended towards significance ( $p=0.09$ ). Meat from lambs fed Chicory was ranked the least tender by 44% of consumers. Meat from lambs fed PRG/WC was most often ranked as the most tender by 47% of consumers in the panel. The meat from Raphanobrassica fed lambs was most often ranked intermediate (Figure 7.2).



**Figure 7.2: Consumer responses for Question 2: Tenderness of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least tender, a score of 3 = most tender**

#### 7.3.4.3 Flavour intensity ranking

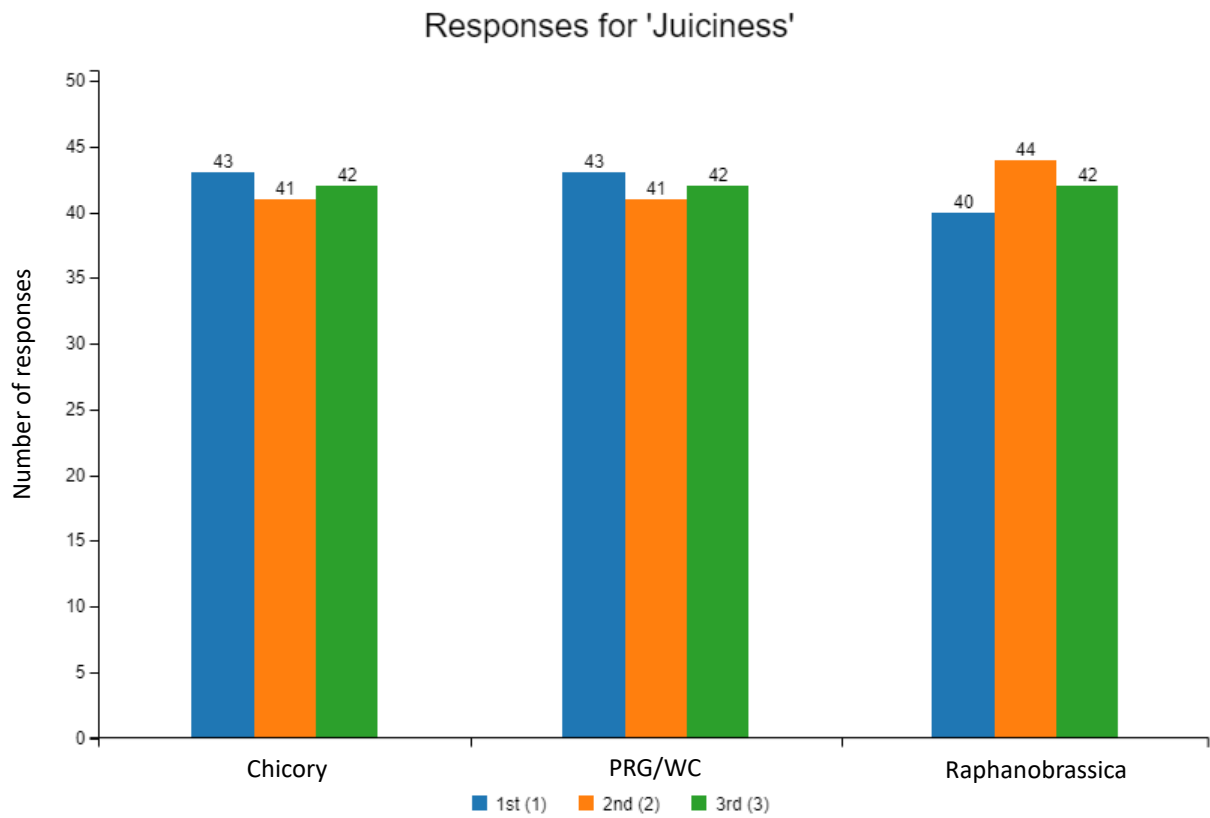
Meat from Raphanobrassica fed lambs was most often ranked as having the greatest flavour intensity, with 40% of consumers in panel giving this response. Meat from lambs fed Chicory was ranked as having the least flavour intensity by 37% of consumers. Meat from PRG/WC-fed animals was most often ranked between meat from Chicory and Raphanobrassica-fed lambs (Figure 7.3)



**Figure 7.3: Consumer responses for Question 3: Flavour intensity of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least flavour intensity, a score of 3 = most flavour intensity**

#### *7.3.4.4 Juiciness ranking*

The distribution of ranks for juiciness of meat was very similar across meat from lambs fed Chicory, PRG/WC or Raphanobrassica. Between 40-43 of responses ranked the meat from each forage treatment as being least juicy and for all three forage treatments the juiciness was ranked in third place as most juicy by 33% of the responses (Figure 7.4).



**Figure 7.4: Consumer responses for Question 4: Juiciness of meat from lambs that had grazed PRG/WC, Chicory or Raphanobrassica for 102 days. A score of 1 = least juicy, a score of 3 = most juicy**

## 7.4 Discussion

The overall liking of meat from lambs that had grazed Chicory was less frequently ranked low compared to the meat of lambs that had grazed Raphanobrassica however the mean score did not reach statistical difference. The ranks for overall liking were divided with the greatest frequency of panellists ranking the overall liking of Raphanobrassica as either split between the highest rank (best) or lowest rank (worst) resulting in the greatest number of intermediary ranks for Chicory and PRG/WC. This split in ranking for overall liking may be partly due to the differences in ranking for the individual attributes of tenderness and flavour that contribute to the liking of meat. Chicory had a tendency to be ranked less tender and Raphanobrassica had the greatest frequency of most intense flavour rankings.

### 7.4.1 Tenderness

Consumers tended towards scoring meat from lambs fed Chicory as being the least tender. Tenderness is influenced by the concentration and solubility of collagen, pH, extent of contraction, the activity of proteolytic enzymes and the level of fatness in the carcass and meat (Schreurs & Kenyon, 2017). Meat pH was measured as being similar to the other treatments but was a significant covariate on shear force values suggesting that meat ultimate pH could be having a partial influence on tenderness ranking. The Chicory fed lambs had greater final liveweight and carcass weight compared to the other forage treatments. As lambs get older and heavier, tenderness decreases, mainly due to reduced collagen solubility (Hopkins et al., 2013; Purchas et al., 2002; Young et al., 1993). It is possible that due to the chicory fed lambs having larger carcasses and having developed larger muscles the concentration and solubility of collagen could have reduced the tenderness ranking. However, the muscle and collagen attributes were not measured directly in this study so the lower score for tenderness is difficult to fully explain. There was no difference in the objective measure of tenderness through shear force values but previous research has only been able to link objective shear force measurements to perceived tenderness with a low level of accuracy and precision (Hopkins et al., 2006). The presence of intramuscular fat can positively influence tenderness as it dilutes the connective tissue and muscle fibres (Schreurs et al., 2013). However, for this study, the greater IMF% (0.8% greater than PRG/WC) measured in the meat of lambs fed Chicory was not sufficient to increase the tenderness measured either objectively or subjectively, compared to the meat from the PRG/WC and Raphanobrassica forage treatments.

#### 7.4.2 Flavour Intensity

Meat from lambs fed Raphanobrassica was most frequently ranked by the consumer panel as having the greatest flavour intensity. An American review identified flavour as the greatest determinant of consumer liking in lamb (Miller, 2020), however a recent New Zealand study found tenderness to be equally important, suggesting the difference could be due to New Zealand typically slaughtering lambs at a younger age so mutton-type flavours associated with older sheep would have less influence (Realini et al., 2021). Flavour is influenced by several on-farm factors including animal age, diet, time on feed, gender and breed (Font-i-Furnols & Guerrero, 2014; Realini et al., 2017). Lambs sourced for this study were all ewe lambs, sourced from one flock of ewes and grazed on their treatments for the same time duration to avoid confounding factors. Previous research has delivered mixed results when considering the effect of a forage brassica diet on lamb meat, with most research to date done on forage rape and none on Raphanobrassica. A key piece of Australian research utilised the combination of a trained panel, a consumer panel and volatile data to compare two forage rape cultivars to lucerne and perennial ryegrass and found no evidence of brassica lamb taint when lambs grazed brassica for at least 42 days (Frank, Watkins, et al., 2016). In fact, brassica feeding improved sensory properties and consumer liking over perennial ryegrass (Frank, Watkins, et al., 2016). Other Australasian studies found that meat from lambs fed forage rape was stronger in flavour compared to meat from lambs fed perennial ryegrass or lucerne, however this was not consistent across cultivars (Elmes, 2013; Hopkins, Beattie, et al., 1995).

Fatty acid composition influences the firmness and oiliness of adipose tissue and the oxidative stability of muscle, both of which affect the meat flavour and colour (Wood et al., 2008). In cattle, monounsaturated fatty acids are associated with lower melting points than saturated fatty acids, which positively affects meat tenderness and flavour (Hayakawa et al., 2015). Lambs grazing forage diets had modest associations between individual fatty acids and fatty acid groups with sensory scores, where flavour and tenderness liking scores were positively correlated with MUFA and negatively correlated with PUFA, n-6 and n-3 fatty acids (Realini et al., 2021). Similar effects have been recorded in beef, where increased MUFA is associated with greater consumer preference and PUFA reduced preference (Baublits et al., 2009; Hwang & Joo, 2017). PUFA are susceptible to oxidation, thus meat with elevated levels can have reduced shelf life and off-flavours, however increasing intakes PUFA by method of grazing forages can partially mediate this due to presence of vitamin E or other antioxidants in these plants, which protects PUFA from oxidation (Howes et al., 2015). Additionally, given that animals with higher levels of PUFA typically have lower levels of IMF, and IMF is known to influence sensory scores, the two effects are difficult to separate. In the current study, levels of MUFA were similar between

treatments and the increased level of PUFA and long chain fatty acids in Chicory fed lambs over PRG/WC fed lambs did not result in a difference in flavour intensity scores. Given that levels of PUFA and long chain fatty acids in Raphanobrassica fed lambs were intermediate to Chicory and PRG/WC fed lambs, it is unlikely that levels of these fatty acids are causing the trend towards greater flavour intensity in meat from Raphanobrassica fed lamb.

Study 2 identified sulphur based volatile compounds as being potential markers of meat from lambs fed a Raphanobrassica finishing diet. While the two studies utilised different lambs and so direct links can't be made, there is a possibility the consumers were detecting sulphur compounds when they tended to rank meat from Raphnanobrassica fed lamb as having the most intense flavour. Sulphur compounds have been associated with sulfurous, onion, cabbage, cauliflower or burnt odours (Pavan et al., 2021).

#### 7.4.3 Juiciness

Consumers in this study did not detect any differences in juiciness between the meat samples. Juiciness is a complex attribute of eating quality of meat which is highly influenced by the end point cooking temperature, meaning cooking practices of different countries and cultures lead to differences in perceived juiciness (Winger & Hagyard, 1994). Increasing levels of intramuscular fat have been associated with increased juiciness scores, attributed to the greater retention of water during cooking and increased saliva production by the consumer (Angood et al., 2008). This relationship has been recorded in studies with trained panellists and untrained consumers (Frank, Ball, et al., 2016). Lambs fed Chicory had greater IMF% levels than lambs fed PRG/WC in the current study, however the difference of 0.8% was not sufficient to result in a difference in juiciness ranking by consumers in the sensory panel. Interestingly, another recent study on New Zealand lamb found a link between IMF% and all sensory traits except juiciness indicating that the eating attribute of juiciness is less easily discriminated with New Zealand consumers (Realini et al., 2021).

#### 7.4.4 Overall liking

Overall liking of lamb meat is highly correlated with other key sensory and meat quality attributes such as tenderness, flavour, juiciness and intramuscular fat (Pannier et al., 2014; Realini et al., 2021). Despite a difference in tenderness scores between treatments in the current study, and trends evident in flavour intensity, the overall liking was similar between treatments. As discussed above, intramuscular fat generally has a positive influence on tenderness, flavour and juiciness. Levels of intramuscular fat ranged from 3.0% for meat from PRG/WC fed lambs to 3.8% for meat from chicory fed lambs, with all

meat samples achieving levels higher than the New Zealand average of 2.69% (Craigie et al., 2017). A New Zealand study has shown consumer liking of lamb increases significantly at 3% IMF, achieving maximum scores at 4% (Realini et al., 2021), whilst international studies have suggested optimum levels of between 3.5% and 5% (Heylen et al., 1998; Lambe et al., 2017b; Pannier et al., 2014), with one suggesting a minimum of 5%. However this is very difficult to achieve under New Zealand production systems (Hopkins et al., 2006). Despite meat from chicory fed lambs having greater levels of intramuscular fat than meat from lambs fed PRG/WC, the difference was not great enough to elicit a difference in sensory rankings of the meat from the lambs grazed the three forages.

The same Australasian studies that investigated effect of forage brassica on lamb meat flavour, also investigated consumer acceptance, again finding inconsistent results. The study of Frank, Watkins et al., (2016) found that brassica feeding increased consumer liking. In the study by Hopkins (2006), consumers found meat from lambs fed forage rape less acceptable for one of two muscle types and in the Elmes 2013 study, lamb meat from male lambs that grazed a forage rape cultivar was preferred compared to male lambs that grazed perennial ryegrass, lucerne or a different forage rape cultivar. Due to the greater lamb growth rates on forage rape compared to perennial ryegrass, the forage rape lambs had significantly greater carcass weights and fat scores so these effects could have been influencing panellist acceptability. Other Australasian research has found no difference in sensory scores when comparing meat from lambs fed forage rape to other forage types (Campbell et al., 2011; De Brito et al., 2016; Scales, 1993).

Concentrations of branched chain fatty acids (BCFA) were greater in meat from lambs fed Raphanobrassica compared to meat from lambs fed Chicory. BCFA are known to be influenced by diet, where greater energy intakes can promote deposition of BCFA's in fat of lambs, either by method of concentrate feeding or highly digestible forages (Watkins et al., 2021). They are associated with mutton/barnyard/milky/sour flavours, which can be perceived negatively, particularly by Japanese or Singaporean consumers (Prescott et al., 2001; Prescott et al., 2004). More recent research found a positive relationship between total BCFA's and consumer and sensory scores, where feeding lambs high quality forage rape resulted in greater concentrations of BCFA's in their meat and improved sensory scores over meat from lambs fed perennial ryegrass (Frank, Watkins, et al., 2016). This effect was evident across both Chinese and Australian consumers, suggesting Chinese consumers are less sensitive to BCFA's than other Asian groups, which is important given the large volume of New Zealand lamb exported to China. The authors suggested that up to a certain threshold, BCFA's play a role in defining lamb flavour and acceptance for some consumers (Frank, Watkins, et al., 2016). The greater

BCFA of the meat of lambs fed Raphanobrassica and the dependency of concentration vs consumer perception of BCFA may be a lead into further investigations of the dichotomous overall liking result and the greater frequency of ranking for most intense flavour for the meat of Raphanobrassica fed lambs.

## 7.5 Conclusion

The untrained consumer panel identified meat from Chicory fed lambs as being the least tender, and meat from lambs fed Raphanobrassica tended to have greater flavour intensity than meat from lambs fed Chicory or PRG/WC. The difference in tenderness can be explained by the heavier carcass weights of lambs fed this forage type. Greater flavour intensity of meat from lambs fed Raphanobrassica aligns with the volatile profile results of Study 2 where the forage diets created unique volatile profiles, however the perceived difference in flavour intensity could help to explain the dichotomous overall liking result. Overall, the small differences in sensory scores across the three forage treatments (PRG/WC, Chicory and Raphanobrassica) are positive for the New Zealand sheep industry as it suggests a range of grazed forages can be utilised to grow lambs without risk of impacting meat quality and sensory attributes.

## Chapter 8

### General Discussion

## 8.1 Introduction and research questions

Producing lamb with consistently high eating quality is a key goal of the New Zealand red meat sector. With a large proportion of lamb being exported to a range of countries, ensuring that we meet the expectations of consumers in each of these markets is important to increase the demand and perceived value and to increase the likelihood of repurchase. Research has shown that different lamb production systems result in variation in lamb carcass and meat quality (Chapter 2; Tables 2.3-2.7).

New Zealand lamb production systems are based on lambs grazing perennial ryegrass/white clover-based pastures. Typically, quality of these pastures is high during spring, but declines during summer due to reproductive growth of the perennial ryegrass, as the stem and seedhead has poor nutritional value. The reduction in forage quality and quantity grown over summer is exacerbated by climate variation between locations and between years, and tends to be greater in older, run-out pastures, leading to inconsistent supply of forage to optimise animal production. Farmers in New Zealand utilise summer-active alternative forages for finishing lambs to maximise lamb growth and as part of a pasture renewal programme to upgrade paddocks to modern grass cultivars. Typically, herbs, brassicas, clovers or mixes of these are utilised for this purpose. It is important to understand the impact of feeding these forages on not only animal performance measures, but also the physical and chemical properties of the resulting lamb meat produced. This allows farmers and processors to make better decisions around what production system aspects are useful to achieve specific characteristics for discerning markets or differentiate products to meet the unique requirements of each of our export markets.

Whilst there is some New Zealand-based research on the impacts of feeding alternative forages on carcass measures, meat quality and fat deposition, very few studies have done this using a replicated farmlet style design. This type of study design minimises the influence of external environmental factors and gives the most robust results. The forage species selected for this research are modern cultivars, which is important as animal performance can differ based on agronomic differences between cultivars, as was previously shown in plantain. The first study of this research included six forage based diets, with the second and third studies narrowing in on three of these diets and explored the impact of these further by including different grazing durations and assessing sensory characteristics via volatile profile and a sensory panel. The three forage diets studied throughout this research were Raphanobrassica, Chicory and Perennial ryegrass/white clover. Raphanobrassica provided the greatest forage dry matter growth under challenging conditions in the first study and is a relatively new species of forage brassica utilised for lamb finishing, and minimal research on animal

performance or meat quality with this forage is available. Chicory is the 'gold standard' for fat deposition when finishing lambs in New Zealand but agronomic reasons mean it does not suit all farm systems and environments. Finally, perennial ryegrass and white clover was included as the control as this forms the base of most lamb finishing systems in New Zealand. Regarding the two species only included in the first study – Red clover is an excellent finishing feed however does not establish as quickly as the other species studied, making direct comparison difficult. Feeding Leafy turnip resulted in lambs that grew quickly and deposited fat, however slow plant regrowth under dry conditions meant that of the two forage brassicas studied, Raphanobrassica was better suited to dry environments.

The production of lamb meat is a value chain involving farmers, processors and consumers. Each of these groups need to be considered when contemplating a change to the production process. This research was designed to be end-to-end and considers the impact on the farmer (lamb growth and carcass performance), processor (carcass performance, meat quality and fat deposition) and the consumer (meat quality, volatile profile and sensory characteristics).

The following research questions were addressed in this PhD thesis:

1. How does the meat quality and fatty acid composition of lamb meat differ between lambs fed alternative forages compared to perennial ryegrass/white clover?
2. How does the summer production of alternative forages effect lamb growth and carcass performance?
3. How much lamb production per hectare can be produced off three forage types over summer?
4. Does the length of time grazing a forage influence the degree of change to meat quality and fat characteristics of lamb meat?
5. Does feeding alternative forages to perennial ryegrass/white clover affect the volatile profile and sensory characteristics of lamb meat?

## 8.2 Summary of each research question

### 8.2.1 How does the meat quality and fatty acid composition of lamb meat differ between lambs fed alternative forages compared to perennial ryegrass/white clover?

The results of Chapters 4 and 6 found that feeding alternative forages to perennial ryegrass/white clover had only minor influences on meat quality of lambs. There were treatment differences in pH, with lambs fed PRG/WC having a higher pH than other forage treatments in Chapter 4. In Chapter 6, Chicory fed lambs had a lower pH than other forage treatments after 35 days and lambs fed Raphanobrassica had a higher pH than other forage treatments after 67 days. The higher pH of lambs fed PRG/WC in Chapter 4 could potentially be attributed to low glycogen stores as these lambs had low growth rates of 50 g/day indicating that surplus nutrients for storing as glycogen were not available. The lower pH in the meat from Chicory fed lambs after 35 days could be explained by its high nutritive value and potentially higher animal intakes giving a greater energy intake to allow for greater glycogen stores. With the exception of PRG/WC fed lambs in Chapter 4, all lamb meat had a pH of less than 5.8 which is the acceptable threshold for meat quality (Egan & Shay, 1988).

After adjusting the remaining meat quality measures for pH, only subtle differences were measured between forage treatments. Differences in meat colour across both studies were minimal which aligns with other research comparing forage diets (De Brito et al., 2016; Ye, Schreurs et al., 2020), and all colour measurements were within the thresholds suggested to ensure consumer satisfaction in previous research (Khliji et al., 2010). It is more likely that forage diet would influence fat colour due to deposition of carotenoid pigments from plants however this was not measured in this research (Priolo et al., 2001). Measures of shear force were similar across treatments and across the two studies, with all measuring below the threshold of 40 N (4.08 kgF) proposed by Hopkins et al. (2006) for “good every day” lamb.

Treatment effects on intramuscular fat varied between the two studies, in Chapter 4 feeding alternative forages to perennial ryegrass/white clover increased IMF% but in Chapter 6 there were no treatment effects on IMF%. The experiment in Chapter 6 had better quality perennial ryegrass/white clover pasture than the experiment in Chapter 4 (based on lamb growth rates and visual assessment), emphasising that forage quality rather than the forage type specifically is important for depositing IMF. The increase in IMF% for alternative forages in Chapter 4 was due to the faster growth and heavier carcass weights measured on these treatments as adding carcass weight as covariate to the model removed any treatment effect. These results indicate that feeding alternative forages to perennial

ryegrass/white clover during summer can provide a higher feeding value that encourages faster growth and greater deposition of fat, however the degree of change depends on environmental conditions and quality of perennial ryegrass/white clover on offer. The consistency of IMF in meat from lambs fed PRG/WC and alternative forages in Chapter 6 supports the use of modern perennial ryegrass cultivars, considering factors that maximise forage quality and intake such as ploidy and aftermath seedhead production.

The ability of lambs to have a high ME intake is likely a key driver of IMF deposition (Santos Torres et al., 2024) and this was attempted to be explored by providing concentrate alongside pasture in Chapter 4. However, the results were inconclusive as it was difficult to manage concentrate intake in an extensive, outdoor experiment with lambs in groups. Designing a study where forages are cut and carried and fed to lambs in individual feeding crates would enable individual ME intakes to be more closely measured and controlled to elucidate ME intake effects on IMF when feeding forages.

Fatty acid composition varied between forage treatments in Chapter 4 but didn't in Chapter 6 except for n-6 PUFA, following a similar trend to IMF%. In Chapter 4, fatty acids were present in highest amounts in meat from lambs fed Chicory, with Leafy Turnip being very similar to Chicory except for PUFA and n-6 PUFA which were lower. The high amounts of fatty acids resulting from feeding these forages can be explained by the greater amounts of IMF deposited. PUFA are preferentially deposited in the phospholipid, so leaner animals tend to have higher concentrations of PUFA compared to fatter animals. The process of depositing fat dilutes PUFA as neutral storage lipid tends to have a more saturated composition (Fisher et al., 2000). Adjusting fatty acid results for IMF reduced some of the dietary effects, however the polyunsaturated long-chain fatty acids remained the greatest in the meat from PRG/WC fed lambs. The process of depositing more fat is associated with fat that is more saturated, and the low amount of IMF deposited in the meat of PRG/WC fed lambs, even when comparing at an equal IMF, was causing a more unsaturated fatty acid profile.

The forages studied in this research delivered different amounts of fatty acids to the lambs. As well as differences in fatty acids measured on a dry matter basis, the chemical composition of alternative forages in summer mean they are digested quickly by grazing animals, resulting in faster rumen outflow rates than summer pasture. With the forage spending less time in the rumen, there is less time for biohydrogenation to occur, resulting in increased duodenal flow of PUFAs. Additionally, greater daily intakes are possible with highly digestible forage which will increase overall intake of alpha linolenic acid (ALA). In Chapter 4, Chicory and Red Clover forage samples had the highest amount of PUFA and

ALA, but only meat of lambs fed Chicory were observed to have higher ALA and PUFA. In Chapter 6, the differing levels of PUFA and ALA in the forage samples were not reflected in the meat samples, as there were no differences between treatments for either PUFA, ALA or EPA + DHA.

Across the two studies, 100g of fresh lamb muscle could provide 27 to 41 mg EPA + DHA, with the greatest concentration coming from the Pasture fed lambs in Chapter 4. All treatments had EPA + DHA values that exceeded the threshold of 23mg/100g muscle to be considered a 'source' of EPA + DHA under Food Standards of Australia and New Zealand (FSANZ, 2012), however no treatment provided enough to be considered a 'good source' at 44mg/100g muscle (FSANZ, 2012). Given that a large proportion of NZ lamb is exported, it is important to consider the nutritional guidelines and regulations of those markets. Only the Pasture treatment in Chapter 4 provided sufficient EPA + DHA to be considered a source (40mg/100g muscle) under the Commission Regulation of European Union (EU) and none of the forage treatments provided a 'good source' at 80mg/100g muscle.

Overall, the difference between forage treatments for meat quality and fatty acids were small, with the differences in fatty acids driven by the lambs growth and deposition of IMF.

### 8.2.2 How does the summer production of alternative forages effect lamb growth and carcass performance?

Chapters 3 and 5 demonstrated that forage type influenced lamb growth and carcass performance, in particular liveweight gain (g/day), final live weight, carcass weight and dressing out percentage. All alternative forages studied (Chicory, Raphanobrassica, Red Clover and Leafy Turnip) as well as supplementation with concentrate, increased lamb performance over Perennial Ryegrass/White Clover.

Lamb growth on alternative forages tended to be greater in the later parts of the studies, (in Chapter 3 this was D<sub>23</sub>-D<sub>64</sub> and in Chapter 5 this was D<sub>36</sub>-D<sub>67</sub>) creating a greater gap between perennial ryegrass/white clover and the alternative forages. The reason for this was twofold, the first being that lambs took time to transition onto their new forage diet and to realise the potential feeding value of that forage. This effect was particularly evident with the brassica treatments, Raphanobrassica and Leafy Turnip, which aligns with previous research indicating that when lambs are introduced to brassica, they initially experience slower growth while their rumen microbiomes adjust, so these forage types are suited to longer feeding durations (Barry, 2013). The effect of transition for the Chicory fed lambs was less, with these lambs growing quickly immediately after being introduced. Forage growth of Chicory declined during the studies as indicated by the lower pre grazing masses and lamb stocking rate in Chapter 5 (Table 5.5). Despite this, the growth rates of the individual lambs were still

high. This was expected given the low NDF and high digestibility of Chicory measured in this phase and provides evidence of faster growth rates seen with lambs grazed on Chicory being due to a higher nutritive value rather than solely due to an increased forage availability increasing intake.

The second reason is that the two studies ran over summer, so forage quality of perennial ryegrass/white clover declined over the trial period due to high temperatures and low rainfall. Forage quality testing in Chapter 5 showed that between D<sub>17</sub> and D<sub>55</sub> the perennial ryegrass/white clover treatment had an increase in neutral detergent fibre and a decrease in digestibility and metabolisable energy. This decline of forage quality in the summer months is typical of Perennial Ryegrass and is a key reason why alternative forages are utilised for summer lamb finishing.

Overall, lamb growth rates per head were highest on Chicory and Red Clover, intermediate on Raphanobrassica and Leafy Turnip and lowest on Pasture. The supplementation of concentrate in Chapter 3 increased the growth rate of these lambs over perennial ryegrass/white clover, but these lambs did not grow as fast as those fed alternative forages. Although in a mob grazing situation it is difficult to ascertain the effect of the concentrate fully as individual intakes weren't able to be measured.

Final live weight and carcass weight was greatest for lambs fed Chicory. In Chapter 3, the lambs fed Leafy Turnip also had an equally highest final live weight and carcass weight to the lambs fed Chicory. Final liveweight of lambs fed Raphanobrassica was similar to Pasture after 35 days but was greater after 64-67 days of grazing. In all slaughters, carcass weight of lambs fed Raphanobrassica was greater than lambs fed Pasture, due to a greater dressing out percentage of Raphanobrassica fed lambs alongside heavier carcass weights. Across both studies, dressing out percentage was higher on all alternative forages compared to perennial ryegrass/white clover indicating that perennial ryegrass/white clover diets are associated with more gut fill, likely a consequence of slower rumen outflow due to lower degradability and greater Neutral Detergent Fibre.

In the experiment in Chapter 5, at the end of 35 days grazing (Phase 1), the lambs grazing the crossover treatments transferred over from a perennial ryegrass/white clover diet to their new forage type, either Chicory or Raphanobrassica. Final live weight and carcass weight of the Phase 2 lambs after 67 days grazing was again highest on Chicory (67 days grazing), followed by Raphanobrassica (67 days grazing) and PRG/Chic (35/32 days grazing). Dressing out percentages were lower on perennial ryegrass/white clover than all other treatments, including the crossover treatments. This

demonstrates that increases in dressing out percentages can be realised within 32 days (the length of Phase 2). The increased dressing out percentages on the alternative forages across all slaughters was partially due to increased carcass weights, and partially due to reduced gut fill from grazing forages with greater digestibility than perennial ryegrass/white clover. Using alternative forages to increase dressing out percentage benefits lamb finishers as lambs achieve a higher carcass weight at a set live weight and helps producers optimise carcass value by placing lambs in the most profitable carcass classification classes.

In summary, both Chicory and Raphanobrassica demonstrated improved carcass performance over perennial ryegrass/white clover, especially in Phase 2 of the study in Chapter 5 where warm, dry weather conditions caused the forage quality of perennial ryegrass/white clover to decline. However, these results also highlight that performance on a per lamb basis was consistently highest with Chicory, attributable to its high feeding value and quick time to transition.

### 8.2.3 How much animal production per hectare can be produced off three forage types over summer?

When planning this research, it was important to consider not only individual lamb performance on the forages studied, but to include per hectare performance to best understand the impact of these forages on the overall production system. Very few studies have considered per hectare performance of lambs grazing forages, and even fewer in a replicated farmlet design. Measuring stocking rate in combination with per head growth rates helps understand the drivers of per hectare production to aid in forage selection on farm. In Chapter 5, both liveweight gained per hectare and carcass weight produced per hectare were considered over the summer and autumn period (17 Jan – 1 May) to ensure relevance to both lamb breeders and finishers.

The cumulative live weight gain per hectare over the entire study duration (17 Jan – 1 May) was greatest for Raphanobrassica (621 kg/ha), followed by Chicory (508 kg/ha) then Pasture (385 kg/ha). For total carcass weight produced, Raphanobrassica had the greatest at 1611 kg/ha, with Chicory and PRG/WC being similar at 767 and 831 kg/ha respectively. The contribution of each Phase to the total live weight gain and carcass weight was different for each forage type, and delving into this helps to understand the strengths and weaknesses of each forage (see Table 5.6).

In Phase 1 (17 Jan – 20 Feb), both Chicory and Raphanobrassica had greater live weight gained per hectare and carcass weight per hectare than PRG/WC. The greater gains observed in Chicory can be

explained by the faster growth rates measured for individual lambs as the stocking rate was the same as PRG/WC in Phase 1 and lower than PRG/WC in Phase 2. However, for Raphanobrassica, the increase over PRG/WC can be attributed to an increased stocking rate (made possible by higher pre grazing masses measured on this forage type) although the per head performance of the lambs was lower.

From Phase 2 onwards, Raphanobrassica had greater per hectare performance compared to Chicory and PRG/WC. The greater per hectare performance on Raphanobrassica was again primarily driven by the higher stocking rate than the other treatments, however in Phase 2 of the study Raphanobrassica lambs also grew faster on a per lamb basis than PRG/WC fed lambs, as the effect of transition onto Raphanobrassica lessened and the quality of PRG/WC decreased. Chicory lambs maintained high growth rates per lamb in Phase 2, but per hectare performance was not as high as Raphanobrassica due to summer dry conditions restricting regrowth, reducing the pre-grazing mass and subsequently stocking rate to achieve *ad libitum* feeding. For both Chicory and Raphanobrassica, their higher dressing out percentages compared to PRG/WC also influenced the greater carcass weight produced per hectare.

Due to dry conditions and insufficient herbage mass no lambs were introduced to Chicory in Phase 3 of the study. This highlights the greater potential of Raphanobrassica compared to Chicory for finishing lambs later in the summer into the early autumn when conditions are dry.

In summary, both Chicory and Raphanobrassica provided advantages over Pasture on a per hectare basis. The way they promote lamb growth performance is different, and each has a different impact on the overall farm system. In the current study, Chicory had superior per lamb performance compared to Raphanobrassica, the lambs fed this forage transitioned quickly and did not need to be grazed for as long to reach target live weights. However, forage growth under very dry conditions was poor and it could not support large numbers of grazing lambs. Raphanobrassica had poorer per lamb performance than Chicory as the lambs took longer to transition meaning that the feeding value of this forage took longer to be realised. The benefit of Raphanobrassica was that superior forage growth under challenging conditions meant that available biomass was high and large numbers of lambs were able to be grazed which resulted in higher per hectare performance. These results suggest that the two forages would have different uses in the farm system, with larger lambs being grazed on Chicory for faster growth and finishing and increased dressing out percentage. Raphanobrassica would be targeted at smaller lambs or lambs born later in the season which would graze for longer, allowing time for transition and a sustained source of quality feed which also provides a higher dressing out percentage than summer pasture. The increased per hectare performance of both forage types over

Pasture and understanding the drivers of this provides useful information to lamb producers when deciding which forages best suit their farm system.

A logical next step would be to include a financial analysis of including a summer forage crop on the farm system, including establishment costs, opportunity costs and regrassing costs in combination with the income from finishing lambs. Understanding the financial implications of making a change to the farm system supports farmers decision making on which forage types may best suit their farm business.

#### 8.2.4 Does the length of time on a forage influence the degree of change to meat quality and fat characteristics of lamb meat?

The design of Study 2 (Chapter 6) meant that two grazing durations were able to be assessed which spanned two seasons (mid-summer and late summer/early autumn). For the Chicory and Raphanobrassica treatments, at D<sub>1</sub> (17 January) lambs were transferred from a diet of perennial ryegrass/white clover to either Chicory or Raphanobrassica. Ten lambs from each treatment were slaughtered on D<sub>35</sub> (20 February, end of Phase 1), with another 10 slaughtered on D<sub>67</sub> (25 March, end of Phase 2). The lambs assigned to crossover treatments grazed perennial ryegrass/white clover for Phase 1 (35 days grazing), then on D<sub>35</sub>, transferred to either Chicory or Raphanobrassica for Phase 2. This resulted in 32 days on the new forage type (D<sub>35</sub> – D<sub>67</sub>), and was late summer/early autumn, from 20 February until 25 March. Thus, there were lambs that had grazed an alternative forage for 35 days in mid-summer, lambs that had grazed an alternative forage for 32 days in late summer/early autumn after a 35-day background on perennial ryegrass/white clover, and lambs that had grazed an alternative forage for 67 days from mid-summer to early autumn.

Lambs slaughtered after 67 days (25 March) were heavier and had greater fat deposition than lambs slaughtered after 35 days (20 February) which explains most of the differences in meat quality and fat characteristics observed. Within a slaughter date, there were minimal differences between forage treatments.

Lambs that had grazed for 67 days had greater fat deposition (intramuscular fat % and ViaScan-GR) compared to lambs that had grazed for 35 days regardless of treatment. This was expected as the lambs were older at the end of Phase 2, and as they were growing, they were bigger and closer to maturity and in a physiological growth phase of depositing fat. Lambs slaughtered after 67 days had greater IMF% which is positive for eating quality, however all lambs were lower than the New Zealand

average of 2.7% (Craigie et al., 2017). VIAScan-GR (V-GR) was greater after 67 days compared to 35 days for all treatments except PRG/WC. V-GR was greater in lambs fed either Chicory or Raphanobrassica compared to PRG/WC across all grazing durations, supporting the findings of faster growth on these alternative forages compared to summer pasture.

Comparing meat quality measures across the grazing durations, small differences in shear force and drip loss were found in this study. Meat from lambs grazed for 67 days had higher shear force work done and peak force values than meat from lambs grazed for 35 days. These lambs were older and heavier at slaughter, so this increase in shear force can likely be explained by the decrease in collagen solubility that occurs as animals age (Hopkins et al., 2013; Purchas et al., 2002; Young et al., 1993). When lambs become closer to maturity, the proportion of fat in the carcass increases, as discussed above with the increase in IMF and V-GR observed. Increasing IMF positively influences eating quality, typically increasing tenderness if the increase in IMF outweighs the associated reduction in collagen solubility (Hopkins et al., 2006). The increase in IMF in this study was not sufficient to offset this and shear force values increased as a result. Days grazing influenced drip loss with meat from lambs grazed for 67 days having higher drip loss than meat from lambs grazed for 35 days. These lambs had higher carcass weights than the lambs from slaughter 1 and lower water holding capacity has been attributed to lambs that are heavier at slaughter (Vergara et al., 1999).

Fatty acid composition showed similar trends to the meat quality results, where different grazing durations had a much larger effect than did the forages themselves. Grazing duration effects were observed across all of the fatty acid measures except branched chain fatty acids and n6:n3 ratio. Lambs that had grazed their forage treatments for 67 days had a fatty acid profile that was more saturated. This is typical of lambs that are older and larger at slaughter, as more neutral storage lipid is deposited which dilutes the PUFA deposited in the phospholipid. This was particularly evident in Chicory fed lambs, where lambs fed Chicory for 67 days or fed perennial ryegrass/white clover for 35 days then switched to Chicory for 32 days had lower levels of EPA + DHA and long chain n-3 PUFA than those same treatments after 35 days grazing. Despite no differences in IMF% between Chicory fed lambs and other treatments, V-GR was greatest in lambs fed Chicory for 67 days indicating greater fat deposition when feeding Chicory.

The statistical model for fatty acid profile was also run with IMF as a covariate to account for the fatty acid profile of meat being driven by the level of fat deposition in the meat (Ponnampalam et al., 2021). Chapter 6 indicated that fatty acid profile is driven by differences in the amount of IMF deposited except for PUFA, C18:3 n-3 (ALA), n-3 PUFA and n-6 PUFA which are under some direct influence of the

diet. Of these, only n-6 PUFA was different between treatments, with short feeding durations of Chicory increasing n-6 PUFA in meat, however not enough to influence the n-6:n-3 ratio. The human health benefits attributed to consumption of meat lipids are primarily from long chain n-3 PUFA, particularly EPA + DHA (Russell & Bürgin-Maunder, 2012). In the current study, meat from lambs fed perennial ryegrass/white clover, Chicory or Raphanobrassica provided 27 to 30 mg EPA + DHA per 100g muscle with no differences evident between forage treatments. Therefore, forage feeding in itself and the quality of the forage, rather than specific forage species, is the impetus for determining fatty acid profile in the meat of lambs that are grazing.

A previous review found that the composition of fatty acids in lamb muscle continued to change until about 42 days after the change in diet and didn't change markedly thereafter (Howes et al., 2015). There is an anecdotal industry standard in New Zealand of a minimum of 35 days grazing on high quality forage prior to slaughter to positively influence fat characteristics and eating quality. In the current study, 35 days was not sufficient to elicit differences in meat quality and fatty acid composition. Possible reasoning for this could be due to the perennial ryegrass/white clover treatment of the experiment in Chapter 6 being spring sown tetraploid perennial ryegrass and white clover, meaning its forage quality was likely higher than an older pasture, and closer in quality to the alternative forages. Younger grass typically contains more nitrogen and ALA (Watkins et al., 2013), and analysis of the forages in the current study did show the perennial ryegrass/white clover treatment as having similar ALA levels to Chicory at the first sampling date ( $D_{17}$ ), to crossover Chicory at the second sampling date ( $D_{55}$ ) and greater than Raphanobrassica at both sampling dates. This result demonstrates the benefit of regrassing older pastures to include modern perennial ryegrass genetics to maximise leaf production (and hence ALA) to promote the deposition of health beneficial fatty acids in meat. Whilst minimal differences in meat quality and fatty acid composition were observed, the key differences that resulted from the alternative forages were in animal production measures, both per head and per hectare as discussed above.

#### 8.2.5 Does feeding alternative forages to perennial ryegrass/white clover affect the volatile profile and sensory characteristics of lamb meat?

Flavour perception is influenced by previous experience and cultural background, with consumers typically preferring lamb from production systems they are familiar with (i.e. pasture vs concentrate feeding). New Zealand exports lamb meat to a variety of markets, each with unique preferences and gaining insights into these is key to ensure customer satisfaction and repurchase. The review from Watkins et al., (2013) showed that the effect of diet is diverse and sometimes inconsistent, with

responses ranging from “no effect” to “unacceptable”. Additionally, there was not yet a consensus on which volatiles are essential for desirable meat flavour and very little information on non-volatile taste components of lamb flavour.

In this thesis, Chapter 6 included an analysis of volatile profile from lamb meat from lambs which grazed perennial ryegrass/white clover, Chicory or Raphanobrassica for 35 or 67 days. Chapter 7 utilised a separate mob of lambs grazing the same three forage types to produce meat to assess if there was a difference in sensory characteristics detected by untrained consumers. The sensory panel of untrained consumers in the current study found minimal differences between treatments when ranking sensory characteristics: overall liking, flavour intensity, tenderness and juiciness. Meat from lamb fed Chicory was ranked as least tender, likely owing to the higher carcass weights of lambs that had grazed this forage. Whilst differences in flavour intensity were not significant, meat from lamb fed Raphanobrassica trended towards having the greatest flavour intensity. Overall liking was similar between treatments; however consumers were dichotomous in their ranking of meat from lamb fed Raphanobrassica, either ranking it as their least or most liked, potentially due to the more intense flavour.

Based on the volatile analysis, the three alcohols (1-hexanol, Z-2-penten-1-ol and 1-octen-3-ol) appear to all be linked to Chicory feeding. Given that these alcohol volatiles are derived from lipid oxidation, this aligns with the higher PUFA levels in meat from lamb fed Chicory in this study, particularly in the first grazing period of 35 days. For the study of Pavan et al., 2021, 1-hexanol was found to be influential on overall liking by untrained consumers, with one cluster positively correlating it with overall liking and another cluster negatively correlated with overall liking, suggesting that the influence of 1-hexanol is not consistent across all consumers.

Dimethyl sulfide was positively associated with overall liking scores for one cluster of consumers and not influential with another consumer cluster (Pavan et al., 2021). A greater relative abundance of dimethyl sulfide was measured in meat from lambs fed Raphanobrassica and Chicory compared to those fed PRG/WC for 35 days in Chapter 6. Pavan et al (2021) also reported greater relative abundance of this volatile in the meat of Chicory fed lambs compared to Pasture fed.

Terpenes such as toluene and limonene originate directly from diet, and toluene is very often detected in forage fed lamb meat (Sivadier et al., 2010). Terpene biosynthesis occurs exclusively in plants and is a marker of pasture feeding (Vasta & Priolo, 2006). After 35 days grazing, meat from lambs fed

PRG/WC had higher abundance of Toulene. PRG/WC fed lambs also had a greater abundance of 1-octene in the meat compared to meat from lamb fed Chicory or Raphanobrassica, indicating the potential of these hydrocarbons as markers of a perennial ryegrass pasture diet. Toulene was not correlated with overall liking in either cluster in Pavan et al., (2021).

In Study 3 (Chapter 7) the dichotomy of ranking by untrained consumers for the liking of meat from the Raphanobrassica fed lambs suggests that dimethyl sulfide could lend itself to being a marker of Raphanobrassica grazing so that product could be differentiated for different markets or sets of consumers. Likewise 1-hexanol, could be a marker for chicory feeding when taken in context with the clustering of consumers of lamb in the Pavan et al. (2021) study and this study reiterated the potential of toulene and 1-octene in the meat as indicators of perennial ryegrass pasture feeding. Technology such as REIMS (Rapid Evaporative Ionisation Mass Spectrometry) which is being developed could lend itself to being used to rapidly identify the volatiles at processing (Ross et al., 2021).

Overall, the separation of treatments in the stepwise analysis indicates that the volatiles in lamb meat have a unique “finger print” from feeding Chicory, Raphanobrassica or perennial ryegrass/white clover. The meat from lamb fed has previously been linked to unacceptable odours (Watkins et al., 2013) and for some consumers in the sensory study (Chapter 7) there was an effect of Raphanobrassica grazing resulting in a low ranking for overall liking and a tendency to rank it with the most intense flavour. The unique profile of volatiles identified with Raphanobrassica feeding may have contributed to these sensory aspects, although feeding lambs brassica is not always associated with a negative flavour attribution of the meat (Frank et al., 2016) as noted by some consumers ranking its overall liking highly in Chapter 7. Overall liking ranks for Raphanobrassica in Chapter 7 were a consequence of more than just the flavour profile and there needs to be caution extrapolating between the two studies in Chapter 6 and 7 which utilised different lambs.

Like the volatiles, the grazing of Chicory, Raphanobrassica and perennial ryegrass/white clover resulted in a unique fatty acid profile in Chapter 4, 6 and 7 and fatty acids can contribute to flavour and eating quality. The differences in fatty acid profile obtained between forage feeding treatments in Chapter 7, including a significant difference in the concentration of BCFA were not sufficient to induce a strong difference in sensory rankings. This corroborated Realini et al., (2021) which considered fatty acids to have only a modest association with sensory characteristics.

In general, the volatiles that were identified in Chapter 6 as separating the forage treatments did not seem to influence consumer liking in the sensory study of Chapter 7, although direct links can't be made due to being different lambs and locations. This aspect highlights an interesting area of further work for lamb meat from forage-based systems and signifies an opportunity to design an experiment to explicitly study the link between volatiles and eating experience, helping to predict traits that shape the eating experience of lamb meat. Additionally, consumer clustering can be a useful tool to understand drivers of consumer preference by segmenting consumers with similar liking patterns. Future research could segment consumers from some high value export markets and combine this with a questionnaire to understand if sociodemographic or behavioural factors are driving differences. Increasing knowledge in this area could enable the industry to tailor products to these markets and drive value.

### 8.3 Practical implications for lamb finishing

This thesis compared lamb performance, meat quality, fat characteristics and sensory characteristics of perennial ryegrass/white clover to alternative forages over the summer period, with the focus being on the alternative forages Chicory and Raphanobrassica. All alternative forages to perennial ryegrass/white clover provided superior lamb performance per head (liveweight gain/day and carcass weight) during summer, including Leafy Turnip and Red Clover which were only included in the first study (Chapters 3 & 4).

Several grazing durations were utilised across the studies, with time spent grazing an alternative forage ranging from 32 days (crossover treatments at slaughter 2 (Chapter 5)) to 67 days (Phases 1 & 2 of Chapter 5). Despite final live weight of Chicory and Raphanobrassica fed lambs not always being greater than the perennial ryegrass/white clover fed lambs in the shorter grazing durations, increases in carcass weight were always evident, owing to greater dressing out percentages on the alternative forages to pasture. The greater dressing out percentages are likely to be attributed to increased fat deposition (ViaScan-GR) and digestibility of the alternative forages to PRG/WC over summer. In Chapter 5, both Chicory and Raphanobrassica had greater metabolizable energy, digestibility (in vitro DMD, DOMD, OMD), and lower fibre content (NDF%/ADF%) than pasture at both sampling dates. Greater forage quality allows for more efficient digestion, increasing rumen outflow rates and reducing rumen fill (Litherland et al., 2010). This research demonstrates that lambs grazing alternative forages during summer (even for short feeding durations of 32-35 days) can result in lambs that have increased dressing out percentages which can increase production in lamb finishing operations.

Chapter 5 demonstrated the importance of considering stocking rate of alternative forages in combination with individual lamb performance in order to examine per hectare performance. Very little research has been done in this area, so this provides valuable insight into the overall impact of alternative forages using a replicated farmlet design. Chicory and Raphanobrassica both provided increased per hectare performance over PRG/WC, with different drivers for each forage type. Chicory fed lambs had greater individual lamb performance, the lambs transitioned quickly and grew faster than Raphanobrassica or PRG/WC. However inferior forage regrowth under dry conditions meant that stocking rate on Chicory was lower than Raphanobrassica, especially in later stages of the study. Lambs grazing Raphanobrassica took longer to transition to their new feed type and grew slower than Chicory fed lambs. However rapid forage growth under dry conditions meant that Raphanobrassica was able to support a higher stocking rate, and as a result the per hectare liveweight gain and carcass weight produced was greatest in this forage type. Additionally, the sustained regrowth later into summer and autumn meant that Raphanobrassica could be utilised to finish smaller lambs or later born lambs. Lamb finishers can utilise this information to make decisions on which alternative forage would best suit their farm system based on their unique needs.

Understanding how an alternative forage may impact overall performance of the lamb production system is key to aid decision making and encompasses other benefits on farm such as reduced internal parasite burden and greater efficiency of production. With animals growing faster they spend less time on farm and thus require less feed for maintenance purposes and contribute less greenhouse gas emissions. These alternative forages can also decrease internal parasite burdens by reducing intakes of L3 larvae (Moss et al., 2011; Moss & Vlassoff, 1993), thus reducing the requirement for frequent anthelmintic drenching. Lower drench frequency helps to decrease the rate of parasite resistance and ensures the sustainability of lamb finishing systems.

Meat quality results indicated only very minor and inconsistent differences between alternative forages and pasture, with most of these being attributable to differences in lamb growth or fat deposition. In New Zealand and Australia, a food can legally be claimed to be a source of omega-3 fatty acids if EPA + DHA is greater than 30 mg per serving of food (FSANZ, 2012) and in this research, all forages were able to deliver sufficient ALA to the grazing animal for the meat to meet source requirements. Differences in fatty acid composition were smaller than expected and this may have been due to newly sown tetraploid perennial ryegrass being used, which would have contained more ALA than older established pasture. This is a positive result for lamb finishers and the New Zealand red

meat industry as it means a range of forages can be utilized to suit each farms production system and environmental conditions without compromising the end product.

This collection of studies highlights that the goal for producing more IMF and hence the potential to have more beneficial PUFA in the lamb meat comes from feeding a forage of high quality (i.e., high digestibility and ME content) in sufficient quantity to maximise growth rate. The aim is to achieve lambs that are growing in a positive energy balance or have a state of "nutrient overflow" and the exact type of forage is less relevant, suggesting forages (or a combination of forages) should be selected to suit the farm system and environment to enable a consistent supply of high quality forage and dietary fatty acids.

## References

- Ablikim, B., Liu, Y., Kerim, A., Shen, P., Abdurerim, P., & Zhou, G. H. (2016). Effects of breed, muscle type, and frozen storage on physico-chemical characteristics of lamb meat and its relationship with tenderness. *Cyta-Journal of Food*, *14*, 109-116.
- Alvarenga, T. I. R. C., Chen, Y., Furusho-Garcia, I. F., Perez, J. R. O., & Hopkins, D. L. (2015). Manipulation of Omega-3 PUFAs in lamb: Phenotypic and genotypic views [Article]. *Comprehensive Reviews in Food Science and Food Safety*, *14*(3), 189-204. <https://doi.org/10.1111/1541-4337.12131>
- Anderson, F., Pannier, L., Pethick, D. W., & Gardner, G. E. (2015). Intramuscular fat in lamb muscle and the impact of selection for improved carcass lean meat yield. *Animal*, *9*(6), 1081-1090. <https://doi.org/10.1017/s1751731114002900>
- Angood, K., Wood, J., Nute, G., Whittington, F., Hughes, S., & Sheard, P. (2008). A comparison of organic and conventionally-produced lamb purchased from three major UK supermarkets: Price, eating quality and fatty acid composition. *Meat Science*, *78*(3), 176-184.
- Aprea, E., Romanzin, A., Corazzin, M., Favotto, S., Betta, E., Gasperi, F., & Bovolenta, S. (2016). Effects of grazing cow diet on volatile compounds as well as physicochemical and sensory characteristics of 12-month-ripened Montasio cheese. *Journal of Dairy Science*, *99*(8), 6180-6190.
- Aurousseau, B., Bauchart, D., Faure, X., Galot, A. L., Prache, S., Micol, D., & Priolo, A. (2007). Indoor fattening of lambs raised on pasture. Part 1: Influence of stall finishing duration on lipid classes and fatty acids in the longissimus thoracis muscle. *Meat Science*, *76*(2), 241-252. <https://doi.org/https://doi.org/10.1016/j.meatsci.2006.11.005>
- Aurousseau, B., Bauchart, D., Galot, A. L., Prache, S., Micol, D., & Priolo, A. (2007). Indoor fattening of lambs raised on pasture: 2. Influence of stall finishing duration on triglyceride and phospholipid fatty acids in the longissimus thoracis muscle. *Meat Science*, *76*(3), 417-427. <https://doi.org/10.1016/j.meatsci.2006.12.001>
- Barry, T. N. (1998). The feeding value of chicory (*Cichorium intybus*) for ruminant livestock. *The Journal of Agricultural Science*, *131*(3), 251-257. <https://doi.org/10.1017/S002185969800584X>
- Barry, T. N. (2013). The feeding value of forage brassica plants for grazing ruminant livestock. *Animal Feed Science and Technology*, *181*(1), 15-25. <https://doi.org/https://doi.org/10.1016/j.anifeedsci.2013.01.012>
- Bas, P., & Morand-Fehr, P. (2000). Effect of nutritional factors on fatty acid composition of lamb fat deposits. *Livestock Production Science*, *64*(1), 61-79. [https://doi.org/10.1016/s0301-6226\(00\)00176-7](https://doi.org/10.1016/s0301-6226(00)00176-7)
- Baublits, R. T., Pohlman, F. W., Brown Jr, A. H., Johnson, Z. B., Rule, D. C., Onks, D. O., Murrieta, C. M., Richards, C. J., Sandelin, B. A., Loveday, H. D., & Pugh, R. B. (2009). Correlations and prediction equations for fatty acids and sensory characteristics of beef longissimus rib steaks from forage-fed cattle and retail USDA choice and select rib steaks [Article]. *Journal of Muscle Foods*, *20*(1), 1-17. <https://doi.org/10.1111/j.1745-4573.2008.00129.x>
- Becker, T. (2000). Consumer perception of fresh meat quality: a framework for analysis [Article]. *British Food Journal*, *102*(3), 158-176. <https://doi.org/10.1108/00070700010371707>
- Beef and Lamb. (2020). *Mid-Season Update 2019-20*.
- Beef and Lamb. (2023). *Compendium of New Zealand Farm Facts 2023*.
- Bernabéu, R., Rabadán, A., El Orche, N. E., & Díaz, M. (2018). Influence of quality labels on the formation of preferences of lamb meat consumers. A Spanish case study. *Meat Science*, *135*, 129-133.
- Bessa, R. J. B., Lourenco, M., Portugal, P. V., & Santos-Silva, J. (2008). Effects of previous diet and duration of soybean oil supplementation on light lambs carcass composition, meat quality

- and fatty acid composition. *Meat Science*, 80(4), 1100-1105.  
<https://doi.org/10.1016/j.meatsci.2008.05.001>
- Boufaïed, H., Chouinard, P. Y., Tremblay, G. F., Petit, H. V., Michaud, R., & Bélanger, G. (2003). Fatty acids in forages. I. Factors affecting concentrations [Article]. *Canadian Journal of Animal Science*, 83(3), 501-511. <https://doi.org/10.4141/A02-098>
- Brown, H. E., Moot, D. J., & Pollock, K. M. (2005). Herbage production, persistence, nutritive characteristics and water use of perennial forages grown over 6 years on a Wakanui silt loam. *New Zealand Journal of Agricultural Research*, 48(4), 423-439.  
<https://doi.org/10.1080/00288233.2005.9513677>
- Burke, J. L., Waghorn, G. C., & Chaves, A. V. (2002, Jan). *Improving animal performance using forage-based diets* Proceedings of the New Zealand Society of Animal Production, Palmerston North.
- Calkins, C. R., & Hodgen, J. M. (2007). A fresh look at meat flavor. *Meat Science*, 77(1), 63-80.
- Camacho, A., Torres, A., Capote, J., Mata, J., Viera, J., Bermejo, L. A., & Argüello, A. (2017). Meat quality of lambs (hair and wool) slaughtered at different live weights. *Journal of Applied Animal Research*, 45(1), 400-408.
- Campbell, A. W., Maclennan, G., Judson, H. G., Lindsay, S., Behrent, M. R., Mackie, A., & Kerlake, J. I. (2011, Jan). *BRIEF COMMUNICATION: The effects of different forage types on lamb performance and meat quality* Proceedings of the New Zealand Society of Animal Production, Invercargill.
- Campidonico, L., Toral, P. G., Priolo, A., Luciano, G., Valenti, B., Hervás, G., Frutos, P., Copani, G., Ginane, C., & Niderkorn, V. (2016). Fatty acid composition of ruminal digesta and longissimus muscle from lambs fed silage mixtures including red clover, sainfoin, and timothy. *Journal of Animal Science*, 94(4), 1550-1560.
- Chakwizira, E., Maley, S., & Dumbleton, A. (2021). Water use efficiency of Raphanobrassica and forage rape.
- Clapham, W. M., Foster, J. G., Neel, J. P. S., & Fedders, J. M. (2005). Fatty Acid Composition of Traditional and Novel Forages. *Journal of Agricultural and Food Chemistry*, 53(26), 10068-10073. <https://doi.org/10.1021/jf0517039>
- Commission Regulation of European Union. (2010). *Amending regulation (EC) no 1924/2006 of the European parliament and of the council with regard to the list of nutrition claims*.
- Conte, F., Cincotta, F., Conduro, C., Verzera, A., & Panebianco, A. (2021). Odor emissions from raw meat of freshly slaughtered cattle during inspection. *Foods*, 10(10), 2411.
- Cooper, S. L., Sinclair, L. A., Wilkinson, R. G., Hallett, K. G., Enser, M., & Wood, J. D. (2004). Manipulation of the n-3 polyunsaturated fatty acid content of muscle and adipose tissue in lambs. *Journal of Animal Science*, 82(5), 1461-1470. <Go to ISI>://WOS:000221010400023
- Craigie, C. R., Agnew, M. P., Stuart, A. D., Shorten, P. R., Reis, M. M., Taukiri, K. R., & Johnson, P. L. (2017). Intramuscular fat content of New Zealand lamb M. longissimus lumborum. *Proceedings of the New Zealand Society of Animal Production*, 77, 189-193.
- Cranston, L. M., Kenyon, P. R., Morris, S. T., & Kemp, P. D. (2015). A review of the use of chicory, plantain, red clover and white clover in a sward mix for increased sheep and beef production. *Journal of New Zealand Grasslands*, 77, 89-94. <https://doi.org/10.33584/jnzs.2015.77.475>
- Cranston, L. M., Ridler, A., Kenyon, P., Greer, A. (2017). Sheep Production. In K. Stafford (Ed.), *Livestock Production in New Zealand*. Massey University Press.
- Crush, J. R., & Evans, J. P. M. (1990). Shoot growth and herbage element concentrations of 'Grasslands Puna' chicory (*Cichorium intybus* L.) under varying soil pH. *Proceedings of the New Zealand Grassland Association*, 51, 163-166.
- De Brito, G. F., Holman, B. W. B., McGrath, S. R., Friend, M. A., van de Ven, R., & Hopkins, D. L. (2017). The effect of forage-types on the fatty acid profile, lipid and protein oxidation, and retail colour stability of muscles from White Dorper lambs. *Meat Science*, 130, 81-90.  
<https://doi.org/10.1016/j.meatsci.2017.04.001>

- De Brito, G. F., McGrath, S. R., Holman, B. W. B., Friend, M. A., Fowler, S. M., Van De Ven, R. J., & Hopkins, D. L. (2016). The effect of forage type on lamb carcass traits, meat quality and sensory traits. *Meat Science*, *119*, 95-101. <https://doi.org/10.1016/j.meatsci.2016.04.030>
- Department of Health. (1994). *Nutritional Aspects of Cardiovascular Disease* (Report on health and social subjects 46, Issue).
- Dewhurst, R. J., Scollan, N. D., Lee, M. R., Ougham, H. J., & Humphreys, M. O. (2003). Forage breeding and management to increase the beneficial fatty acid content of ruminant products. *Proceedings of the Nutrition Society*, *62*(2), 329-336.
- Dewhurst, R. J., Scollan, N. D., Youell, S. J., Tweed, J. K. S., & Humphreys, M. O. (2001). Influence of species, cutting date and cutting interval on the fatty acid composition of grasses [Article]. *Grass and Forage Science*, *56*(1), 68-74. <https://doi.org/10.1046/j.1365-2494.2001.00247.x>
- Díaz, M. T., Álvarez, I., De la Fuente, J., Sanudo, C., Campo, M. M., Oliver, M. A., Furnols, M. F. I., Montossi, F., San Julian, R., Nute, G. R., & Caneque, V. (2005). Fatty acid composition of meat from typical lamb production systems of Spain, United Kingdom, Germany and Uruguay. *Meat Science*, *71*(2), 256-263. <https://doi.org/10.1016/j.meatsci.2005.03.020>
- Dierking, R. M., Kallenbach, R. L., & Grun, I. U. (2010). Effect of forage species on fatty acid content and performance of pasture-finished steers. *Meat Science*, *85*(4), 597-605. <https://doi.org/10.1016/j.meatsci.2010.03.010>
- Doreau, M., Bauchart, D., & Chilliard, Y. (2010). Enhancing fatty acid composition of milk and meat through animal feeding1. *Animal Production Science*, *51*(1), 19-29.
- Dove, H., & Milne, J. (2006). Intake and productivity of lambs grazing leafy or stemmy forage rape and the effect of energy or protein supplements. *Australian Journal of Experimental Agriculture*, *46*(7), 763-769.
- Duckett, S., Klein, T., Dodson, M., & Snowden, G. (1998). Tenderness of normal and callipyge lamb aged fresh or after freezing\*. *Meat Science*, *49*(1), 19-26.
- Dumbleton, A., Box, G. M., Foley, F., Westwood, C. T., & Wright, E. M. (2021). The development of Pallaton raphanobrassica for New Zealand farming systems [Article]. *Journal of New Zealand Grasslands*, *83*, 107-114. <https://doi.org/10.33584/jnzg.2021.83.3505>
- Dutson, T. R., Hostetler, R. L., & Carpenter, Z. L. (1976). Effect of collagen levels and sarcomere shortening on muscle tenderness. *Journal of Food Science*, *41*, 863-866. <Go to ISI>://WOS:A1976BW01200030
- Egan, A., & Shay, B. (1988). Long-term storage of chilled fresh meats.
- Elgersma, A., Ellen, G., Van Der Horst, H., Boer, H., Dekker, P., & Tamminga, S. (2004). Quick changes in milk fat composition from cows after transition from fresh grass to a silage diet. *Animal Feed Science and Technology*, *117*(1-2), 13-27.
- Elgersma, A., Ellen, G., Van Der Horst, H., Muuse, B. G., Boer, H., & Tamminga, S. (2003). Influence of cultivar and cutting date on the fatty acid composition of perennial ryegrass (*Lolium perenne* L.) [Article]. *Grass and Forage Science*, *58*(3), 323-331. <https://doi.org/10.1046/j.1365-2494.2003.00384.x>
- Elmes, S. (2013). *An investigation of on-farm factors that may affect lamb growth, carcass characteristics and meat quality* Massey University]. Palmerston North.
- Farmer, L. J. (1994). The role of nutrients in meat flavour formation. *Proceedings of the Nutrition Society*, *53*(2), 327-333.
- Faustman, C. (2014). Myoglobin chemistry and modifications that influence (color and) color stability. American Meat Science Association, 67th Annual Reciprocal Meat Conference,
- Fisher, A. V., Enser, M., Richardson, R. I., Wood, J. D., Nute, G. R., Kurt, E., Sinclair, L. A., & Wilkinson, R. G. (2000). Fatty acid composition and eating quality of lamb types derived from four diverse breed x production systems. *Meat Science*, *55*(2), 141-147. [https://doi.org/10.1016/s0309-1740\(99\)00136-9](https://doi.org/10.1016/s0309-1740(99)00136-9)
- Fisher, R. A. (1936). The use of multiple measurements in taxonomic problems. *Annals of eugenics*, *7*(2), 179-188.

- Fletcher, A., Sinton, S., Gillespie, R., Maley, S., Sim, R., Ruiter, J. D., & Meenken, E. (2010). Drought response and water use efficiency of forage brassica crops.
- Font-i-Furnols, M., & Guerrero, L. (2014). Consumer preference, behavior and perception about meat and meat products: An overview. *Meat Science*, *98*(3), 361-371. <https://doi.org/10.1016/j.meatsci.2014.06.025>
- Food Standards Australia New Zealand. (2012). Nutrition Information User Guide Part B - Nutrition Claims.
- Ford, J., & Barrett, B. (2011). Improving red clover persistence under grazing. Proceedings of the New Zealand Grassland Association,
- Fowler, S. M., Morris, S., & Hopkins, D. L. (2019). Nutritional composition of lamb retail cuts from the carcasses of extensively finished lambs. *Meat Science*, *154*, 126-132. <https://doi.org/10.1016/j.meatsci.2019.04.016>
- Frame, J. (1993). Herbage mass. *Sward Measurement Handbook*, 39-67.
- Frank, D., Ball, A., Hughes, J., Krishnamurthy, R., Piyasiri, U., Stark, J., Watkins, P., & Warner, R. (2016). Sensory and flavor chemistry characteristics of Australian beef: Influence of intramuscular fat, feed, and breed. *Journal of Agricultural and Food Chemistry*, *64*(21), 4299-4311.
- Frank, D., Watkins, P., Ball, A., Krishnamurthy, R., Piyasiri, U., Sewell, J., Ortuño, J., Stark, J., & Warner, R. (2016). Impact of Brassica and Lucerne Finishing Feeds and Intramuscular Fat on Lamb Eating Quality and Flavor. A Cross-Cultural Study Using Chinese and Non-Chinese Australian Consumers. *Journal of Agricultural and Food Chemistry*, *64*(36), 6856-6868. <https://doi.org/10.1021/acs.jafc.6b02018>
- Fraser, M. D., Speijers, M. H. M., Theobald, V. J., Fychan, R., & Jones, R. (2004). Production performance and meat quality of grazing lambs finished on red clover, lucerne or perennial ryegrass swards. *Grass and Forage Science*, *59*(4), 345-356. <https://doi.org/10.1111/j.1365-2494.2004.00436.x>
- Fraser, T. J., & Rowarth, J. S. (1996). Legumes, herbs or grass for lamb performance? *Proceedings of the New Zealand Grassland Association*, *58*, 49-52. <Go to ISI>://CABI:19970709268
- Fraser, T. J., Scott, S. M., & Rowarth, J. S. (1996). Pasture species effects on carcass and meat quality. *Proceedings of the New Zealand Grassland Association*, 63-66. <https://doi.org/10.33584/jnzg.1996.58.2218>
- Geay, Y., Bauchart, D., Hocquette, J.-F., & Culioli, J. (2001). Effect of nutritional factors on biochemical, structural and metabolic characteristics of muscles in ruminants, consequences on dietetic value and sensorial qualities of meat. *Reproduction Nutrition Development*, *41*(1), 1-26.
- Gkarane, V., Brunton, N. P., Harrison, S. M., Gravador, R. S., Allen, P., Claffey, N. A., Diskin, M. G., Fahey, A. G., Farmer, L. J., Moloney, A. P., & Monahan, F. J. (2018). Volatile Profile of Grilled Lamb as Affected by Castration and Age at Slaughter in Two Breeds [Article]. *Journal of Food Science*, *83*(10), 2466-2477. <https://doi.org/10.1111/1750-3841.14337>
- Golding, K. P., Wilson, E. D., Kemp, P. D., Pain, S. J., Kenyon, P. R., Morris, S. T., & Hutton, P. G. (2011). Mixed herb and legume pasture improves the growth of lambs post-weaning [Article]. *Animal Production Science*, *51*(8), 717-723. <https://doi.org/10.1071/AN11027>
- Grennan, E. J. M., N. (2005). *Finish lambs on summer pasture and response to creep feeding* (End of Project Report: Sheep Series No 23, Issue.
- Griswold, K., Apgar, G., Robinson, R., Jacobson, B., Johnson, D., & Woody, H. (2003). Effectiveness of short-term feeding strategies for altering conjugated linoleic acid content of beef. *Journal of Animal Science*, *81*(7), 1862-1871.
- Grunert, K. G., Bredahl, L., & Brunso, K. (2004). Consumer perception of meat quality and implications for product development in the meat sector - a review. *Meat Science*, *66*(2), 259-272. [https://doi.org/10.1016/s0309-1740\(03\)00130-x](https://doi.org/10.1016/s0309-1740(03)00130-x)
- Hayakawa, K., Sakamoto, T., Ishii, A., Yamaji, K., Uemoto, Y., Sasago, N., Kobayashi, E., Kobayashi, N., Matsushashi, T., Maruyama, S., Matsumoto, H., Oyama, K., Mannen, H., & Sasazaki, S. (2015).

- The g.841G>C SNP of FASN gene is associated with fatty acid composition in beef cattle [Article]. *Animal Science Journal*, 86(8), 737-746. <https://doi.org/10.1111/asj.12357>
- Hegarty, R., Shands, C., Marchant, R., Hopkins, D., Ball, A., & Harden, S. (2006). Effects of available nutrition and sire breeding values for growth and muscling on the development of crossbred lambs. 1: Growth and carcass characteristics. *Australian Journal of Agricultural Research - AUST J AGR RES*, 57. <https://doi.org/10.1071/AR04275>
- Hejcmanová, P., Ortmann, S., Stoklasová, L., & Clauss, M. (2020). Digesta passage in common eland (*Taurotragus oryx*) on a monocot or a dicot diet. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 246, 110720.
- Henchion, M., McCarthy, M., Resconi, V. C., & Troy, D. (2014). Meat consumption: Trends and quality matters. *Meat Science*, 98(3), 561-568.
- Heylen, K., Suess, R., Freudenreich, P., & Von Lengerken, G. (1998). Relationship between intramuscular fat content and meat quality in lambs with emphasis on sensory characteristics [Article]. *Archiv fur Tierzucht*, 41(1-2), 111-122. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032360531&partnerID=40&md5=e4b0cd52756af7e00c3920eb8b881660>
- Hocquette, J. F., Gondret, F., Baeza, E., Medale, F., Jurie, C., & Pethick, D. W. (2010). Intramuscular fat content in meat-producing animals: development, genetic and nutritional control, and identification of putative markers. *Animal*, 4(2), 303-319. <https://doi.org/10.1017/s1751731109991091>
- Hodgson, J., & Brookes, I. (1999). Nutrition of grazing animals. In J. Hodgson & J. White (Eds.), *New Zealand Pasture and Crop Science* (pp. 133-153). Oxford University Press.
- Hodgson, J., Cameron, K., Clark, D., Condrón, L., Fraser, T., Hedley, M., Holmes, C., Kemp, P., Lucas, R., & Moot, D. (2019). New Zealand's pastoral industries: efficient use of grassland resources. In *Grasslands* (pp. 181-205). CRC Press.
- Hodgson, J., Cameron, K., Clark, D., Condrón, L., Fraser, T., Hedley, M., Holmes, C., Kemp, P., Lucas, R., Moot, D., Morris, S., Nicholas, P., Shadbolt, N., Sheath, G., Valentine, I., Waghorn, G., & Woodfield, D. (2005). New Zealand's pastoral industries: Efficient use of grassland resources. *Grasslands: Developments Opportunities Perspectives*, 181-205. <Go to ISI>://CCC:000232852800009
- Hopkins, D., Stanley, D., Martin, L., Ponnampalam, E., & Ven, R. (2007). Sire and growth path effects on sheep meat production. 1. Growth and carcass characteristics. *Animal Production Science*, 47, 1208-1218. <https://doi.org/10.1071/EA06319>
- Hopkins, D., Walker, P., Thompson, J. M., & Pethick, D. (2005). Effect of sheep type on meat and eating quality of sheep meat. *Australian Journal of Experimental Agriculture*, 45(5), 499-507.
- Hopkins, D. L., Allingham, P. G., Colgrave, M., & Van de Ven, R. (2013). Interrelationship between measures of collagen, compression, shear force and tenderness. *Meat Science*, 95(2), 219-223.
- Hopkins, D. L., Beattie, A. S., & Pirlot, K. L. (1995). MEAT QUALITY, CARCASS FATNESS, AND GROWTH OF SHORT SCROTUM LAMBS GRAZING EITHER FORAGE RAPE OR IRRIGATED PERENNIAL PASTURE. *Australian Journal of Experimental Agriculture*, 35(4), 453-459. <https://doi.org/10.1071/ea9950453>
- Hopkins, D. L., Hegarty, R. S., Walker, P. J., & Pethick, D. W. (2006). Relationship between animal age, intramuscular fat, cooking loss, pH, shear force and eating quality of aged meat from sheep. *Australian Journal of Experimental Agriculture*, 46(6-7), 879-884. <https://doi.org/10.1071/ea05311>
- Hopkins, D. L., Holst, P. J., Hall, D. G., & Atkinson, W. R. (1995). CARCASS AND MEAT QUALITY OF 2ND-CROSS CRYPTORCHID LAMBS GRAZED ON CHICORY (*CICHORIUM-INTYBUS*) OR LUCERNE (*MEDICAGO-SATIVA*). *Australian Journal of Experimental Agriculture*, 35(6), 693-697. <https://doi.org/10.1071/ea9950693>

- Hopkins, D. L., Safari, E., Thompson, J. M., & Smith, C. R. (2004). Video image analysis in the Australian meat industry - precision and accuracy of predicting lean meat yield in lamb carcasses [Article]. *Meat Science*, *67*(2), 269-274. <https://doi.org/10.1016/j.meatsci.2003.10.015>
- Horcada, A., García-Infante, M., Liu, J., & Álvarez, C. (2024). The use of biomarkers in fresh meat and dairy products to identify the feeding regime in ruminants: a review. *Cogent Food & Agriculture*, *10*(1), 2359943.
- Howes, N. L., Bekhit, A. E.-D. A., Burritt, D. J., & Campbell, A. W. (2015). Opportunities and Implications of Pasture-Based Lamb Fattening to Enhance the Long-Chain Fatty Acid Composition in Meat. *Comprehensive Reviews in Food Science and Food Safety*, *14*(1), 22-36. <https://doi.org/10.1111/1541-4337.12118>
- Hu, F. B., Manson, J. E., & Willett, W. C. (2001). Types of dietary fat and risk of coronary heart disease: A critical review. *Journal of the American College of Nutrition*, *20*(1), 5-19. <https://doi.org/10.1080/07315724.2001.10719008>
- Hwang, Y. H., & Joo, S. T. (2017). Fatty acid profiles, meat quality, and sensory palatability of grain-fed and grass-fed beef from Hanwoo, American, and Australian crossbred cattle [Article]. *Korean Journal for Food Science of Animal Resources*, *37*(2), 153-161. <https://doi.org/10.5851/kosfa.2017.37.2.153>
- Itoh, M., Johnson, C. B., Cosgrove, G. P., Muir, P. D., & Purchas, R. W. (1999). Intramuscular fatty acid composition of neutral and polar lipids for heavy-weight Angus and Simmental steers finished on pasture or grain [Article]. *Journal of the Science of Food and Agriculture*, *79*(6), 821-827. [https://doi.org/10.1002/\(SICI\)1097-0010\(19990501\)79:6<821::AID-JSFA291>3.0.CO;2-N](https://doi.org/10.1002/(SICI)1097-0010(19990501)79:6<821::AID-JSFA291>3.0.CO;2-N)
- Jiang, H., Wang, Z., Ma, Y., Qu, Y., Lu, X., Guo, H., & Luo, H. (2015). Effect of dietary lycopene supplementation on growth performance, meat quality, fatty acid profile and meat lipid oxidation in lambs in summer conditions. *Small Ruminant Research*, *131*, 99-106.
- Kalač, P., & Samková, E. (2010). The effects of feeding various forages on fatty acid composition of bovine milk fat: A review. *Czech Journal of Animal Science*, *55*(12), 521-537.
- Kaur, R., Garcia, S. C., Fulkerson, W. J., & Barchia, I. M. (2011). Degradation kinetics of leaves, petioles and stems of forage rape (*Brassica napus*) as affected by maturity [Article]. *Animal Feed Science and Technology*, *168*(3-4), 165-178. <https://doi.org/10.1016/j.anifeedsci.2011.04.093>
- Kearns, M., Ponnampalam, E. N., Jacquier, J. C., Grasso, S., Boland, T. M., Sheridan, H., & Monahan, F. J. (2023). Can botanically-diverse pastures positively impact the nutritional and antioxidant composition of ruminant meat? – Invited review [Review]. *Meat Science*, *197*, Article 109055. <https://doi.org/10.1016/j.meatsci.2022.109055>
- Kemp, P., Kenyon, P., & Morris, S. (2010). The use of legume and herb forage species to create high performance pastures for sheep and cattle grazing systems. *Revista Brasileira De Zootecnia-brazilian Journal of Animal Science - REV BRAS ZOOTECHN*, *39*. <https://doi.org/10.1590/S1516-35982010001300019>
- Kemp, P. D., Kenyon, P. R., & Morris, S. T. (2010). The use of legume and herb forage species to create high performance pastures for sheep and cattle grazing systems. *Revista Brasileira de Zootecnia*, *39*(Supplement), 169-174. <https://doi.org/10.1590/s1516-35982010001300019>
- Kempster, A. J. (1981). Fat partition and distribution in the carcasses of cattle, sheep and pigs: A review [Article]. *Meat Science*, *5*(2), 83-98. [https://doi.org/10.1016/0309-1740\(81\)90007-3](https://doi.org/10.1016/0309-1740(81)90007-3)
- Kenyon, P. R., Morel, P. C. H., Corner-Thomas, R. A., Perez, H. L., Somasiri, S. C., Kemp, P. D., & Morris, S. T. (2017). Improved per hectare production in a lamb finishing system using mixtures of red and white clover with plantain and chicory compared to ryegrass and white clover [Article]. *Small Ruminant Research*, *151*, 90-97. <https://doi.org/10.1016/j.smallrumres.2017.04.019>

- Kenyon, P. R., & Webby, R. W. (2007). Pastures and supplements in sheep production systems. In P. V. Rattray, I. Brookes, & A. Nichol (Eds.), *Occasional publication No 14: Pastures and supplements for grazing animals* (pp. 255-286). New Zealand Society of Animal Production.
- Kerr, P. (2000). *A guide to improved lamb growth 400 plus* (New Zealand Sheep Council, Issue).
- Khlijji, S., van de Ven, R., Lamb, T. A., Lanza, M., & Hopkins, D. L. (2010). Relationship between consumer ranking of lamb colour and objective measures of colour. *Meat Science*, *85*(2), 224-229. <https://doi.org/10.1016/j.meatsci.2010.01.002>
- Kim, Y. H. B., Stuart, A., Rosenvold, K., & Maclennan, G. (2013). Effect of forage and retail packaging types on meat quality of long-term chilled lamb loins. *Journal of Animal Science*, *91*(12), 5998-6007. <https://doi.org/10.2527/jas.2013-6780>
- Kirton, A. H. (1989). Chapter 11: Principles of classification and grading. In R. W. Purchas, B. W. Butler-Hogg, & A. S. Davis (Eds.), *Meat Production and Processing, Occasional Publication 11*. New Zealand Society of Animal Production.
- Kitessa, S., Liu, S., Briegel, J., Pethick, D., Gardner, G., Ferguson, M., Allingham, P., Nattrass, G., McDonagh, M., Ponnampalam, E., & Hopkins, D. (2010). Effects of intensive or pasture finishing in spring and linseed supplementation in autumn on the omega-3 content of lamb meat and its carcass distribution. *Animal Production Science*, *50*(2), 130-137. <https://doi.org/10.1071/an09095>
- Kliem, K., Humphries, D., Lignou, S., & Juniper, D. (2025). Grazing lambs on a low-input, multispecies pasture for an extended period has no detrimental effect on meat nutritional or sensory quality. *Livestock Science*, *292*, 105629.
- Kliem, K. E., Thomson, A. L., Crompton, L. A., & Givens, D. I. (2018). Effect of selected plant species within biodiverse pasture on in vitro fatty acid biohydrogenation and tissue fatty acid composition of lamb. *Animal*, *12*(11), 2415-2423.
- Lambe, N. R., McLean, K. A., Gordon, A., Evans, D., Clelland, N., & Bunger, L. (2017). Prediction of intramuscular fat content using CT scanning of packaged lamb cuts and relationships with meat eating quality. *Meat Science*, *123*, 112-119. <https://doi.org/10.1016/j.meatsci.2016.09.008>
- Lee, J. M., Hemmingson, N. R., Minnee, E. M. K., & Clark, C. E. F. (2015). Management strategies for chicory (*Cichorium intybus*) and plantain (*Plantago lanceolata*): Impact on dry matter yield, nutritive characteristics and plant density [Article]. *Crop and Pasture Science*, *66*(2), 168-183. <https://doi.org/10.1071/CP14181>
- Lee, M. R. F., Evans, P. R., Nute, G. R., Richardson, R. I., & Scollan, N. D. (2009). A comparison between red clover silage and grass silage feeding on fatty acid composition, meat stability and sensory quality of the M-Longissimus muscle of dairy cull cows. *Meat Science*, *81*(4), 738-744. <https://doi.org/10.1016/j.meatsci.2008.11.016>
- Lee, M. R. F., Harris, L. J., Dewhurst, R. J., Merry, R. J., & Scollan, N. D. (2003). The effect of clover silages on long chain fatty acid rumen transformations and digestion in beef steers [Article]. *Animal Science*, *76*(3), 491-501. <https://doi.org/10.1017/s1357729800058719>
- Lee, M. R. F., Parfitt, L. J., Scollan, N. D., & Minchin, F. R. (2007). Lipolysis in red clover with different polyphenol oxidase activities in the presence and absence of rumen fluid [Article]. *Journal of the Science of Food and Agriculture*, *87*(7), 1308-1314. <https://doi.org/10.1002/jsfa.2849>
- Lee, M. R. F., Tweed, J. K. S., Minchin, F. R., & Winters, A. L. (2009). Red clover polyphenol oxidase: Activation, activity and efficacy under grazing [Article]. *Animal Feed Science and Technology*, *149*(3-4), 250-264. <https://doi.org/10.1016/j.anifeedsci.2008.06.013>
- Lee, M. R. F., Winters, A. L., Scollan, N. D., Dewhurst, R. J., Theodorou, M. K., & Minchin, F. R. (2004). Plant-mediated lipolysis and proteolysis in red clover with different polyphenol oxidase activities [Article]. *Journal of the Science of Food and Agriculture*, *84*(13), 1639-1645. <https://doi.org/10.1002/jsfa.1854>

- Li, G., & Kemp, P. D. (2005). Forage Chicory (*Cichorium intybus* L.): A Review of Its Agronomy and Animal Production [Review]. *Advances in Agronomy*, 88, 187-222.  
[https://doi.org/10.1016/S0065-2113\(05\)88005-8](https://doi.org/10.1016/S0065-2113(05)88005-8)
- Li, Z., Ha, M., Frank, D., McGilchrist, P., & Warner, R. D. (2021). Volatile Profile of Dry and Wet Aged Beef Loin and Its Relationship with Consumer Flavour Liking. *Foods*, 10(12), 3113.  
<https://www.mdpi.com/2304-8158/10/12/3113>
- Lindsay, C. L., Kemp, P. D., Kenyon, P. R., & Morris, S. T. (2007). Summer lamb finishing on forage crops. *Proceedings of the New Zealand Society of Animal Production*, 67, 121-125. <Go to ISI>://CABI:20103032823
- Litherland, A., Dynes, R., & Moss, R. (2010). Factors affecting dressing-out percentage of lambs. *Proceedings of the New Zealand Society of Animal Production*,
- Litherland, A. J., & Lambert, M. G. (2007). Factors affecting the quality of pastures and supplements produced on farms. In P. V. Rattray, I. M. Brooks, & A. M. Nicol (Eds.), *Pasture and Supplements for Grazing Animals* (Vol. Occasional Publication No. 14, pp. 81-96). New Zealand Society of Animal Production.
- Liu, S., Yang, Y., Luo, H., Pang, W., & Martin, G. B. (2024). Fat deposition and partitioning for meat production in cattle and sheep. *Animal Nutrition*.
- Lourenço, M., De Smet, S., Raes, K., & Fievez, V. (2007). Effect of botanical composition of silages on rumen fatty acid metabolism and fatty acid composition in longissimus muscle and subcutaneous fat of lambs [Article]. *Animal*, 1(6), 911-921.  
<https://doi.org/10.1017/S1751731107000316>
- Lourenco, M., Van Ranst, G., De Smet, S., Raes, K., & Fievez, V. (2007). Effect of grazing pastures with different botanical composition by lambs on rumen fatty acid metabolism and fatty acid pattern of longissimus muscle and subcutaneous fat. *Animal*, 1(4), 537-545.  
<https://doi.org/10.1017/s1751731107703531>
- Lourenço, M., Van Ranst, G., Vlaeminck, B., De Smet, S., & Fievez, V. (2008). Influence of different dietary forages on the fatty acid composition of rumen digesta as well as ruminant meat and milk. *Animal Feed Science and Technology*, 145(1), 418-437.  
<https://doi.org/https://doi.org/10.1016/j.anifeedsci.2007.05.043>
- Lucero-Borja, J., Pouzo, L. B., De La Torre, M., Langman, L., Carduza, F., Corva, P. M., Santini, F. J., & Pavan, E. (2014). Slaughter weight, sex and age effects on beef shear force and tenderness. *Livestock Science*, 163, 140-149.
- Male, J. (2012). *Lamb Finishing Systems - Maximising the margins on grain finishing lambs*.
- Mashele, G. A., Parker, M. E., & Schreurs, N. M. (2017). Effect of slaughter age between 5 to 14 months of age on the quality of sheep meat. *Proceedings of the New Zealand Society of Animal Production*, 77, 177-180. <Go to ISI>://CABI:20183132622
- McAfee, A. J., McSorley, E. M., Cuskelly, G. J., Moss, B. W., Wallace, J. M. W., Bonham, M. P., & Fearon, A. M. (2010). Red meat consumption: An overview of the risks and benefits. *Meat Science*, 84(1), 1-13. <https://doi.org/10.1016/j.meatsci.2009.08.029>
- McDermott, A., Saunders, C., Zellman, E., Hope, T., & Fisher, A. (2008). *The Key Elements of Success and Failure in the NZ Sheep Meat Industry from 1980-2007, Research Report No. 308*.
- McGuire, M., & McGuire, M. (1999). Conjugated linoleic acid (CLA): A ruminant fatty acid with beneficial effects on human health. *J Anim Sci*, 77.  
<https://doi.org/10.2527/jas2000.00218812007700ES0033x>
- McPhee, M. J., Hopkins, D. L., & Pethick, D. W. (2008). Intramuscular fat levels in sheep muscle during growth. *Australian Journal of Experimental Agriculture*, 48(7), 904-909.  
<https://doi.org/10.1071/ea08046>
- Meat Industry Association. (2020). *MIA Annual Report 2020*.
- Meat Industry Association. (2023). *Annual Report 2023*.
- Meilgaard, M. C., Carr, B. T., & Civille, G. V. (1999). *Sensory evaluation techniques*. CRC press.

- Merchen, N. R., & Bourquin, L. D. (1994). Processes of digestion and factors influencing digestion of forage-based diets by ruminants. *Forage quality, evaluation, and utilization*, 564-612.
- Miller, R. (2020). Drivers of consumer liking for beef, pork, and lamb: A review. *Foods*, 9(4), Article 428. <https://doi.org/10.3390/foods9040428>
- Miller, R. K. (2014). Palatability. In *Encyclopedia of Meat Sciences* (pp. 252-261). <https://doi.org/10.1016/B978-0-12-384731-7.00085-4>
- Min, B., Barry, T., Attwood, G., & McNabb, W. (2003). The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. *Animal Feed Science and Technology*, 106(1-4), 3-19.
- Mir, Z., Rushfeldt, M. L., Mir, P. S., Paterson, L. J., & Weselake, R. J. (2000). Effect of dietary supplementation with either conjugated linoleic acid (CLA) or linoleic acid rich oil on the CLA content of lamb tissues. *Small Ruminant Research*, 36(1), 25-31. [https://doi.org/10.1016/S0921-4488\(99\)00087-5](https://doi.org/10.1016/S0921-4488(99)00087-5)
- Montossi, F., Font-i-Furnols, M., del Campo, M., San Julián, R., Brito, G., & Sañudo, C. (2013). Sustainable sheep production and consumer preference trends: Compatibilities, contradictions, and unresolved dilemmas. *Meat Science*, 95(4), 772-789. <https://doi.org/https://doi.org/10.1016/j.meatsci.2013.04.048>
- Moorehead, A., Judson, H., & Stewart, A. (2002, Jan). *Liveweight gain of lambs grazing 'Ceres Tonic' plantain (Plantago lanceolata) or perennial ryegrass (Lolium perenne)* Proceedings of the New Zealand Society of Animal Production, Palmerston North.
- Moot, D., Brown, H., Pollock, K., & Mills, A. (2008). Yield and water use of temperate pastures in summer dry environments. *Proceedings of the New Zealand Grassland Association*, 70, 51-57. <https://doi.org/10.33584/jnzc.2008.70.2724>
- Moot, D., & Davison, R. (2021). Changes in New Zealand red meat production over the past 30 yr. *Animal Frontiers*, 11, 26-31. <https://doi.org/10.1093/af/vfab027>
- Morris, S. T. (2013). Sheep and beef cattle production systems. In J. R. Dymond (Ed.), *Ecosystem services in New Zealand: conditions and trends* (pp. 79-84). Manaaki Whenua Press.
- Morris, S. T., & Kenyon, P. R. (2014). Intensive sheep and beef production from pasture—A New Zealand perspective of concerns, opportunities and challenges. *Meat Science*, 98(3), 330-335.
- Mortimer, S. I., van der Werf, J. H. J., Jacob, R. H., Hopkins, D. L., Pannier, L., Pearce, K. L., Gardner, G. E., Warner, R. D., Geesink, G. H., Edwards, J. E. H., Ponnampalam, E. N., Ball, A. J., Gilmour, A. R., & Pethick, D. W. (2014). Genetic parameters for meat quality traits of Australian lamb meat. *Meat Science*, 96(2), 1016-1024. <https://doi.org/10.1016/j.meatsci.2013.09.007>
- Moss, R., Dynes, R., & Goulter, C. (2011). Effect of herbage species and renewal technique on the free living stages of gastro-intestinal roundworms. *New Zealand Journal of Agricultural Research*, 54(1), 15-22.
- Moss, R., & Vlassoff, A. (1993). Effect of herbage species on gastro-intestinal roundworm populations and their distribution. *New Zealand Journal of Agricultural Research*, 36(3), 371-375.
- Mottram, D. S. (1998). Flavour formation in meat and meat products: a review. *Food Chemistry*, 62(4), 415-424.
- Muir, P. D., Deaker, J. M., & Bown, M. D. (1998). Effects of forage- and grain-based feeding systems on beef quality: A review. *New Zealand Journal of Agricultural Research*, 41(4), 623-635. <https://doi.org/10.1080/00288233.1998.9513346>
- Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M. S., & Bernabucci, U. (2010). Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science*, 130(1-3), 57-69. <https://doi.org/10.1016/j.livsci.2010.02.011>
- Nichol, A., Bryant, R. H., Ridgway, M. J., & Edwards, G. (2010). Liveweight gain per head and per ha throughout the year of lambs grazing conventional pastures and those that switch from grass to clover. Proceedings of the New Zealand Grassland Association,

- Niderkorn, V., Martin, C., Bernard, M., Le Morvan, A., Rochette, Y., & Baumont, R. (2019). Effect of increasing the proportion of chicory in forage-based diets on intake and digestion by sheep. *Animal*, *13*(4), 718-726. <https://doi.org/https://doi.org/10.1017/S1751731118002185>
- Noble, A. C. (1996). Taste-aroma interactions. *Trends in Food Science & Technology*, *7*(12), 439-444.
- Nudda, A., Battacone, G., Boaventura, O., Cannas, A., Francesconi, A. H. D., Atzori, A. S., & Pulina, G. (2014). Feeding strategies to design the fatty acid profile of sheep milk and cheese. *Revista Brasileira de Zootecnia*, *43*(8), 445-456.
- Nudda, A., Cannas, A., Correddu, F., Atzori, A. S., Lunesu, M. F., Battacone, G., & Pulina, G. (2020). Sheep and goats respond differently to feeding strategies directed to improve the fatty acid profile of milk fat. *Animals*, *10*(8), 1290.
- Nudda, A., McGuire, M. A., Battacone, G., & Pulina, G. (2005). Seasonal variation in conjugated linoleic acid and vaccenic acid in milk fat of sheep and its transfer to cheese and ricotta. *Journal of Dairy Science*, *88*(4), 1311-1319.
- O'Quinn, T. G., Legako, J. F., Brooks, J. C., & Miller, M. F. (2018). Evaluation of the contribution of tenderness, juiciness, and flavor to the overall consumer beef eating experience<sup>1</sup>. *Translational Animal Science*, *2*(1), 26-36. <https://doi.org/10.1093/tas/txx008>
- Ochoa, J. J., Farquharson, A. J., Grant, I., Moffat, L., Heys, S. D., & Wahle, K. W. (2004). Conjugated linoleic acids (CLAs) decrease prostate cancer cell proliferation: different molecular mechanisms for cis-9, trans-11 and trans-10, cis-12 isomers. *Carcinogenesis*, *25*(7), 1185-1191.
- Pannier, L., Pethick, D. W., Geesink, G. H., Ball, A. J., Jacob, R. H., & Gardner, G. E. (2014). Intramuscular fat in the longissimus muscle is reduced in lambs from sires selected for leanness. *Meat Science*, *96*(2), 1068-1075. <https://doi.org/10.1016/j.meatsci.2013.06.014>
- Park, M. K., & Choi, Y.-S. (2025). Effective strategies for understanding meat flavor: A review. *Food Science of Animal Resources*, *45*(1), 165.
- Parsons, A., Newman, J., Penning, P. D., Harvey, A., & Orr, R. (1994). Diet Preference of Sheep: Effects of Recent Diet, Physiological State and Species Abundance. *Journal of Animal Ecology*, *63*, 465-478. <https://doi.org/10.2307/5563>
- Pavan, E., Subbaraj, A. K., Eyres, G. T., Silcock, P., & Realini, C. E. (2022). Association of metabolomic and lipidomic data with Chinese and New Zealand consumer clusters showing preferential likings for lamb meat from three production systems. *Food Research International*, *158*, 111504.
- Pavan, E., Ye, Y., Eyres, G. T., Guerrero, L., Reis, M. G., Silcock, P., Johnson, P. L., & Realini, C. E. (2021). Relationships among consumer liking, lipid and volatile compounds from New Zealand commercial lamb loins [Article]. *Foods*, *10*(5), Article 1143. <https://doi.org/10.3390/foods10051143>
- Pearce, K. L., Rosenvold, K., Andersen, H. J., & Hopkins, D. L. (2011). Water distribution and mobility in meat during the conversion of muscle to meat and ageing and the impacts on fresh meat quality attributes - A review [Review]. *Meat Science*, *89*(2), 111-124. <https://doi.org/10.1016/j.meatsci.2011.04.007>
- Percival, N., Bond, D., & Hunter, R. (1986). Evaluation of new forage brassica cultivars on the central plateau.
- Perry, D., Thompson, J. M., Hwang, I. H., Butchers, A., & Egan, A. F. (2001). Relationship between objective measurements and taste panel assessment of beef quality [Article]. *Australian Journal of Experimental Agriculture*, *41*(7), 981-989. <https://doi.org/10.1071/EA00023>
- Pethick, D., & Rowe, J. (1996). The effect of nutrition and exercise in carcass parameters and the level of glycogen in skeletal muscle of Merino sheep. *Australian Journal of Agricultural Research*, *47*(4), 525-537.
- Pethick, D. W., Ball, A. J., Banks, R. G., Gardner, G. E., Rowe, J. B., & Jacob, R. H. (2014). Translating science into the next generation meat quality program for Australian lamb. *Meat Science*, *96*(2, Part B), 1013-1015. <https://doi.org/https://doi.org/10.1016/j.meatsci.2013.09.011>

- Pethick, D. W., Hopkins, D. L., D'Souza, D. N., Thompson, J. M., & Walker, P. J. (2005). Effects of animal age on the eating quality of sheep meat. *Australian Journal of Experimental Agriculture*, 45(5), 491-498. <https://doi.org/https://doi.org/10.1071/EA03256>
- Phelps, M., Garmyn, A., Brooks, J., Mafi, G., Duckett, S., Legako, J., & Miller, M. (2018). Effects of marbling and postmortem aging on consumer assessment of United States lamb loin. *Meat and Muscle Biology*, 2(1), 221-232.
- Phelps, M. R., Garmyn, A., Brooks, J., Martin, J., Carr, C., Campbell, J., McKeith, A., & Miller, M. (2018). Consumer assessment of lamb loin and leg from Australia, New Zealand, and United States. *Meat and Muscle Biology*, 2(1).
- Ponnampalam, E. N., Burnett, V. F., Norng, S., Warner, R. D., & Jacobs, J. L. (2012). Vitamin E and fatty acid content of lamb meat from perennial pasture or annual pasture systems with supplements. *Animal Production Science*, 52(4), 255-262. <https://doi.org/10.1071/an11054>
- Ponnampalam, E. N., Butler, K. L., Jacob, R. H., Pethick, D. W., Ball, A. J., Edwards, J. E. H., Geesink, G., & Hopkins, D. L. (2014). Health beneficial long chain omega-3 fatty acid levels in Australian lamb managed under extensive finishing systems. *Meat Science*, 96(2), 1104-1110. <https://doi.org/10.1016/j.meatsci.2013.04.007>
- Ponnampalam, E. N., Butler, K. L., Pearce, K. M., Mortimer, S. I., Pethick, D. W., Ball, A. J., & Hopkins, D. L. (2014). Sources of variation of health claimable long chain omega-3 fatty Australian lamb slaughtered at similar weights. *Meat Science*, 96(2), 1095-1103. <https://doi.org/10.1016/j.meatsci.2012.11.039>
- Ponnampalam, E. N., Kearns, M., Kiani, A., Santhiravel, S., Vahmani, P., Prache, S., Monahan, F. J., & Mapiye, C. (2024). Enrichment of ruminant meats with health enhancing fatty acids and antioxidants: feed-based effects on nutritional value and human health aspects – invited review [Review]. *Frontiers in Animal Science*, 5, Article 1329346. <https://doi.org/10.3389/fanim.2024.1329346>
- Ponnampalam, E. N., Plozza, T., Kerr, M. G., Linden, N., Mitchell, M., Bekhit, A. E.-D. A., Jacobs, J. L., & Hopkins, D. L. (2017). Interaction of diet and long ageing period on lipid oxidation and colour stability of lamb meat. *Meat Science*, 129, 43-49. <https://doi.org/10.1016/j.meatsci.2017.02.008>
- Ponnampalam, E. N., Priyashantha, H., Vidanarachchi, J. K., Kiani, A., & Holman, B. W. B. (2024). Effects of Nutritional Factors on Fat Content, Fatty Acid Composition, and Sensorial Properties of Meat and Milk from Domesticated Ruminants: An Overview. *Animals*, 14(6), 840. <https://www.mdpi.com/2076-2615/14/6/840>
- Ponnampalam, E. N., Sinclair, A. J., & Holman, B. W. B. (2021). The Sources, Synthesis and Biological Actions of Omega-3 and Omega-6 Fatty Acids in Red Meat: An Overview. *Foods*, 10(6), 1358. <https://www.mdpi.com/2304-8158/10/6/1358>
- Prache, S., Schreurs, N., & Guillier, L. (2022). Review: Factors affecting sheep carcass and meat quality attributes. *Animal*, 16, 100330. <https://doi.org/https://doi.org/10.1016/j.animal.2021.100330>
- Prescott, J., Young, O., & O'Neill, L. (2001). The impact of variations in flavour compounds on meat acceptability: A comparison of Japanese and New Zealand consumers. *Food Quality and Preference*, 12, 257-264. [https://doi.org/10.1016/S0950-3293\(01\)00021-0](https://doi.org/10.1016/S0950-3293(01)00021-0)
- Prescott, J., Young, O., Zhang, S., & Cummings, T. (2004). Effects of added "flavour principles" on liking and familiarity of a sheepmeat product: A comparison of Singaporean and New Zealand consumers [Article]. *Food Quality and Preference*, 15(2), 187-194. [https://doi.org/10.1016/S0950-3293\(03\)00057-0](https://doi.org/10.1016/S0950-3293(03)00057-0)
- Priolo, A., Micol, D., & Agabriel, J. (2001). Effects of grass feeding systems on ruminant meat colour and flavour. A review. *Animal Research*, 50(3), 185-200. <Go to ISI>://WOS:000170297700001
- Purchas, R. (1990). An assessment of the role of pH differences in determining the relative tenderness of meat from bulls and steers. *Meat Science*, 27(2), 129-140.

- Purchas, R., & Aungsupakorn, R. (1993). Further investigations into the relationship between ultimate pH and tenderness for beef samples from bulls and steers. *Meat Science*, *34*(2), 163-178.
- Purchas, R., Burnham, D., & Morris, S. (2002). Effects of growth potential and growth path on tenderness of beef longissimus muscle from bulls and steers. *Journal of Animal Science*, *80*(12), 3211-3221.
- Purchas, R. W. (2003). Factors affecting carcass composition and beef quality. In D. C. Smeaton (Ed.), *Profitable beef production: a guide to beef production in New Zealand* (pp. 124-152). New Zealand Beef Council.
- Purchas, R. W., Butler-Hogg, B. W., & Davies, A. S. (1989). *Meat production and processing*: Hamilton, N.Z. : New Zealand Society of Animal Production.
- Ramirez, R., Rusildi-González, C., Hernandez-Piñeiro, J., & Maiti, R. (1997). Nutritional Profile and Leaf Surface Structure of Some Monocotyledonous and Dicotyledonous Species for Grazing Ruminants in Semiarid Regions of Northeastern Mexico. *Journal of Applied Animal Research*, *12*(2), 153-162.
- Realini, C. E., Bianchi, G., Bentancur, O., & Garibotto, G. (2017). Effect of supplementation with linseed or a blend of aromatic spices and time on feed on fatty acid composition, meat quality and consumer liking of meat from lambs fed dehydrated alfalfa or corn. *Meat Science*, *127*, 21-29. <https://doi.org/10.1016/j.meatsci.2016.12.013>
- Realini, C. E., Pavan, E., Johnson, P. L., Font-i-Furnols, M., Jacob, N., Agnew, M., Craigie, C. R., & Moon, C. D. (2021). Consumer liking of M. longissimus lumborum from New Zealand pasture-finished lamb is influenced by intramuscular fat [Article]. *Meat Science*, *173*, Article 108380. <https://doi.org/10.1016/j.meatsci.2020.108380>
- Reid, R., Puoli, J., Jung, G., Cox-Ganser, J. M., & McCoy, A. (1994). Evaluation of Brassicas in grazing systems for sheep: I. Quality of forage and animal performance. *Journal of Animal Science*, *72*(7), 1823-1831.
- Resconi, V. C., Escudero, A., & Campo, M. M. (2013). The development of aromas in ruminant meat [Review]. *Molecules*, *18*(6), 6748-6781. <https://doi.org/10.3390/molecules18066748>
- Ribeiro, C., Oliveira, D., Juchem, S., Silva, T. M., & Nalério, E. (2011). Fatty acid profile of meat and milk from small ruminants: a review. *Revista Brasileira de Zootecnia*, *40*(1), S121-S137.
- Robertson, J. B., & Van Soest, P. J. (1981). The detergent system of analysis and its application to human foods. *The Analysis of Dietary Fibre in Food*, 123-158.
- Rodríguez-Pereira, R., Subiabre, I., Moscoso, C. J., Realini, C. E., & Morales, R. (2025). Forage Turnip (*Brassica rapa* L.) as a Dietary Supplement to Improve Meat Quality. *Animals*, *15*(9), 1277.
- Ross, A., Brunius, C., Chevallier, O., Dervilly, G., Elliott, C., Guitton, Y., Prenni, J. E., Savolainen, O., Hemeryck, L., & Vidkjær, N. H. (2021). Making complex measurements of meat composition fast: Application of rapid evaporative ionisation mass spectrometry to measuring meat quality and fraud. *Meat Science*, *181*, 108333.
- Roughan, P. G., & Holland, R. (1977). Predicting in-vivo digestibilities of herbage by exhaustive enzymic hydrolysis of cell walls. *Journal of the Science of Food and Agriculture*, *28*(12), 1057-1064. <https://doi.org/10.1002/jsfa.2740281204>
- Russell, F. D., & Bürgin-Maunders, C. S. (2012). Distinguishing health benefits of eicosapentaenoic and docosahexaenoic acids. *Marine Drugs*, *10*(11), 2535-2559. <https://doi.org/10.3390/md10112535>
- Ruxton, C., Reed, S. C., Simpson, M., & Millington, K. (2004). The health benefits of omega-3 polyunsaturated fatty acids: a review of the evidence. *Journal of human nutrition and dietetics*, *17*(5), 449-459.
- Salvatori, G., Pantaleo, L., Di Cesare, C., Maiorano, G., Filetti, F., & Oriani, G. (2004). Fatty acid composition and cholesterol content of muscles as related to genotype and vitamin E treatment in crossbred lambs. *Meat Science*, *67*(1), 45-55.
- Santos Torres, R. D. N., Ghedini, C. P., Chardulo, L. A. L., Baldassini, W. A., Curi, R. A., Pereira, G. L., Schoonmaker, J. P., Almeida, M. T. C., Costa, C., & Neto, O. R. M. (2024). Potential of different

- strategies to increase intramuscular fat deposition in sheep: A meta-analysis study [Article]. *Small Ruminant Research*, 234, Article 107258.  
<https://doi.org/10.1016/j.smallrumres.2024.107258>
- Sañudo, C., Alfonso, M., San Julián, R., Thorkelsson, G., Valdimarsdottir, T., Zygoiannis, D., Stamataris, C., Piasentier, E., Mills, C., Berge, P., Dransfield, E., Nute, G. R., Enser, M., & Fisher, A. V. (2007). Regional variation in the hedonic evaluation of lamb meat from diverse production systems by consumers in six European countries. *Meat Science*, 75(4), 610-621.  
<https://doi.org/https://doi.org/10.1016/j.meatsci.2006.09.009>
- Savell, J. W., & Cross, H. R. (1988). The role of fat in the palatability of beef, pork, and lamb. *Designing Foods*, 345-355.
- Savell, J. W., Mueller, S. L., & Baird, B. E. (2005). The chilling of carcasses. *Meat Science*, 73(2), 177-184.
- Scales, G. H. (1993). CARCASS FATNESS IN LAMBS GRAZING VARIOUS FORAGES AT DIFFERENT RATES OF LIVEWEIGHT GAIN. *New Zealand Journal of Agricultural Research*, 36(2), 243-251. <Go to ISI>://WOS:A1993LP67000009
- Schreurs, N., & Kenyon, P. R. (2017). Animal and on-farm factors affecting sheep and lamb meat quality. In J. Greyling (Ed.), *Achieving sustainable production of sheep* (pp. 29-52). Burleigh Dodds Science Publishing Limited.
- Schreurs, N. M., & Kenyon, P. R. (2017). Factors affecting sheep carcass characteristics. In J. Greyling (Ed.), *Achieving sustainable production of sheep* (pp. 3-21). Burleigh Dodds Science Publishing.
- Schreurs, N. M., Kenyon, P. R., Morris, S. T., Blair, H. T., Somasiri, S. C., & Kemp, P. D. (2013). BRIEF COMMUNICATION: Effect of different herbage mixes on lamb meat quality. *Proceedings of the New Zealand Society of Animal Production*, 73, 65-67. <Go to ISI>://BIOABS:BACD201700348341
- Scollan, N., Hocquette, J.-F., Nuernberg, K., Dannenberger, D., Richardson, I., & Moloney, A. (2006). Innovations in beef production systems that enhance the nutritional and health value of beef lipids and their relationship with meat quality. *Meat Science*, 74(1), 17-33.  
<https://doi.org/10.1016/j.meatsci.2006.05.002>
- Senter, S. D., Arnold, J. W., & Chew, V. (2000). APC values and volatile compounds formed in commercially processed, raw chicken parts during storage at 4 and 13 C and under simulated temperature abuse conditions. *Journal of the Science of Food and Agriculture*, 80(10), 1559-1564.
- Shimada, A., & Barry, T. N. (1997). Rumen digestion and rumen outflow rate in deer fed fresh chicory (*Cichorium intybus*) or perennial ryegrass (*Lolium perenne*) [Article]. *Journal of Agricultural Science*, 128(1), 87-94. <https://doi.org/10.1017/S0021859696003954>
- Silvestre, A. M., Souza, J. M., & Millen, D. D. (2023). Adoption of adaptation protocols and feed additives to improve performance of feedlot cattle. *Journal of Applied Animal Research*, 51(1), 282-299. <https://doi.org/10.1080/09712119.2023.2191679>
- Simopoulos, A. P. (2008). The importance of the omega-6/omega-3 fatty acid ratio in cardiovascular disease and other chronic diseases [Short survey]. *Experimental Biology and Medicine*, 233(6), 674-688. <https://doi.org/10.3181/0711-MR-311>
- Sivadier, G., Ratel, J., & Engel, E. (2010). Persistence of pasture feeding volatile biomarkers in lamb fats [Article]. *Food Chemistry*, 118(2), 418-425.  
<https://doi.org/10.1016/j.foodchem.2009.02.088>
- Smit, H., Tas, B., Taweel, H., Tamminga, S., & Elgersma, A. (2005). Effects of perennial ryegrass (*Lolium perenne* L.) cultivars on herbage production, nutritional quality and herbage intake of grazing dairy cows. *Grass and Forage Science*, 60, 297-309. <https://doi.org/10.1111/j.1365-2494.2005.00480.x>
- Somasiri, S. C. (2014). *Effect of herb-clover mixes on weaned lamb growth* [Massey University]. Palmerston North.

- Somasiri, S. C., Kenyon, P. R., Kemp, P. D., Morel, P., & Morris, S. T. (2013). Herb and clover mixes increase average daily gain (ADG) of finishing lambs in different seasons. Proceedings of the International Grasslands Congress,
- Somasiri, S. C., Kenyon, P. R., Kemp, P. D., Morel, P. C. H., & Morris, S. T. (2015). Growth performance and carcass characteristics of lambs grazing forage mixes inclusive of plantain (*Plantago lanceolata* L.) and chicory (*Cichorium intybus* L.) [Review]. *Small Ruminant Research*, *127*, 20-27. <https://doi.org/10.1016/j.smallrumres.2015.04.005>
- Somasiri, S. C., Kenyon, P. R., Kemp, P. D., Morel, P. C. H., & Morris, S. T. (2016). Mixtures of clovers with plantain and chicory improve lamb production performance compared to a ryegrass-white clover sward in the late spring and early summer period [Article]. *Grass and Forage Science*, *71*(2), 270-280. <https://doi.org/10.1111/gfs.12173>
- Speijers, M. H. M., Fraser, M. D., Theobald, V. J., & Haresign, W. (2004). The effects of grazing forage legumes on the performance of finishing lambs [Article]. *Journal of Agricultural Science*, *142*(4), 483-493. <https://doi.org/10.1017/S0021859604004496>
- Stafford, K. J. (2017). *Livestock production in New Zealand* [Bibliographies Non-fiction]. Massey University Press.  
<http://ezproxy.massey.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat00245a&AN=massey.b3716112&site=eds-live&scope=site>
- Stewart, A. V., Kerr, G., Rowarth, J. S., & Stevens, D. (2022). *Pasture and forage plants for New Zealand 2022* (5th edition. ed.) [Bibliographies Non-fiction]. New Zealand Grassland Association.  
<https://search.ebscohost.com/login.aspx?direct=true&AuthType=sso&db=cat09011a&AN=mul.oai.edge.massey.folio.ebsco.com.fs00001086.527ff377.b1a5.4f95.b736.354d57cde37e&site=eds-live&scope=site&authtype=sso&custid=s3027306>
- Thompson, J. M., Gee, A., Hopkins, D., Pethick, D., Baud, S., & O'Halloran, W. (2005). Development of a sensory protocol for testing palatability of sheep meats. *Australian Journal of Experimental Agriculture*, *45*(5), 469-476.
- Thomson, N., & Poel, W. v. d. (2000). Seasonal variation of the fatty acid composition of milkfat from Friesian cows grazing pasture.
- Tozer, K. N., Chapman, D. F., Bell, N. L., Crush, J. R., King, W. M., Rennie, G. M., Wilson, D. J., Mapp, N. R., Rossi, L., Aalders, L. T., & Cameron, C. A. (2014). Botanical survey of perennial ryegrass-based dairy pastures in three regions of New Zealand: implications for ryegrass persistence. *New Zealand Journal of Agricultural Research*, *57*(1), 14-29.  
<https://doi.org/10.1080/00288233.2013.863785>
- Troy, D. J., & Kerry, J. P. (2010). Consumer perception and the role of science in the meat industry [Review]. *Meat Science*, *86*(1), 214-226. <https://doi.org/10.1016/j.meatsci.2010.05.009>
- US Department of Agriculture & US Department of Health and Human Services. (2010). *Dietary Guidelines for Americans 2010*.
- Van Oeckel, M., Warnants, N., & Boucqué, C. V. (1999). Comparison of different methods for measuring water holding capacity and juiciness of pork versus on-line screening methods. *Meat Science*, *51*(4), 313-320.
- Vasta, V., & Priolo, A. (2006). Ruminant fat volatiles as affected by diet. A review [Article]. *Meat Science*, *73*(2), 218-228. <https://doi.org/10.1016/j.meatsci.2005.11.017>
- Verbeke, W. (2006). Functional foods: Consumer willingness to compromise on taste for health? *Food Quality and Preference*, *17*(1-2), 126-131.
- Vergara, H., Molina, A., & Gallego, L. (1999). Influence of sex and slaughter weight on carcass and meat quality in light and medium weight lambs produced in intensive systems. *Meat Science*, *52*(2), 221-226.
- VSN-International. (2024). *Genstat for Windows 24th Edition*.

- Waghorn, G. C., Burke, J. L., & Kolver, E. S. (2007). PRINCIPLES OF FEEDING VALUE. In I. M. B. P.V. Rattray, A.M. Nicol (Ed.), *Pasture and Supplements for Grazing Animals* (pp. 35-60). New Zealand Society of Animal Production (Inc).
- Warner, R., Greenwood, P., Pethick, D., & Ferguson, D. (2010). Genetic and environmental effects on meat quality. *Meat Science*, *86*(1), 171-183.
- Warren, H. E., Scollan, N. D., Enser, M., Hughes, S. I., Richardson, R. I., & Wood, J. D. (2008). Effects of breed and a concentrate or grass silage diet on beef quality in cattle of 3 ages. I: Animal performance, carcass quality and muscle fatty acid composition. *Meat Science*, *78*(3), 256-269. <https://doi.org/10.1016/j.meatsci.2007.06.008>
- Watkins, P. J., Frank, D., Singh, T. K., Young, O. A., & Warner, R. D. (2013). Sheepmeat flavor and the effect of different feeding systems: A review [Review]. *Journal of Agricultural and Food Chemistry*, *61*(15), 3561-3579. <https://doi.org/10.1021/jf303768e>
- Watkins, P. J., Jaborek, J. R., Teng, F., Day, L., Castada, H. Z., Baringer, S., & Wick, M. (2021). Branched chain fatty acids in the flavour of sheep and goat milk and meat: A review. *Small Ruminant Research*, *200*, 106398. <https://doi.org/https://doi.org/10.1016/j.smallrumres.2021.106398>
- Weston, A., Rogers, R., & Althen, T. (2002). Review: The role of collagen in meat tenderness. *The Professional Animal Scientist*, *18*, 107-111.
- Westwood, C., & Mulcock, H. (2012). Nutritional evaluation of five species of forage brassica. *Proceedings of the New Zealand Grassland Association*, *74*, 31. <https://doi.org/10.33584/jnzg.2012.74.2881>
- White, J. G. H., & Hodgson, J. (1999). *New Zealand pasture and crop science* [Bibliographies Non-fiction]. Oxford University Press. <http://ezproxy.massey.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=catt00245a&AN=massey.b1626467&site=eds-live&scope=site>
- Winger, R., & Hagyard, C. (1994). Juiciness—its importance and some contributing factors. In *Quality attributes and their measurement in meat, poultry and fish products* (pp. 94-124). Springer.
- Wood, J. D., & Enser, M. (1997). Factors influencing fatty acids in meat and the role of antioxidants in improving meat quality. *British Journal of Nutrition*, *78*(1), S49-S60. <https://doi.org/10.1079/bjn19970134>
- Wood, J. D., Enser, M., Fisher, A. V., Nute, G. R., Sheard, P. R., Richardson, R. I., Hughes, S. I., & Whittington, F. M. (2008). Fat deposition, fatty acid composition and meat quality: A review. *Meat Science*, *78*(4), 343-358. <https://doi.org/10.1016/j.meatsci.2007.07.019>
- Wood, J. D., Richardson, R. I., Nute, G. R., Fisher, A. V., Campo, M. M., Kasapidou, E., Sheard, P. R., & Enser, M. (2004). Effects of fatty acids on meat quality: a review. *Meat Science*, *66*(1), 21-32. [https://doi.org/10.1016/s0309-1740\(03\)00022-6](https://doi.org/10.1016/s0309-1740(03)00022-6)
- Woodmartin, S., Crofton, E., Creighton, P., Boland, T., Monaghan, A., Ovenden, C., & McGovern, F. (2024). How does the inclusion of a companion forage alongside perennial ryegrass influence production performance, sensory perception and consumer liking of lamb meat? [Article]. *Small Ruminant Research*, *232*, Article 107230. <https://doi.org/10.1016/j.smallrumres.2024.107230>
- World Health Organisation. (2008). Interim summary of conclusions and dietary recommendations on total fat & fatty acids. *The joint FAO/WHO expert consultation of fats and fatty acids in human nutrition*.
- Ye, Y., Eyres, G. T., Reis, M. G., Schreurs, N. M., Silcock, P., Agnew, M. P., Johnson, P. L., Maclean, P., & Realini, C. E. (2020). Fatty acid composition and volatile profile of m. Longissimus thoracis from commercial lambs reared in different forage systems [Article]. *Foods*, *9*(12), Article 1885. <https://doi.org/10.3390/foods9121885>
- Ye, Y., Maes, E., Deb-Choudhury, S., Hefer, C. A., Schreurs, N. M., & Realini, C. E. (2022). Proteomic Profile of M. Longissimus Thoracis from Commercial Lambs Reared in Different Forage Systems [Article]. *Foods*, *11*(10), Article 1419. <https://doi.org/10.3390/foods11101419>

- Ye, Y., Schreurs, N. M., Johnson, P. L., Corner-Thomas, R. A., Agnew, M. P., Silcock, P., Eyres, G. T., Maclennan, G., & Realini, C. E. (2020). Carcass characteristics and meat quality of commercial lambs reared in different forage systems [Article]. *Livestock Science*, 232, Article 103908. <https://doi.org/10.1016/j.livsci.2019.103908>
- Young, O., Hogg, B., Mortimer, B., & Waller, J. (1993). Collagen in two muscles of sheep selected for weight as yearlings. *New Zealand Journal of Agricultural Research*, 36(1), 143-150.
- Young, O., & West, J. (2001). Meat colour. In Y. H. Hui, W. Nip, R. Rogers, & O. Young (Eds.), *Meat science and applications* (pp. 39-69). Marcel Dekker.
- Young, O. A., & Braggins, T. J. (1993). Tenderness of ovine semimembranosus: Is collagen concentration or solubility the critical factor? *Meat Science*, 35, 213-222. <http://www.sciencedirect.com/science/article/pii/0309174093900511>
- Young, O. A., Cruickshank, G. J., Maclean, K. S., & Muir, P. D. (1994). QUALITY OF MEAT FROM LAMBS GRAZED ON 7 PASTURE SPECIES IN HAWKES BAY. *New Zealand Journal of Agricultural Research*, 37(2), 177-186. <https://doi.org/10.1080/00288233.1994.9513055>
- Young, O. A., Lane, G. A., Priolo, A., & Fraser, K. (2003). Pastoral and species flavour in lambs raised on pasture, lucerne or maize. *Journal of the Science of Food and Agriculture*, 83(2), 93-104. <https://doi.org/10.1002/jsfa.1282>
- Zhang, Z., Wang, X., Jin, Y., Zhao, K., & Duan, Z. (2022). Comparison and analysis on sheep meat quality and flavor under pasture-based fattening contrast to intensive pasture-based feeding system. *Animal bioscience*, 35(7), 1069.