

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.

**DETERMINATION OF DIGESTION
PARAMETERS TO DEVELOP AND
EVALUATE FORAGE MIXTURES FOR
PASTURE-FED RUMINANTS**

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

Jennifer Leighann Burke

2004

ABSTRACT

Animal production can be improved by lessening the dependence on ryegrass-based pastures as the sole source of nutrients for production. Ryegrass varies in quality and availability and supplementation with appropriate forages will maintain or improve production. This thesis defines the nutritive characteristics of a range of forages, including temperate and tropical grasses, legumes with and without condensed tannins, herbs and silages, in terms of chemical composition, products of degradation and rates of digestion using *in sacco* and *in vitro* methods. The forages assessed varied in crude protein concentration (CP; 7.6 – 29.9 % of dry matter; DM) and neutral detergent fibre (NDF; 22.4 – 57.8% DM), with commensurate net appearance of plant N as ammonia (0 to 49%) and *in sacco* DM, CP and NDF degradation rates (%/h) from 3 – 26, 3 – 19 and 4 – 28, respectively. The Cornell Net Carbohydrate Protein System (CNCPS) was used to evaluate the ability of forages to meet the energy and protein requirements of dairy cows. Data suggested sulla (*Hedysarum coronarium*), lucerne (*Medicago sativa*), red clover (*Trifolium pratense*) and white clover (*Trifolium repens*) as potential forages for feeding with medium to low quality pasture.

Lambs were fed pasture, white clover, lucerne and sulla alone or in mixtures and production, rumen digestion parameters and estimates of protein synthesis were measured. Lambs fed white clover, sulla, lucerne:sulla and white clover:sulla had the highest daily intakes (1.47 – 1.54 kg DM) and liveweight gains (281 – 308 g) compared to lambs fed pasture (1.10 kg DM; 116 g). Sulla had potential for feeding with pasture and lucerne, but energy limited production. Protein synthesis between lambs fed lucerne, sulla and lucerne:sulla were similar (162 – 180 g/day) and greater than pasture (93 g/day). In a trial with dairy cows fed pasture (P), supplementation with maize silage (M) or sulla (S) did affect *in sacco* degradation and the maize silage lowered *in sacco* DM degradation rates (P, 7; M, 4; S, 16; P:M; 5; P:S, 11 and P:M:S, 6 %/h).

The work presented provides a foundation for formulating mixed forage rations to meet cow nutrient requirements and improve productivity in ryegrass-based pasture systems. Animal trials demonstrated synergistic effects of dietary components on both animal production and rumen microbial function.

ACKNOWLEDGEMENTS

This PhD has been a team effort between those directly involved with the experimental components, that is my supervisors and people from AgResearch Grasslands, Massey University and Dexcel that provided technical and scientific assistance, and those that were on the periphery that kept my life normal (my family and friends). This PhD would not have been completed without the involvement of all these people.

Firstly, my deepest thanks and appreciation must go to my supervisors, Dr Garry Waghorn (AgResearch, Grasslands) and Dr Ian Brookes (IFNHH, Massey University) who provided me with helpful advice, scientific knowledge and encouragement throughout the PhD. Particular thanks must go to Garry who provided a majority of the assistance for this thesis and general moral support throughout the last five years, both on a working and personal level. Thanks also goes to Dr Eric Kolver (Dexcel) who provided expert knowledge about the CNCPS model. Dr Warren McNabb, Dr Nicole Roy and Emma Bermingham, together with Garry, helped immensely while I tried to get my head around and understand the protein metabolism part of this thesis (Chapter 5) and without your help I may still be struggling.

Recognition goes to the financial supporters of this PhD, the Agricultural and Marketing Research and Development Trust (AGMARDT) who provided financial assistance to me personally, and the Global Feeding Programme who provided most of the funds to carry out the experiments conducted during this PhD.

Many thanks and appreciation goes to all those who helped or were involved in some way in the experiments conducted during this PhD including: Graeme Attwood, Adrienne Cavanagh, Andrea Death, Matt Deighton, Paul Doyle, Tony Dunn, Duncan Hedderley, Wilhelmina Martin, German Molano, Jason Peters, Cesar Pinares, Clare Reynolds, Dan Robinson, Bruce Sinclair, Bryan Treloar, Dr Sharon Woodward and the Waghorn boys, Scott, Luke, and Phillip.

Special mention must go to my fellow PhD students. To Alex and Emma, who provided encouragement, support and knowledge as we conducted experiments,

analysed data, wrote chapters and eventually completed together. My sincere thanks goes to Dr Penny Back for her valuable input during the glucose challenge and protein metabolism component of this thesis.

I would also like to thank those in the Nutrition and Behaviour platform at AgResearch, Grasslands who provided a great working environment, and IVABS at Massey University for allowing me time to complete this thesis.

My family, friends and flatmates must be thanked as they kept me sane and endured the high and low points of the last five years. Recognition must go to my mum, dad and brothers for the encouragement and “harping on” that kept me on track to finish. I am forever grateful to my partner, Jason, for his support, encouragement, patience and help over the last two-and-a-half years of this PhD. The last 12 months have been the hardest, but your support and patience have been greatly appreciated and not forgotten.

Yippee.....I've finished!!

TABLE OF CONTENTS

| | |
|---|---------------|
| ABSTRACT | I |
| ACKNOWLEDGEMENTS..... | III |
| TABLE OF CONTENTS..... | V |
| LIST OF TABLES..... | XI |
| LIST OF FIGURES | XIX |
| LIST OF PHOTOGRAPHS | XXIII |
| LIST OF APPENDICES..... | XXV |
| LIST OF ABBREVIATIONS..... | XXIX |
| LIST OF PUBLICATIONS..... | XXXIII |
| | |
| CHAPTER 1: GENERAL INTRODUCTION..... | 3 |
| 1.1 INTRODUCTION..... | 3 |
| 1.2 OBJECTIVES | 4 |
| 1.3 FORMAT OF THE THESIS..... | 4 |
| | |
| CHAPTER 2: REVIEW OF LITERATURE..... | 9 |
| 2.1 INTRODUCTION..... | 9 |
| 2.2 NUTRITION OF THE GRAZING RUMINANT..... | 9 |
| 2.3 CHEMICAL COMPOSITION OF PASTURE..... | 14 |
| 2.3.1 Carbohydrates..... | 14 |
| 2.3.1.1 <i>Structural carbohydrates (cell wall)</i> | 14 |
| 2.3.1.2 <i>Non-structural carbohydrates (NSC)</i> | 18 |
| 2.3.2 Protein..... | 20 |
| 2.3.3 Lipids | 21 |
| 2.3.4 Condensed Tannins..... | 22 |
| 2.4 PASTURE AS A NUTRIENT SOURCE..... | 23 |
| 2.4.1 Limitations to pasture | 23 |
| 2.4.2 Seasonal changes in pasture | 23 |
| 2.4.3 Dry matter content of pasture..... | 27 |
| 2.4.4 Particle size and fibre content of pasture | 27 |
| 2.5 DIGESTION AND FERMENTATION OF NUTRIENTS..... | 28 |
| 2.5.1 Carbohydrates..... | 29 |
| 2.5.2 Protein..... | 30 |
| 2.5.3 Lipids | 31 |
| 2.5.4 Condensed tannins and the effect on ruminants..... | 32 |
| 2.6 ENERGY AND OTHER NUTRIENT REQUIREMENTS OF DAIRY COWS..... | 33 |

| | | |
|---------|--|----|
| 2.7 | TECHNIQUES TO MEASURE THE DIGESTION AND FERMENTATION OF FEEDS..... | 37 |
| 2.7.1 | <i>In sacco</i> digestibility..... | 38 |
| 2.7.1.1 | Bag characteristics..... | 41 |
| 2.7.1.2 | Sample preparation..... | 42 |
| 2.7.1.3 | Diet effects..... | 46 |
| 2.7.1.4 | Animal effects..... | 46 |
| 2.7.1.5 | Rumen techniques for incubation..... | 47 |
| 2.7.1.6 | Post incubation techniques..... | 47 |
| 2.7.1.7 | Microbial contamination..... | 48 |
| 2.7.1.8 | Statistical analyses..... | 48 |
| 2.7.1.9 | Model fitting..... | 49 |
| 2.7.2 | <i>In vitro</i> incubations..... | 52 |
| 2.7.2.1 | Preparation of feed sample..... | 57 |
| 2.7.2.2 | Buffering systems..... | 57 |
| 2.7.2.3 | Effect of gassing and reducing agents..... | 58 |
| 2.7.2.4 | Effect of pH..... | 58 |
| 2.7.2.5 | Effect of rumen inoculum..... | 58 |
| 2.8 | THE FEEDING VALUE OF FORAGES..... | 59 |
| 2.9 | SIMULATION MODELLING..... | 63 |
| 2.10 | CONCLUSIONS..... | 64 |

| | | |
|-------------------|--|-----------|
| CHAPTER 3: | DIGESTION KINETICS OF CONTRASTING FORAGE SPECIES..... | 69 |
| 3.1 | ABSTRACT..... | 69 |
| 3.2 | INTRODUCTION..... | 70 |
| 3.3 | METHOD..... | 71 |
| 3.3.1 | Experimental procedure..... | 71 |
| 3.3.2 | Forage collection and processing..... | 72 |
| 3.3.3 | Particle size distribution..... | 72 |
| 3.3.4 | <i>In sacco</i> and <i>in vitro</i> digestion..... | 73 |
| 3.3.4.1 | <i>In sacco</i> digestion..... | 73 |
| 3.3.4.2 | <i>In vitro</i> digestion..... | 75 |
| 3.3.4.3 | pH, ammonia and VFA analyses..... | 76 |
| 3.3.5 | Statistics..... | 78 |
| 3.4 | RESULTS..... | 81 |
| 3.4.1 | Chemical composition..... | 81 |
| 3.4.2 | Particle size distribution..... | 83 |
| 3.4.3 | Variation between incubations..... | 85 |
| 3.4.4 | <i>In sacco</i> digestion..... | 88 |
| 3.4.4.1 | Dry matter digestion kinetics..... | 88 |
| 3.4.4.2 | Dry matter effective degradability..... | 91 |
| 3.4.4.3 | Crude protein digestion kinetics..... | 91 |
| 3.4.4.4 | Fibre digestion kinetics..... | 94 |
| 3.4.5 | <i>In vitro</i> digestion..... | 104 |
| 3.4.5.1 | <i>In vitro</i> pH..... | 104 |
| 3.4.5.2 | Ammonia yield..... | 105 |
| 3.4.5.3 | VFA yield..... | 109 |

| | | |
|---------|--|-----|
| 3.5 | DISCUSSION | 118 |
| 3.5.1 | <i>In sacco</i> digestion kinetics | 119 |
| 3.5.2 | Forage characteristics and animal production | 122 |
| 3.5.3 | The <i>in sacco</i> procedure | 125 |
| 3.5.2 | <i>In vitro</i> products of fermentation | 126 |
| 3.5.3 | CNCPS diet evaluation | 129 |
| 3.5.3.1 | <i>Evaluation of individual forages</i> | 135 |
| 3.5.3.2 | <i>Evaluation of mixed forage rations</i> | 141 |
| 3.6 | CONCLUSIONS | 146 |

CHAPTER 4: AN EVALUATION OF SULLA (*HEDYSARUM CORONARIUM*) WITH PASTURE, WHITE CLOVER AND LUCERNE FOR LAMBS 149

| | | |
|---------|--|-----|
| 4.1 | ABSTRACT | 149 |
| 4.2 | INTRODUCTION | 150 |
| 4.3 | MATERIALS AND METHODS | 152 |
| 4.3.1 | Experimental design | 152 |
| 4.3.2 | Animals and diets | 153 |
| 4.3.3 | Lamb production | 156 |
| 4.3.4 | Rumen measurements | 157 |
| 4.3.5 | Blood measurements | 158 |
| 4.3.6 | Statistical Analysis | 158 |
| 4.4 | RESULTS | 162 |
| 4.4.1 | Feed Composition | 162 |
| 4.4.2 | Lamb production | 169 |
| 4.4.2.1 | <i>Liveweight gain</i> | 169 |
| 4.4.2.2 | <i>Fed versus fasted liveweight gain</i> | 172 |
| 4.4.2.3 | <i>Carcass characteristics</i> | 172 |
| 4.4.2.4 | <i>Wool production</i> | 176 |
| 4.4.2.5 | <i>Feed intakes</i> | 178 |
| 4.4.2.6 | <i>Efficiency of DM and ME utilisation</i> | 184 |
| 4.4.3 | Rumen pH, ammonia and volatile fatty acids | 187 |
| 4.4.3.1 | <i>Rumen pH</i> | 187 |
| 4.4.3.2 | <i>Rumen ammonia</i> | 189 |
| 4.4.3.3 | <i>Volatile fatty acids</i> | 191 |
| 4.4.4 | Blood glucose and lactate | 192 |
| 4.4.5 | Correlation and multiple regression analyses | 196 |
| 4.4.5.1 | <i>Liveweight gain</i> | 198 |
| 4.4.5.2 | <i>Carcass weight</i> | 198 |
| 4.4.5.3 | <i>ME content vs. nutrient composition</i> | 199 |
| 4.4.5.4 | <i>DM intake vs. nutrient composition</i> | 200 |
| 4.4.6 | Predicting DM and ME intake and LW gain | 200 |
| 4.5 | DISCUSSION | 202 |
| 4.5.1 | Animal production | 202 |
| 4.5.1.1 | <i>Carcass characteristics</i> | 205 |
| 4.5.2 | Rumen fermentation | 206 |
| 4.6 | CONCLUSIONS | 208 |

| | |
|---|------------|
| CHAPTER 5: PROTEIN SYNTHESIS AND FRACTIONAL SYNTHESIS RATES OF LAMBS FED FORAGE-BASED DIETS..... | 211 |
| 5.1 ABSTRACT | 211 |
| 5.2 INTRODUCTION..... | 212 |
| 5.3 MATERIALS AND METHODS | 214 |
| 5.3.1 Experimental design | 214 |
| 5.3.2 Animals and feeds..... | 217 |
| 5.3.3 Surgical procedures..... | 217 |
| 5.3.4 Whole Body Absolute Protein Synthesis Rates..... | 218 |
| 5.3.4.1 <i>Isotopes and infusion rates</i> | 218 |
| 5.3.4.2 <i>Sampling</i> | 219 |
| 5.3.4.3 <i>Processing and analysis</i> | 219 |
| 5.3.4.4 <i>Calculations</i> | 223 |
| 5.3.4.5 <i>Criteria to accept or reject values</i> | 224 |
| 5.3.5 Tissue Protein Fractional Synthesis Rates | 226 |
| 5.3.5.1 <i>Isotopes and infusion rates</i> | 226 |
| 5.3.5.2 <i>Sampling</i> | 226 |
| 5.3.5.3 <i>Tissue extraction</i> | 227 |
| 5.3.5.4 <i>Processing and analysis</i> | 227 |
| 5.3.5.5 <i>Calculations</i> | 229 |
| 5.3.6 Statistical Analyses | 230 |
| 5.3.6.1 <i>Whole body protein synthesis</i> | 230 |
| 5.3.6.2 <i>Fractional protein synthesis</i> | 230 |
| 5.4 RESULTS | 231 |
| 5.4.1 Feed intake and composition..... | 231 |
| 5.4.2 Absolute whole body protein synthesis | 233 |
| 5.4.2.1 <i>Cysteine</i> | 235 |
| 5.4.2.2 <i>Inorganic sulphate</i> | 235 |
| 5.4.3 Fractional Protein Synthesis..... | 238 |
| 5.4.3.1 <i>Valine concentrations</i> | 238 |
| 5.4.3.2 <i>Specific radioactivity of valine</i> | 240 |
| 5.4.3.3 <i>Fractional synthesis rates of tissues</i> | 241 |
| 5.5 DISCUSSION | 246 |
| 5.5.1 Diet nutrient supply | 246 |
| 5.5.2 Absolute whole body protein synthesis | 247 |
| 5.5.2 Fractional synthesis rates of tissues..... | 251 |
| 5.5.2.1 <i>Effect of diet</i> | 257 |
| 5.6 CONCLUSIONS..... | 257 |

| | |
|---|------------|
| CHAPTER 6: DIGESTION KINETICS OF FRESH FORAGES AND MIXTURES IN LACTATING DAIRY COWS..... | 261 |
| 6.1 ABSTRACT..... | 261 |
| 6.2 INTRODUCTION..... | 262 |
| 6.3 METHOD..... | 263 |
| 6.3.1 Experimental procedure..... | 263 |
| 6.3.2 Animals and treatments..... | 264 |
| 6.3.3 Feeding regimens..... | 267 |
| 6.3.3.1 <i>Grazing</i> | 267 |
| 6.3.3.2 <i>Indoor feeding</i> | 267 |
| 6.3.3.3 <i>Collection and analysis of herbage, milk and rumen contents</i> | 268 |
| 6.3.4 Digestion and fermentation kinetics..... | 269 |
| 6.3.4.1 <i>Uniformity period</i> | 269 |
| 6.3.4.2 <i>Dietary treatment period</i> | 269 |
| 6.3.4.3 <i>Chemical analyses</i> | 271 |
| 6.3.5 Statistical analysis..... | 272 |
| 6.3.5.1 <i>Cow Ruminant Characteristics</i> | 272 |
| 6.3.5.2 <i>In sacco digestion kinetics</i> | 273 |
| 6.3.5.3 <i>In vitro incubations</i> | 275 |
| 6.4 RESULTS..... | 276 |
| 6.4.1 Chemical composition and particle size distribution of forages..... | 276 |
| 6.4.2 Animal production..... | 279 |
| 6.4.3 Cow ruminal characteristics..... | 281 |
| 6.4.3.1 <i>Uniformity period</i> | 281 |
| 6.4.3.2 <i>Dietary treatment period</i> | 283 |
| 6.4.4 <i>In sacco</i> digestion of forages and mixtures..... | 286 |
| 6.4.4.1 <i>Lucerne hay digestion across feeding periods</i> | 286 |
| 6.4.4.2 <i>Forage effects</i> | 287 |
| 6.4.4.3 <i>Cow-diet effects</i> | 291 |
| 6.4.4.4 <i>Forage x cow-diet interaction</i> | 294 |
| 6.4.5 <i>In vitro</i> fermentation of forages and mixtures..... | 294 |
| 6.4.5.1 <i>Lucerne standard fermentation across feeding periods</i> | 294 |
| 6.4.5.2 <i>Forage effect</i> | 296 |
| 6.4.5.3 <i>Cow-diet effect</i> | 301 |
| 6.4.5.4 <i>Diet x forage interaction</i> | 306 |
| 6.5 DISCUSSION..... | 306 |
| 6.5.1 Forage effects..... | 307 |
| 6.5.2 Protein degradation and supply..... | 309 |
| 6.5.3 Effect of cow-diet..... | 310 |
| 6.5.4 Evaluation of forage diets using CNCPS..... | 312 |
| 6.6 CONCLUSIONS..... | 314 |
| | |
| CHAPTER 7: OVERALL DISCUSSION AND CONCLUSIONS | 317 |
| 7.1 OVERALL DISCUSSION..... | 317 |
| 7.2 SUMMARY AND CONCLUSIONS..... | 324 |
| | |
| REFERENCES | 329 |
| APPENDICES..... | 367 |

LIST OF TABLES

| | |
|--|----|
| TABLE 2.1. Comparative feeding value in terms of sheep liveweight gain, forage dry matter (DM) content, composition (% of DM), and metabolisable energy concentration for fresh species (Burke <i>et al.</i> , 2002b)..... | 12 |
| TABLE 2.2. Mean annual milk production, liveweight and body condition score of New Zealand and overseas Holstein-Friesians ¹ grazing pasture (Grass) or fed total mixed ration (TMR) during the 2000/2001 season (Kolver <i>et al.</i> , 2002)..... | 13 |
| TABLE 2.3. Typical concentrations of carbohydrates (g/kg DM) in temperate legumes, and temperate and tropical grasses (Moore and Hatfield, 1994)..... | 17 |
| TABLE 2.4. Average (and standard deviation) nutrient composition of pasture from dairy farms through New Zealand. | 26 |
| TABLE 2.5. Nutrient requirements for a 400 kg dairy cow compared to nutrients supplied in a ryegrass-based pasture and total mixed ration (TMR) (Adapted from Moller <i>et al.</i> , 1996; Kolver, 2000; NRC, 2001; Waghorn, 2002)..... | 34 |
| TABLE 2.6. Efficiency of energy capture (as high-energy phosphate bonds) from a range of substrates in support of maintenance processes (Waghorn and Barry, 1987; Baldwin, 1995; Holmes <i>et al.</i> 2002)..... | 35 |
| TABLE 2.7. Correlations (r) between <i>in sacco</i> DM degradability and <i>in vivo</i> digestibility..... | 40 |
| TABLE 2.8. Particle size distribution of DM in boli (chewed during eating) or rumen contents of sheep ^{1, 2, 3, 5} and cows ⁴ compared to average particle size of minced grasses, legumes and minced forage ⁵ . Data are % DM retained on sieves with aperture sizes (sides of square hole) as indicated. | 45 |
| TABLE 2.9. Direct and indirect gas production from glucose fermented to different acidic endpoints..... | 54 |
| TABLE 2.10. Lactation responses of New Zealand cows in the second half of lactation when fed supplements with medium to low quality pasture or fed high quality legumes..... | 62 |
| TABLE 3.1. Statistics to support the accuracy of Near InfraRed Reflectance Spectroscopy (NIRS) calibration equation to estimate the composition of <i>in sacco</i> residues (% of DM)..... | 74 |
| TABLE 3.2. Forage dry matter (DM) content and composition (% of DM) and predicted organic matter digestibility (OMD) determined by Near InfraRed Reflectance Spectroscopy for fresh and conserved species..... | 82 |
| TABLE 3.3. Particle size distribution of minced forages used for <i>in sacco</i> and <i>in vitro</i> incubations. Data are % of dry matter (DM) retained on sieves with aperture sizes (sides of square hole; mm) indicated, or passing through a sieve with 0.25 mm aperture size (soluble and residues). | 84 |
| TABLE 3.4. Rumen pH (n = 1), rumen ammonia (NH ₃ ; n = 4) and volatile fatty acid (VFA) concentrations (n = 1) and molar percentages of inocula ¹ used for eight <i>in sacco</i> incubation runs..... | 86 |

| | |
|--|-----|
| TABLE 3.5. <i>In vitro</i> pH and NH ₃ of freeze-dried and ground lucerne at 2 and 8 hours when incubated in eight separate <i>in vitro</i> incubation runs. <i>In vitro</i> NH ₃ and pH data are the least-square (LS) means of triplicate samples at each time in each incubation run (n = 3). LS means and associated standard error of the means (SEM) are presented. | 87 |
| TABLE 3.6. <i>In sacco</i> forage dry matter (DM) degradation characteristics (% of DM) as defined by soluble (A) and degradable insoluble (B) fractions, potential degradability (PD), fractional degradation rate (k, %/h), lag time (hours) and effective degradability (ED) which takes into account the effect of passage from the rumen. The R ² value (square of the correlation coefficient) of the non-linear regression equation is presented to illustrate the goodness of fit. (Standard errors for A, B, k and Lag parameters are presented in Appendix 3.9)..... | 90 |
| TABLE 3.7. Crude protein (CP) concentration in the DM and <i>in sacco</i> degradation characteristics (% of CP) of forages as defined by soluble (A) and degradable insoluble (B) fractions, potential degradability (PD), fractional degradation rate (k, %/h), lag time (hours) and effective degradability (ED) which takes into account the effect of passage from the rumen. The R ² value (square of the correlation coefficient) of the non-linear regression equation is presented to illustrate the goodness of fit. (Standard errors for A, B, k and Lag parameters are presented in Appendix 3.10)..... | 93 |
| TABLE 3.8. Neutral detergent fibre (NDF) concentration in the DM and <i>in sacco</i> degradation characteristics (% of NDF) of forages as defined by soluble (A) and degradable insoluble (B) fractions, potential degradability (PD), fractional degradation rate (k, %/h), lag time (hours) and effective degradability (ED) ¹ . The R ² value (square of the correlation coefficient) of the non-linear regression equation is presented to illustrate the goodness of fit. (Standard errors for A, B, k and Lag parameters are presented in Appendix 3.11)..... | 96 |
| TABLE 3.9. Acid detergent fibre (ADF) concentration in the DM and <i>in sacco</i> degradation characteristics (% of ADF) of forages as defined by soluble (A) and degradable insoluble (B) fractions, potential degradability (PD), fractional degradation rate (k, %/h), lag time (hours) and effective degradability (ED) which takes into account the effect of passage from the rumen. The R ² value (square of the correlation coefficient) of the non-linear regression equation is presented to illustrate the goodness of fit. (Standard errors for A, B, k and Lag parameters are presented in Appendix 3.12)..... | 97 |
| TABLE 3.10. Multiple regression analysis to indicate dietary components best able to explain the variation in dry matter (DM), crude protein (CP), acid detergent fibre (ADF) and neutral detergent fibre (NDF) kinetic parameters. | 103 |
| TABLE 3.11. Net ammonia production ¹ (% forage nitrogen released as NH ₃) of forages evaluated in <i>in vitro</i> for 24 hours (h). (Standard errors are presented in Appendix 3.14)..... | 107 |
| TABLE 3.12. Net ammonia produced (mmol NH ₃ /mmol forage nitrogen) for each forage incubated between 0 – 6, 6 – 12, 12 – 24 and 0 – 24 hours (h). Data are the average of triplicate bottles of each forage and negative values indicate a net utilisation. | 108 |

| | |
|---|-----|
| TABLE 3.13. <i>In vitro</i> yield of VFA (mg/g DM) after 6 hours (h) of incubation with molar percentages and molar ratios of acetate (A), propionate (P) and butyrate (B). | 114 |
| TABLE 3.14. <i>In vitro</i> yield of VFA (mg/g DM) after 12 hours (h) of incubation with molar percentages and molar ratios of acetate (A), propionate (P) and butyrate (B). | 115 |
| TABLE 3.15. <i>In vitro</i> yield of VFA (mg/g DM) after 24 hours (h) of incubation with molar percentages and molar ratios of acetate (A), propionate (P) and butyrate (B). | 116 |
| TABLE 3.16. Net VFA yields (mg/g DM/h) after 6, 12 and 24 hours (h) and rates of production (mg/g DM/h) from 0 – 6 h, 6 – 12 h, 12 – 24 h and 0 – 24 h..... | 117 |
| TABLE 3.17. Mean data on the composition and digestion by sheep of 20 herbage groups on the basis of dry matter (DM) digestibility (Weston, 1985). | 122 |
| TABLE 3.18. Composition of forages evaluated using the CNCPS model..... | 132 |
| TABLE 3.19. Energy and protein values for forages evaluated by the CNCPS model. | 133 |
| TABLE 3.20. Degradation rates for forages evaluated by the CNCPS model. | 134 |
| TABLE 3.21. Early lactation metabolisable energy (ME; MJ/day) and metabolisable protein (MP; g/day) supplied by forages and predicted milk production of dairy cows expected to produce 22.7 litres milk/day and consume 17.1 kgDM/day using CNCPS. When the ratio between predicted milk from MP and ME (MP:ME milk ratio ¹) is greater than 1, ME is limited and when the ratio is less than 1, MP is limiting..... | 139 |
| TABLE 3.22. Late lactation metabolisable energy (ME; MJ/day) and metabolisable protein (MP; g/day) supplied by forages and predicted milk production of dairy cows expected to produce 15 litres milk/day and consume 14.6 kgDM/day using CNCPS. When the ratio between predicted milk from MP and ME supply (MP:ME milk ratio ¹) is greater than 1, ME is limited and when the ratio is less than 1, MP is limiting. | 140 |
| TABLE 3.23. Early lactation metabolisable energy (ME; MJ/day) and metabolisable protein (MP; g/day) supplied by forage mixtures and predicted milk production of dairy cows expected to produce 22.7 litres milk/day and consume 17.1 kgDM/day using CNCPS. When the ratio between predicted milk from MP and ME (MP:ME milk ratio ¹) is greater than 1, ME is limited and when the ratio is less than 1, MP is limiting..... | 144 |
| TABLE 3.24. Late lactation metabolisable energy (ME; MJ/day) and metabolisable protein (MP; g/day) supplied by forage mixtures and predicted milk production expected to produce 15.0 litres milk/day and consume 14.6 kgDM/day using CNCPS. When the ratio between predicted milk from MP and ME (MP:ME milk ratio ¹) is greater than 1, ME is limited and when the ratio is less than 1, MP is limiting..... | 145 |
| TABLE 4.1. Schedule of events for lambs fed seven contrasting diets for eight weeks. | 160 |

| | |
|---|-----|
| TABLE 4.2. Average dry matter content (DM), percentage of sulla fed, and composition (% of DM) of the seven diets offered to lambs over eight weeks. Means \pm standard errors are presented for each diet (8 feed samples for each diet)..... | 164 |
| TABLE 4.3. Average composition ¹ (% DM) and percentage of feed eaten for the seven diets fed to lambs over eight weeks. Means \pm standard errors are presented for each diet (8 feed samples for each diet)..... | 165 |
| TABLE 4.4. Daily dry matter (DM) intake, liveweight (LW) gain, clean wool yield of lambs fed seven forage diets over eight weeks, carcass weight (CW) and dressing-out % of lambs at slaughter and efficiency of lamb production in terms of LW gain per kg DM eaten, metabolisable energy (ME) eaten and metabolisable protein (MP) supplied. Least-square (LS) means and standard error of the means (SEM) are presented. | 171 |
| TABLE 4.5. Fed and fasted liveweights (LW) of lambs at the start and end of the trial, difference between fed and fasted LW at the start (day 6 and 8) and end (day 58 and 59) of the trial and LW gains of fed and fasted lambs fed seven forage diets over the eight weeks. Least-square (LS) means and standard error of the mean (SEM) are presented..... | 174 |
| TABLE 4.6. Fat depth at the 11 th and 12 th rib (GR; mm), back-fat depth (mm) and eye muscle area ¹ (mm ²) estimated by ultrasound on days 6, 30 and 54 for lambs fed on seven forage diets over eight weeks, and GR fat-depth of lamb carcasses at slaughter (day 61). Least-square (LS) means and standard error of the mean (SEM) are presented..... | 177 |
| TABLE 4.7. Dry matter (DM) intake (kg DM/lamb/day) of individual lambs predicted with alkane markers ¹ and calculated group DM intake during weeks 4 and 5 of the trial ² , and average DM intakes ³ and liveweight (LW) gain over the eight week duration of the trial. Least-square (LS) means and standard error of the mean (SEM) are presented..... | 183 |
| TABLE 4.8. Metabolisable energy (ME) requirement ¹ for maintenance and liveweight (LW) gain and the efficiency which ME used above maintenance was converted into LW gain. | 187 |
| TABLE 4.9. Mean rumen pH and ammonia concentration measured on six occasions during the experiment, predicted rumen ammonia concentration, nitrogen (N) intake and blood glucose and blood lactate concentrations measured on three occasions during the experiment in lambs fed seven forage diets over eight weeks of the experiment. Least-square (LS) means and associated standard error of the means (SEM) are presented..... | 194 |
| TABLE 4.10. Volatile fatty acid concentration in rumen digesta, proportion of acetate, propionate, butyrate and minor (iso-butyrate, valerate and iso-valerate) fatty acids, and ratio of acetate:propionate (A:P) and acetate + butyrate:propionate ((A+B):P) from lambs fed seven forage diets over eight weeks ¹ . Least-square (LS) means and associated standard error of the means (SEM) are presented..... | 195 |
| TABLE 4.11. Correlation coefficients between mean liveweight gain (g/day) or carcass weight (kg) and composition of the diet eaten (% DM) and intake of nutrients (kg). | 197 |

| | |
|--|-----|
| TABLE 5.1. Schedule of events for lambs used for glucose tolerance tests and protein measurements..... | 216 |
| TABLE 5.2 . Processing of plasma and tissue samples taken from lambs infused with ³⁵ S-sulphate (SO ₄), ³⁵ S-cysteine and ³ H-valine..... | 222 |
| TABLE 5.3. Dry matter (DM) content and composition (g/kg DM) of diets offered and consumed by lambs fed pasture, lucerne, sulla and lucerne:sulla. Results presented are least-square means ± standard error of the mean (SEM). ... | 232 |
| TABLE 5.4. Average dry matter (DM) intake and starting and finishing liveweights of lambs fed pasture, lucerne, sulla and lucerne:sulla. Least-square (LS) means ± standard error of the mean (SEM) are presented..... | 233 |
| TABLE 5.5. Effect of diet on plasma cysteine and sulphate concentrations, specific radioactivity and fluxes enabling calculations of whole body (WB) protein synthesis in lambs fed pasture, lucerne, sulla and lucerne:sulla. Data are presented as least square (LS) means ± pooled standard deviation (SD). | 236 |
| TABLE 5.6. Effect of diet on the concentration of valine in plasma and the intracellular pools (nmol/mL) and protein-bound pool (mg/g DM) in tissues of lambs fed pasture, lucerne, sulla and lucerne:sulla. Data are presented as least-square (LS) means ± SEM..... | 239 |
| TABLE 5.7. Specific radioactivity (SRA; dpm/nmol) of valine in plasma and in intracellular (I) and bound protein (B) pools of tissues in lambs fed pasture, lucerne, sulla or lucerne:sulla (n = 4). Results are presented as least-square (LS) means and SEM. Probability (Pr) values are given for comparisons of diet..... | 243 |
| TABLE 5.8. Fractional synthetic rates (FSR; %/day) of protein in tissues using the plasma (P) and intracellular pool (I) as precursor pools in lambs fed pasture, lucerne, sulla or lucerne:sulla (n = 4). Results are presented as least-square (LS) means and SEM. Probability (Pr) values are given for comparisons of diet, pasture with other diets and diets containing condensed tannins (CT) with diets containing no CT. | 244 |
| TABLE 5.9. Differences between fractional synthetic rates (FSR; %/day) of tissues in lambs fed pasture, lucerne, sulla and lucerne:sulla (n = 4) using the plasma (P) as the precursor pools and average FSR _P of tissues. Results are presented as least-square (LS) means and SEM. Probability (Pr) values are given for comparisons of tissues within diets..... | 245 |
| TABLE 5.10. Estimates of absolute whole body protein synthesis (WBPS) reported in other studies with sheep. | 249 |
| TABLE 5.11. Estimates of absolute whole body protein accretion (PA), protein synthesis (PS ¹), protein degradation (PD ²) in g/day relative to metabolisable energy (ME; MJME/day) and crude protein (CP; g/day) intake of lambs fed pasture, lucerne, sulla and lucerne:sulla. | 251 |
| TABLE 5.12a. Estimates of fractional protein synthesis rates (%/day) of tissues in sheep reported in the literature..... | 254 |
| TABLE 5.12b. Estimates of fractional protein synthesis rates (%/day) of tissues in goats and cattle reported in the literature and lambs in this study. | 255 |

| | |
|--|-----|
| TABLE 5.13. Estimate of whole body protein synthesis (g/day) using tissue synthesis rates estimated from the plasma precursor pool (FSR _P) in Tables 5.8 and 5.9..... | 256 |
| TABLE 6.1. Schedule of events for the uniformity and indoor feeding trial from 19 February to 22 March 2001..... | 266 |
| TABLE 6.2. Dry matter (DM) content and composition (% of DM) of P, P:M, P:S and P:M:S ¹ diets fed to cows, and P, M, S, P:M, P:S and P:M:S ¹ forages used for <i>in sacco</i> and <i>in vitro</i> incubations ² | 277 |
| TABLE 6.3. Particle size distribution (% of dry matter) of minced forages and mixtures used for incubations and digesta taken from the mid-rumen of cows fed P, P:M, P:S, and P:M:S ¹ diets..... | 278 |
| TABLE 6.4. Daily dry matter (DM) intake (kg/cow/day), milk, milkfat, milk protein and milksolids ¹ yield (kg/cow/day) and milk composition (%) for cows fed P, P:M, P:S, and P:M:S ² . Least-square (LS) means ± SEM are presented..... | 279 |
| TABLE 6.5. Rumen pH, ammonia (NH ₃) and volatile fatty acid (VFA) concentrations and molar percentage for 16 cows grazing pasture during the uniformity period ² and when fed either P, P:M, P:S or P:M:S ¹ in period B ³ . Molar ratios are given for acetate:propionate (A:P) and (acetate + butyrate):propionate ((A+B):P). Least-square (LS) means ± SEM are presented..... | 282 |
| TABLE 6.6. Rumen pH, ammonia (NH ₃) concentration and <i>in sacco</i> DM losses from four cows grazing pasture during the uniformity period. Least-square (LS) means ± SEM are presented..... | 283 |
| TABLE 6.7. Effect of cow-diet and feeding period on rumen pH, ammonia (NH ₃) and volatile fatty acid (VFA) concentrations and molar percentages for four cows fed either P, P:M, P:S and P:M:S ¹ and used for <i>in sacco</i> and <i>in vitro</i> incubations. Molar ratios are given of acetate:propionate (A:P) and (acetate + butyrate):propionate ((A+B):P). Least-square (LS) means ± SEM are presented..... | 285 |
| TABLE 6.8. <i>In sacco</i> DM loss of lucerne hay at 12 and 24 hours when incubated in cows fed P, P:M, P:S and P:M:S ¹ during feeding periods A and B. Data in each feeding period are the least square (LS) means ± SEM of four values, n = 4..... | 286 |
| TABLE 6.9. Effect of forage and forage mixtures on dry matter (DM), crude protein (CP) and neutral detergent fibre (NDF) degradation parameters ² derived from the lag equation for P, M, S, P:M, P:S and P:M:S. Data presented are the least-square (LS) means ± SEM of four cows over two feeding periods (n = 8)..... | 289 |
| TABLE 6.10. Effect of cow-diet on degradation rates (k) determined with and without a lag period and effective degradability (ED) of dry matter (DM), crude protein (CP) and neutral detergent fibre (NDF) for forages and mixtures incubated in cows fed P, P:M, P:S and P:M:S ¹ . Data presented for DM and NDF are the least-square (LS) means ± SEM of six forages incubated over | |

| | |
|---|-----|
| two feeding periods (n = 12); data presented for CP are the LS means \pm SEM of 5 forages incubated over two feeding periods (n = 10)..... | 293 |
| TABLE 6.11. Effect of feeding period on <i>in vitro</i> pH, and <i>in vitro</i> ammonia (NH ₃) and volatile fatty acid (VFA) yields of freeze-dried lucerne standard using rumen inocula from each of the four cows fed contrasting cow-diets (P, P:M, P:S, P:M:S ¹). NH ₃ and pH data are based on two incubations from each cow in each period (n = 16), but VFA are based on a single (bulked) sample from each cow in each period (n = 8). Least-square (LS) means \pm SEM are presented..... | 295 |
| TABLE 6.12. Effect of forage and forage mixture on <i>in vitro</i> pH at 12 hours and net ammonia (NH ₃) yield at 8, 12 and 24 hours when P, M, S, P:M, P:S and P:M:S ¹ were incubated using rumen inocula from cows fed four dietary treatments (P, P:M, P:S and P:M:S ¹). Least-square (LS) means \pm SEM are presented..... | 298 |
| TABLE 6.13. Effect of forage and forage mixture on <i>in vitro</i> volatile fatty acid (VFA) yields and molar percentages for P, M, S, P:M, P:S and P:M:S ¹ incubated with inocula from cows fed P, P:M, P:S and P:M:S ¹ . Molar ratios are given for acetate:propionate (A:P) and (acetate + butyrate):propionate ((A+B):P). Least-square (LS) means \pm SEM are presented..... | 300 |
| TABLE 6.14. Effect of cow-diet on <i>in vitro</i> pH and <i>in vitro</i> production of ammonia (NH ₃) and volatile fatty acid (VFA) from freeze-dried lucerne when incubated using rumen inoculum from each of four cows fed either P, P:M, P:S and P:M:S ¹ . Ammonia (NH ₃) and pH data are duplicates of two incubation runs during both periods for each of four cows; VFA data are based on a single (bulked) sampled from each incubation run in both periods. Least-square (LS) means \pm SEM are presented..... | 302 |
| TABLE 6.15. Effect of cow-diet on <i>in vitro</i> pH at 12 hours and net ammonia (NH ₃) yield at 2, 4, 8, 12 and 24 hours when P, M, S, P:M, P:S and P:M:S were incubated using rumen inocula from cows fed four dietary treatments (P, P:M, P:S and P:M:S ²). Least-square (LS) means \pm SEM are presented..... | 303 |
| TABLE 6.16. Effect of cow-diet on volatile fatty acid (VFA) yield, molar percentage and ratio of acetate:propionate (A:P) and (acetate + butyrate):propionate ((A+B):P) when forages and forage mixtures ¹ were incubated using rumen inoculum from cows fed P, P:M, P:S and P:M:S ² . Data are the least-square (LS) means \pm SEM of 6 values, n = 6..... | 305 |
| TABLE 6.17. <i>In sacco</i> degradation parameters (A, B, k, Lag) and composition of ryegrass leaf in studies where it has been prepared by mincing fresh forage..... | 308 |

LIST OF FIGURES

| | |
|--|-----|
| FIGURE 2.1. Stylised disappearance curve for dry matter, protein or the fibre component of feed that does not have a lag period (solid curve) and feed that has a lag period (dotted curve)..... | 51 |
| FIGURE 3.1. Dry matter (DM) degradation curves for eight forage types (Section 3.3.5) evaluated <i>in sacco</i> . Means \pm standard error of the mean at each time are presented. | 89 |
| FIGURE 3.2. Effective dry matter (DM) degradability of forage types when DM outflow rate varies from 0 to 20 %/h..... | 91 |
| FIGURE 3.3. Crude protein (CP) degradation curves for eight forage types (Section 3.3.5) evaluated <i>in sacco</i> . Means \pm standard error of the mean at each time are presented..... | 94 |
| FIGURE 3.4. Neutral detergent fibre (NDF) degradation curves for eight forage types (Section 3.3.5) evaluated <i>in sacco</i> . Means \pm standard error of the mean at each time are presented..... | 98 |
| FIGURE 3.5. Acid detergent fibre (ADF) degradation curves for eight forage types (Section 3.3.5) evaluated <i>in sacco</i> . Means \pm standard error of the mean at each time are presented..... | 98 |
| FIGURE 3.6. Relationship between the crude protein content (CP, g/kg DM) and effective rumen degradability of CP (ERDP, g/kg DM) of forages at a rumen outflow rate of 6 %/h..... | 99 |
| FIGURE 3.7. Relationship between the effective degradability of DM (ED _{DM} , % DM) and effective rumen degradability of crude protein (ERDP, g/kg DM) of forages at a rumen outflow rate of 6 %/h..... | 100 |
| FIGURE 3.8. Relationship between the neutral detergent fibre (NDF, g/kg DM) and effective rumen degradability of crude protein (ERDP, g/kg DM) of forages at a rumen outflow rate of 6 %/h. Maize silage and maize grain were not included in the relationship. | 100 |
| FIGURE 3.9a. Relationship between neutral detergent fibre content (NDF, g/kg DM) and dry matter degradation rate (%/h) of forages. (Maize grain was not included in the equation)..... | 101 |
| FIGURE 3.9b. Relationship between neutral detergent fibre content (NDF, g/kg DM) and NDF degradation rate (%/h) of forages. (Maize grain was not included in the equation)..... | 102 |
| FIGURE 3.10. <i>In vitro</i> pH when eight forage types were incubated for 24 hours. Data are the average pH of all forages in each forage type at each time point with associated standard error bars. | 105 |
| FIGURE 3.11. Net ammonia (NH ₃) yield for nine forage types evaluated <i>in vitro</i> | 109 |
| FIGURE 3.12. Net yield of VFA (mg/g DM) produced when forages were evaluated <i>in vitro</i> . Standard error bars for C3 and C4 grasses, legumes with and without CT, grass silage and legume silages..... | 111 |

| | |
|--|-----|
| FIGURE 3.13. Net yield of acetate produced (mg/g DM) when forages were evaluated <i>in vitro</i> . Standard error bars for C3 and C4 grasses, legumes with and without CT, grass silage and legume silages..... | 111 |
| FIGURE 3.14. Net yield of propionate produced (mg/g DM) when forages were evaluated <i>in vitro</i> . Standard error bars for C3 and C4 grasses, legumes with and without CT, grass silage and legume silages..... | 112 |
| FIGURE 3.15. Net yield of butyrate produced (mg/g DM) when forages were evaluated <i>in vitro</i> . Standard error bars for C3 and C4 grasses, legumes with and without CT, grass silage and legume silages..... | 112 |
| FIGURE 4.1. Chemical composition of ryegrass, white clover, lucerne and sulla offered to lambs over the eight week experimental period..... | 166 |
| FIGURE 4.2. Liveweight profile of lambs fed pasture, white clover, lucerne, sulla and 50:50 mixtures of pasture:sulla, white clover:sulla and lucerne:sulla over eight weeks. Least-square (LS) means \pm standard errors of the mean (SEM) are presented..... | 170 |
| FIGURE 4.3. The relationship between carcass weight (kg) and fasted liveweight gain (g/day) for lambs fed seven forage-based diets over eight weeks..... | 173 |
| FIGURE 4.4. The relationship between carcass weight (kg) and eye muscle area (mm ²) on day 54 of the experiment for lambs fed seven forage-based diets over eight weeks..... | 176 |
| FIGURE 4.6. Average metabolisable protein (MP) intake and average liveweight (LW) gain of lambs from day 6 to 58 of the trial when fed seven forage diets. | 180 |
| FIGURE 4.7. The relationship between dry matter (DM) intake (predicted by alkanes) and liveweight gain of all lambs on seven forage diets, and when data from lambs fed lucerne were not included. | 181 |
| FIGURE 4.8. The relationship between metabolisable energy (ME) intake (predicted by alkanes) and liveweight gain of all lambs on seven forage diets and when data from lambs fed lucerne were not included..... | 182 |
| FIGURE 4.9. The relationship between dry matter (DM) intake (predicted by alkanes) and liveweight gain adjusted for over- and under-prediction of group intakes..... | 182 |
| FIGURE 4.10. Relationship between metabolisable energy (ME) requirements and ME intake for lambs fed seven forage diets. | 185 |
| FIGURE 4.11. Relationship between metabolisable protein (MP) requirements and MP intake for lambs fed seven forage diets. | 185 |
| FIGURE 4.12. Relationship between metabolisable energy (ME) eaten above maintenance and net energy (NE) retained as liveweight gain. | 186 |
| FIGURE 4.13. Relationship between metabolisable protein (MP) eaten above maintenance and net protein (NP) retained as liveweight gain and wool..... | 186 |
| FIGURE 4.14. Changes in mean rumen pH from two hours pre-feeding to eight hours post-feeding for lambs fed the seven forage diets on one day of the experiment. Least-square means \pm standard errors of the mean at each time of measurement are presented. | 188 |

- FIGURE 4.15. The relationship between mean rumen pH measured 2 – 4 hours after eating on six occasions during the experiment and mean soluble carbohydrate content (% dry matter; DM) of forages fed to lambs over eight weeks of the experiment. 189
- FIGURE 4.16. Changes in mean rumen ammonia (NH₃) from two hours pre-feeding to eight hours post-feeding for lambs fed the seven forage diets on one day of the experiment. Least-square means ± standard errors of the mean at each time of measurement are presented. 190
- FIGURE 4.17. The relationship between mean rumen ammonia (NH₃) concentration measured 2 – 4 hours after eating on six occasions during the experiment and concentration of crude protein in the diet eaten (% dry matter; DM) for seven forage diets fed to lambs and averaged over eight weeks of the experiment..... 191
- FIGURE 4.18. The relationship between mean blood glucose concentration and acetate:propionate ratio (A:P) of individual lambs fed seven forage diets..... 193
- FIGURE 4.19. Relationship between actual dry matter (DM) intake in this experiment and predicted DM intake using Equation 4.9. 201
- FIGURE 4.20. Relationship between actual metabolisable energy (ME) intake in this experiment and predicted ME intake using Equation 4.10. 201
- FIGURE 4.21. Relationship between actual liveweight (LW) gain in this experiment and predicted LW gain using Equation 4.11. 201
- FIGURE 5.1. Fluxes and equations through the cysteine and sulphate pools when ³⁵S-sulphate and ³⁵S-cysteine were infused. 225
- FIGURE 5.2. Plasma ³⁵S-cysteine specific radioactivity (SRA; dpm/μmol) following a continuous infusion of ³⁵S-cysteine into lambs fed pasture, lucerne, sulla and lucerne:sulla. Each point represents an average ± SEM of four lambs. 234
- FIGURE 5.3. Plasma ³⁵S-sulphate (SO₄) specific radioactivity (SRA; dpm/μmol) following a continuous infusion of ³⁵S-SO₄ into lambs fed pasture, lucerne, sulla and lucerne:sulla. Each point represents an average ± SEM of four lambs..... 234
- FIGURE 5.4. Effect of diet on whole body cysteine and sulphate fluxes (μmol/min) based on infusion of ³⁵S-cysteine and ³⁵S-sulphate in lambs fed pasture (n = 4), lucerne (n = 3), sulla (n = 4) and lucerne:sulla (n = 4). Results are represented as least-square means and associated pooled standard deviation (SD). 237
- FIGURE 5.5. Plasma ³H-valine specific radioactivity (SRA; dpm/μmol) at 6, 7 and 8 hours of infusion for lambs fed pasture, lucerne, sulla and lucerne:sulla. Each point represents an average ± SEM of four lambs..... 241
- FIGURE 6.1. Forage and forage mixture (P, M, S, P:M, P:S and P:M:S¹) on *in sacco* dry matter (DM), crude protein (CP) and fibre (NDF) disappearance curves averaged across four cows over two feeding periods. Means ± SE bars are presented. 290

| | |
|--|-----|
| FIGURE 6.2. Cow-diet (P, P:M, P:S and P:M:S ¹) <i>in sacco</i> dry matter (DM), crude protein (CP) and fibre (NDF) disappearance curves averaged for all incubations. Means \pm SE bars are presented. | 292 |
| FIGURE 6.3. <i>In vitro</i> pH changes over 24 hours when P, M, S, P:M, P:S and P:M:S ¹ were incubated. Data are from two incubations in each feeding period for each of the four cows (n = 16). LS means \pm SEM bars are presented. | 297 |
| FIGURE 6.4. Net ammonia (NH ₃) production (% forage nitrogen, N, recovered as NH ₃) during 24 hour <i>in vitro</i> incubation of P, M, S, P:M, P:S, and P:M:S ¹ . Data from two incubations for each cow in each feeding period (n = 16). LS means \pm SEM bars are presented. | 297 |
| FIGURE 6.5. Cumulative volatile fatty acid (VFA) production from <i>in vitro</i> incubations of P, M, S, P:M, P:S and P:M:S ¹ . Data are from bulked samples from each incubation and both feeding periods giving one sample from each of 4 cows (n = 4). LS means \pm SEM bars are presented. | 299 |
| FIGURE 6.6. Effect of cow-diet on <i>in vitro</i> pH when inoculum from cows fed P, P:M, P:S and P:M:S ¹ were used to incubate P, M, S, P:M, P:S and P:M:S ¹ for 24 hours. Data are the average pH of duplicate bottles for each of six forages at each time from both feeding periods (n = 24). LS means \pm SEM bars are presented. | 301 |
| FIGURE 6.7. Effect of cow-diet on net ammonia (NH ₃) production (% forage nitrogen, N, recovered as NH ₃) when forages were incubated <i>in vitro</i> using rumen inoculum from cows fed P, P:M, P:S and P:M:S ¹ . LS means \pm SEM bars are presented. | 303 |
| FIGURE 6.8. Effect of cow-diet on total VFA yield (mmol/g DM incubated) for forages incubated <i>in vitro</i> using rumen inoculum from cows fed P, P:M, P:S and P:M:S ¹ . LS means \pm SEM bars are presented. | 304 |

LIST OF PHOTOGRAPHS

| | |
|--|-----|
| PHOTOGRAPH 3.1. Kreft compact mincer used to mince fresh forage | 77 |
| PHOTOGRAPH 3.2. Dacron bags that were used for <i>in sacco</i> incubations | 77 |
| PHOTOGRAPH 3.3. 50 mL bottles used for <i>in vitro</i> incubations | 77 |
| PHOTOGRAPH 3.4. Incubator used for <i>in vitro</i> incubations..... | 77 |
| PHOTOGRAPH 4.1. Sulla (<i>Hedysarum coronarium</i>) | 154 |
| PHOTOGRAPH 4.2. Feeding of lambs on feed pads..... | 154 |
| PHOTOGRAPH 6.1: Indoor feeding of cows..... | 268 |

LIST OF APPENDICES

| | |
|--|-----|
| APPENDIX 3.1. Method for measuring particle size distribution | 367 |
| APPENDIX 3.2. Methods for <i>in sacco</i> and <i>in vitro</i> incubations..... | 368 |
| APPENDIX 3.3. Comparison of crude protein (CP), acid detergent fibre (ADF) and neutral detergent fibre (NDF) estimated by wet chemistry and Near InfraRed Spectroscopy (NIRS). | 371 |
| APPENDIX 3.4. Method for measuring pH and collecting samples for ammonia and volatile fatty acid (VFA) analysis..... | 372 |
| APPENDIX 3.5. Method for measuring ammonia concentration (Chaney and Marbach, 1962). | 374 |
| APPENDIX 3.6. Method for measuring volatile fatty acid concentration. | 379 |
| APPENDIX 3.7. Particle size distribution of minced forages used for <i>in sacco</i> and <i>in vitro</i> incubations. | 380 |
| APPENDIX 3.8. Particle size distribution in swallowed boli and rumen contents of sheep and cattle fed contrasting diets compared to the average particle size distribution of contrasting forages in this study (summarised by Waghorn, unpublished)..... | 381 |
| APPENDIX 3.9. <i>In sacco</i> forage dry matter (DM) degradation characteristics (% of DM) \pm SEM as defined by soluble (A) and degradable insoluble (B) fractions, fractional degradation rate (k, %/h) and lag time (hours). | 382 |
| APPENDIX 3.10. Crude protein (CP) concentration in the DM and <i>in sacco</i> degradation characteristics \pm SEM (% of CP) of forages as defined by soluble (A) and degradable insoluble (B) fractions, fractional degradation rate (k, %/h) and lag time (hours). | 383 |
| APPENDIX 3.11. Neutral detergent fibre (NDF) concentration in the DM and <i>in sacco</i> degradation characteristics \pm SEM (% of NDF) of forages as defined by soluble (A) and degradable insoluble (B) fractions, fractional degradation rate (k, %/h) and lag time (hours). | 384 |
| APPENDIX 3.12. Acid detergent fibre (ADF) concentration in the DM and <i>in sacco</i> degradation characteristics \pm SEM (% of ADF) of forages as defined by soluble (A) and degradable insoluble (B) fractions, fractional degradation rate (k, %/h) and lag time (hours). | 385 |
| APPENDIX 3.13. <i>In vitro</i> pH of individual forages evaluated over 24 hours (h). | 386 |
| APPENDIX 3.14. Net ammonia production \pm SEM (% forage nitrogen released as NH ₃) of forages evaluated <i>in vitro</i> for 24 hours (h). | 387 |
| APPENDIX 3.15. Net ammonia production (mmol/L) of forages evaluated <i>in vitro</i> over 24 hours (h). | 388 |
| APPENDIX 3.16. Evaluation of forages with effective fibre concentrations of 40% and 60% for early and late lactating dairy cows using the CNCPS model.... | 389 |

| | |
|--|-----|
| APPENDIX 3.17. CNCPS evaluation of forages. Data were used to derive Tables 3.21 and 3.22..... | 399 |
| APPENDIX 3.18. CNCPS evaluation of forage mixtures. Data were used to derive Tables 3.23 and 3.24. | 405 |
| APPENDIX 4.1. Results from preliminary <i>in sacco</i> and <i>in vitro</i> incubations of ryegrass, white clover, lucerne, sulla and mixtures of ryegrass:sulla, lucerne:sulla and white clover:sulla | 411 |
| APPENDIX 4.2. Using alkanes to determine feed intake of lambs fed forages. | 415 |
| APPENDIX 4.3. Average dry matter content (DM), percentage of sulla fed, and composition (% of DM) of the seven diets offered to lambs over eight weeks. | 423 |
| APPENDIX 4.4. Liveweight-adjusted fat depth at the 11 th and 12 th rib (GR; mm) and eye muscle area (mm ²) ¹ estimated by ultrasound, and carcass GR fat depth and back fat depth of lambs fed seven forage diets over eight weeks. Least-square (LS) means ± SEM are presented. | 424 |
| APPENDIX 4.5. Results from <i>in sacco</i> and <i>in vitro</i> incubations using pasture, white clover, lucerne, sulla and mixtures of pasture:sulla, lucerne:sulla and white clover:sulla fed to lambs in Chapter 4..... | 425 |
| APPENDIX 4.6. Metabolisable energy and protein requirements and supply for lambs fed diets..... | 429 |
| Equations and abbreviations for modelling..... | 430 |
| APPENDIX 5.1. Method for processing plasma to measure cysteine concentration and ³⁵ S-cysteine radioactivity..... | 433 |
| APPENDIX 5.2. Method to determine sulphate concentration (Sinclair and Tavendale, unpublished)..... | 433 |
| APPENDIX 5.3. Method for extraction of tissues..... | 434 |
| APPENDIX 5.4. Method for processing plasma and tissue free pool to measure valine concentration..... | 434 |
| APPENDIX 5.5. Chromatography method to determine concentration of amino acids in plasma and tissue free pool. | 435 |
| APPENDIX 5.6. Results for individual lambs when infused with ³⁵ S-sulphate and ³⁵ S-cysteine. | 437 |
| APPENDIX 5.7. Results for individual lambs when infused with ³ H-valine. | 438 |
| APPENDIX 5.7 continued. Results for individual lambs when infused with ³ H-valine..... | 439 |
| APPENDIX 6.1. Method to measure dry matter content using the microwave..... | 440 |
| APPENDIX 6.2. Method for analysing ammonia concentration of rumen samples..... | 440 |
| APPENDIX 6.3. Example of a SAS programme used to determine digestion parameters..... | 441 |
| APPENDIX 6.4: Example of adjusted SAS programme for maize silage DM and NDF where convergence did not occur. | 443 |

| | |
|--|-----|
| APPENDIX 6.5. Particle size distribution of rumen digesta for individual cows fed P, P:M, P:S and P:M:S ¹ . Data are on a DM basis (g/100 g DM)..... | 445 |
| APPENDIX 6.6. Dry matter (DM) disappearance curves for P, M, S, P:M, P:S and P:M:S incubated <i>in sacco</i> in cows fed P, P:M, P:S and P:M:S ¹ . Each figure summarises data for one forage or mixture when incubated in cows fed each of the four diets. | 446 |
| APPENDIX 6.7. Crude protein (CP) disappearance curves for P, M, S, P:M, P:S and P:M:S incubated <i>in sacco</i> in cows fed P, P:M, P:S and P:M:S ¹ . Each figure summarises data for one forage or mixture when incubated in cows fed each of the four diets. | 448 |
| APPENDIX 6.8. Neutral detergent fibre (NDF) disappearance curves for P, M, S, P:M, P:S and P:M:S incubated <i>in sacco</i> in cows fed P, P:M, P:S and P:M:S ¹ . Each figure summarises data for one forage or mixture when incubated in cows fed each of the four diets..... | 450 |
| APPENDIX 6.9. Net ammonia (NH ₃) production from P, M, S, P:M, P:S, P:M:S incubated <i>in vitro</i> using rumen inoculum from cows fed P, P:M, P:S and P:M:S ¹ . Each figure summarises data for one forage or mixture when incubated using inoculum from each cow-diet. | 452 |
| APPENDIX 6.10. Total volatile fatty acids (VFA) produced when P, M, S, P:M, P:S and P:M:S were incubated <i>in vitro</i> using rumen inoculum from cows fed P, P:M, P:S and P:M:S ¹ . Each figure summarises data for one forage or mixture incubated with inocula from each cow-diet. | 454 |

LIST OF ABBREVIATIONS

| | |
|-----------------|---|
| # | number |
| β | beta |
| μ | micro |
| μmol | micromole |
| ^{35}S | labelled sulphur |
| ^3H | labelled hydrogen |
| A | soluble fraction |
| A:P | acetate:propionate ratio |
| (A+B):P | acetate + butyrate:propionate ratio |
| AA | amino acids |
| ADF | acid detergent fibre |
| ADL | acid detergent lignin |
| B | degradable insoluble fraction |
| Bq | becquerel |
| c. | about |
| CP | crude protein |
| CT | condensed tannin |
| CV | coefficient of variation |
| CW | carcass weight |
| DM | dry matter |
| dpm | disintegrations per minute |
| ED | effective degradability |
| EDTA | ethylene diamine tetra acetic acid |
| EMA | eye muscle area |
| FDG | freeze-dried and ground |
| FSR | fractional synthesis rate |
| FV | feeding value |
| g | gram |
| x g | gravitational field |
| GR | fat depth 11 cm from the mid line of the 11 th and 12 th ribs |
| GT | grazing time |
| h | hour |

| | |
|--------------------|--|
| I | intake |
| i.u | international units |
| i.d | internal diameter |
| IB | herbage intake per bite |
| ILR | irreversible loss rate |
| k | fractional disappearance rate per hour |
| kBq | kilobecquerel (10^3) |
| kg | kilogram |
| kJ | kilojoule |
| L | litre |
| LS means | least-square means |
| LW | liveweight |
| M | maize silage |
| MBq | megabecquerel (10^6) |
| ME | metabolisable energy |
| mg | milligram |
| min(s) | minute(s) |
| MJ | megajoule |
| mL | millilitre |
| mm | millimetre |
| mmol | millimole |
| N | nitrogen |
| n | number |
| NAN | non ammonia nitrogen |
| NDF | neutral detergent fibre |
| NH ₃ | ammonia |
| NH ₃ -N | ammonia nitrogen |
| NIRS | Near InfraRed Spectroscopy |
| nmol | nanomole |
| NV | nutritive value |
| o.d | outside diameter |
| °C | degree celcius |
| OM | organic matter |
| OMD | organic matter digestibility |
| P | pasture |

| | |
|-----------------|--|
| PD | potential degradability |
| P:M | pasture:maize silage |
| P:M:S | pasture:maize silage:sulla |
| P:S | pasture:sulla |
| Pr | probability |
| r | correlation coefficient |
| RB | rate of biting |
| REML | residual maximum likelihood |
| RFC | rapidly fermentable carbohydrates |
| S | sulla |
| SC | soluble carbohydrate |
| SD | standard deviation |
| SDS | sodium dodecyl sulphate |
| SEM | standard error of the means |
| SO ₄ | sulphate |
| <i>Sp(p)</i> | species |
| SRA | specific radioactivity |
| SS | sulla silage |
| t DM/ha/yr | tonnes dry matter per hectare per year |
| t | incubation time |
| TBq | Terabecquerel (10 ¹²) |
| TMR | total mixed ration |
| TQ | transfer quotient |
| UDP | undegraded protein |
| US | United States |
| VFA | volatile fatty acids |
| VFI | voluntary feed intake |
| vs. | versus |
| w/v | weight to volume |
| WBPS | whole body protein synthesis |
| WC | white clover |
| x M | maintenance feeding |

LIST OF PUBLICATIONS

Publications produced from this thesis.

- Burke, J.L.; Waghorn, G.C.; Brookes, I.M.; Attwood, G.T.; Kolver, E.S. 2000. Formulating total mixed rations from forages – defining the digestion kinetics of contrasting species. *Proceedings of the New Zealand Society of Animal Production* 60: 9-14.
- Waghorn, G.C.; Burke, J.L. 2001. Screening fresh forages for protein degradation and nutritive value. *XIX International Grasslands Congress, University of Sao Paulo, Brazil*: 420-421.
- Burke, J.L.; Waghorn, G.C.; Barrell, L.G.; Brookes, I.M.; Attwood, G.T.; Kolver, E.S. 2001. Using *in sacco* and *in vitro* incubations to determine the digestion and fermentation kinetics of fresh forages. Joint meeting of the American Dairy Science Association. Abstract 921, Pp 921.
- Burke, J.L.; Waghorn, G.C.; Brookes, I.M. 2002. An evaluation of sulla (*Hedysarum coronarium*) with pasture, white clover and lucerne for lambs. *Proceedings of the New Zealand Society of Animal Production* 62: 152-156.
- Burke, J.L.; Waghorn, G.C. Chaves, A.V. 2002. Improving animal performance using forage-based diets. *Proceedings of the New Zealand Society of Animal Production* 62: 267-272.
- Burke, J.L. 2003. Economic use of complementary feeds in dairy grazing systems. *Proceedings of the Dairy³ Conference* 1: 153-164.
- Burke, J.L.; Waghorn, G.C.; McNabb, W.C.; Brookes, I.M. 2004. The potential of sulla in pasture-based systems. *Proceedings of the Australian Society of Animal Production*: in press.