

BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Improving grassland and pasture management in temperate agriculture

Edited by Professor Athole Marshall & Dr Rosemary Collins
IBERS, Aberystwyth University, UK



Contents

Series list	xi
Introduction	xvi

Part 1 Grassland functions and dynamics

1	The role of grasslands in biogeochemical cycles and biodiversity conservation <i>O. Huguenin-Elie, Agroscope, Switzerland; L. Delaby and K. Klumpp, INRA, France; S. Lemauiel-Lavenant, INRA and Université de Caen Normandie, France; and J. Ryschawy and R. Sabatier, INRA, France</i>	3
	1 Introduction	3
	2 Biogeochemical cycles	4
	3 Grassland biodiversity at the plot scale	10
	4 Grassland roles in biodiversity conservation at the landscape scale	13
	5 Future trends and conclusion	17
	6 References	18
2	The role of pasture in the diet of ruminant livestock <i>Michael R. F. Lee, University of Bristol and Rothamsted Research, UK; M. Jordana Rivero, Rothamsted Research, UK; and John W. Cone, Wageningen University, The Netherlands</i>	31
	1 Introduction	31
	2 Energy	34
	3 Proteins	40
	4 Minerals and vitamins	42
	5 Other nutritional factors	45
	6 Anti-nutritional factors	46
	7 Future trends and conclusion	48
	8 Acknowledgement	49
	9 Where to look for further information	49
	10 References	49
3	Plant–animal interactions in grazing systems <i>D. F. Chapman, DairyNZ Lincoln, New Zealand; and W. M. Griffiths, Hamilton, New Zealand</i>	55
	1 Introduction	55
	2 Control of dry matter intake: pasture offered and herbage nutritive value	58
	3 Control of DMI: managing sward canopy structure	62
	4 Sward canopy structure: systems factors	64
	5 Future trends	67
	6 Conclusions	71
	7 Where to look for further information	71
	8 Acknowledgements	72
	9 References	72

4	Grazing management for sustainable grazing systems	79
	<i>Lilian Elgalise Techio Pereira and Sila Carneiro da Silva, Universidade de São Paulo, Brazil; Cory Matthew and Ignacio F. López, Massey University, New Zealand; and André Fischer Sbrissia, Universidade do Estado de Santa Catarina, Brazil</i>	
	1 Introduction	79
	2 Definitions and concepts of grazing management	82
	3 Growth dynamics in grazed swards	89
	4 Effects of grazing on soil C and N stocks	101
	5 Defining targets for grazing management	106
	6 Mapping future evolution of grassland ecosystems	107
	7 Conclusion	110
	8 Where to look for further information	111
	9 References	112
Part 2 Management of grasslands		
5	Planning and sowing grasslands	125
	<i>David B. Hannaway and Linda J. Brewer, Oregon State University, USA; Steve Fransen, Washington State University, USA; and Glenn Shewmaker, Shannon Williams and Sarah Baker, University of Idaho, USA</i>	
	1 Planning	125
	2 Species and cultivar selection: overview	127
	3 Species and cultivar characteristics: tolerances	129
	4 Species and cultivar characteristics: further characteristics	145
	5 Establishment and renovation: initial considerations	153
	6 Sowing and initial management	157
	7 Key issues in improving forage selection	161
	8 Review of existing selection tools	164
	9 Future trends	168
	10 References	168
6	Managing grassland for forage production: an overview	171
	<i>Deirdre Hennessy, Teagasc, Ireland</i>	
	1 Introduction	171
	2 Stocking rate	172
	3 Grazing management	173
	4 Reseeding/sward renovation	177
	5 Silage	180
	6 Feeding value of grass	181
	7 Where to look for further information	182
	8 References	183
7	Managing grassland systems to optimise livestock production	189
	<i>J. L. Peyraud, L. Delaby and R. Delagarde, INRA-Agrocampus Ouest, France</i>	
	1 Introduction	189
	2 Appropriate cows for successful temperate-grassland-based systems	191
	3 Appropriate grazing management for successful temperate-grassland-based systems	193

4	Appropriate forage production for successful temperate-grassland-based systems	200
5	Decision support systems (DSSs) to develop efficient grassland-based dairy systems	204
6	Future trends	210
7	Where to look for further information	211
8	References	211
8	Persistence and yield stability of temperate grassland legumes for sustainable animal production <i>F. Ortega, L. Inostroza and C. Moscoso, Instituto de Investigaciones Agropecuarias, Chile; and L. Parra and A. Quiroz, Universidad de La Frontera, Chile</i>	219
1	Introduction	219
2	Global cultivation of forage legumes	220
3	Improving red clover persistence	222
4	Abiotic stresses affecting plant persistence	226
5	Future trends and conclusion	230
6	Where to look for further information	230
7	Acknowledgements	231
8	References	231
9	Balancing pasture productivity with environmental and animal health requirements <i>D. R. Woodfield, Grasslands Research Centre, New Zealand; and H. G. Judson, Kimihia Research Centre, New Zealand</i>	237
1	Introduction	237
2	Nutritive value	238
3	Reduced nutrient loss	240
4	Greenhouse gas mitigation	243
5	Genetic resources	245
6	Animal health and welfare challenges	246
7	Future trends	248
8	Where to look for further information	248
9	References	249
10	Managing soil health for grassland <i>D. Barker, The Ohio State University, USA</i>	253
1	Introduction	253
2	Measurement of soil health	254
3	Managing soil health for grassland production	256
4	Fertilization for carbon (C) sequestration	257
5	Earthworms as an indicator of soil health	258
6	Soil nutrient status	258
7	Trace elements and heavy metals	259
8	Conclusion	261
9	Future trends	262
10	Where to look for further information	262
11	References	263

11	Management of water resources for grasslands	265
	<i>Jean L. Steiner, Pradeep Wagle and Prasanna Gowda, Grazing Lands Research Laboratory – USDA-ARS, USA</i>	
	1 Introduction	265
	2 Water requirements of temperate pastures	267
	3 Factors affecting soil health	268
	4 Monitoring and modelling grassland vegetation and water use	270
	5 Impact of drought on grasslands	273
	6 Drought monitoring methods	274
	7 Global climate change impacts on grasslands	276
	8 Water resources management in grasslands	277
	9 Future trends and where to find further information	277
	10 References	278
12	Biological weed control in temperate grasslands	283
	<i>Graeme W. Bourdôt and Michael G. Cripps, AgResearch Limited, New Zealand</i>	
	1 Introduction	283
	2 Classical biological control of weeds	286
	3 Prospects for classical biological weed control in temperate pastures	299
	4 Biological herbicides	300
	5 Future trends	311
	6 Conclusion	311
	7 Where to look for further information	312
	8 References	313
13	Restoring degraded grasslands	325
	<i>Llewellyn L. Manske, North Dakota State University, USA</i>	
	1 Introduction	325
	2 Grass plant responses to defoliation	327
	3 Agronomic practices to increase soil nitrogen levels	330
	4 Effects of rhizosphere organisms on biogeochemical processes	331
	5 Grazing graminivores	332
	6 Management of grazing	333
	7 Degradation of grasslands	334
	8 Initial changes of restoration	340
	9 Future trends and conclusion	345
	10 Where to look for further information	345
	11 Acknowledgement	346
	12 References	346
14	Advances in remote sensing for monitoring grassland and forage production	353
	<i>Michael Wachendorf, University of Kassel, Germany</i>	
	1 Introduction	353
	2 Technical principles of the most common sensors	353
	3 Vegetation characteristics which can be monitored by remote sensing	355
	4 Summary	358
	5 Future trends	359
	6 Where to look for further information	359
	7 References	359

Part 3 Sustainability and wider uses of grasslands

15	Research challenges in adapting grasslands to climate change	365
	<i>Richard Kipling, Aberystwyth University, UK</i>	
	1 Introduction	365
	2 Climate change impacts and challenges	366
	3 External context and the adaptiveness of European grassland systems	368
	4 Case studies of climate change impacts and adaptation options	369
	5 Challenges, limitations and priorities for research	371
	6 Conclusion	374
	7 Where to look for further information	374
	8 References	375
16	Protecting biodiversity in grasslands	381
	<i>J. Isselstein, University of Göttingen, Germany</i>	
	1 Introduction	381
	2 Grassland biodiversity under pressure	382
	3 Critical factors in grassland biodiversity	384
	4 Maintaining biodiversity through grassland management	387
	5 Integration of species-rich grasslands into modern livestock production systems	389
	6 Conclusion	392
	7 Where to look for further information	393
	8 References	393
17	Advances in feeding grass silage	397
	<i>Pekka Huhtanen, Swedish University of Agricultural Sciences, Sweden</i>	
	1 Introduction	397
	2 Energy value and nutrient supply from grass silages	398
	3 Effects of ensiling on silage protein value	400
	4 Silage intake	404
	5 Supplementing grass silage diets: energy supplements	407
	6 Supplementing grass silage diets: protein supplements	411
	7 Round bale silages	415
	8 Future trends and conclusion	417
	9 Where to look for further information	419
	10 References	419
18	Use of grassland for bioenergy and biorefining	425
	<i>Ulrich Thumm, University of Hohenheim, Germany</i>	
	1 Introduction	425
	2 Grassland biomass and biomass quality	426
	3 Alternative uses for biomass from permanent grassland	427
	4 Prospects for using grasslands for bioenergy	431
	5 Conclusions	432
	6 Where to look for further information	433
	7 References	433

19 Organic grassland	437
<i>Thomas F. Döring and Ulrich Köpke, University of Bonn, Germany</i>	
1 Introduction	437
2 Key characteristics of organic grassland	438
3 Multifunctionality of organic grassland	440
4 Challenges in organic grassland	446
5 Case studies	451
6 Conclusions and future trends	453
7 Where to look for further information	454
8 References	454
Index	461

Introduction

Global demand for livestock products continues to increase as a consequence of population growth, changes in consumer preferences and income levels. Increased efficiency of food production to meet consumer demand must also focus on reducing the environmental impact of production and for the livestock sector there is also growing interest in the quality and traceability of products. In many countries, increasing demands on land use (production of food, fuel, industrial use, leisure) mean that its use for food production must compete with other land uses, and this has major implications for the grassland sector.

Improving the sustainable production of livestock products is a recurring research theme among grassland scientists, and provides many challenges but also opportunities for the grassland sector. These include increasing the utilisation of grasslands to improve nutritional quality for livestock production, increasing sustainability by using fewer inputs, and reducing the greenhouse gas emissions associated with agricultural production. Balancing these “traditional” objectives with delivery of ecosystem services and opportunities for exploiting grasslands for energy use is also required.

This volume reviews a range of research on the sustainable use of grasslands to optimise livestock nutrition whilst protecting biodiversity and delivering a range of broader environmental benefits. It assesses the latest research on how temperate grasslands function, surveys best practice in sustainable grassland management and considers wider aspects of sustainability, such as the maintenance of ecosystem services and biodiversity.

Part 1 Grassland functions and dynamics

The first part of the volume assesses grassland functions and dynamics, including plant-soil and plant-animal interactions, nutrient cycling and carbon capture.

The focus of Chapter 1 is the multifunctional role of grasslands in producing forage for animal production systems while providing a wide array of ecosystem services, including the regulation of biogeochemical cycles and the maintenance of biodiversity. The chapter provides an overview of current knowledge on the roles of grasslands in regulating the carbon (C) and nitrogen (N) cycles and conserving biodiversity and how the environmental roles of grasslands are driven by nutrient management, frequency and timing of grazing, the lifespan of the grasslands and their position and diversity in the landscape. The chapter also explains how different grassland types are necessary to target the services of food production, carbon storage in soils, regulation of the N cycle and biodiversity conservation at different levels of grassland intensification.

Chapter 2 moves on to examine the role of pasture in the diet of ruminant livestock. Grazed pasture is the single most important forage feed for ruminants due to its low unit cost and widespread global availability. The chapter describes how grazed pasture provides the energy, proteins, minerals and vitamins and other nutritional factors required by ruminants. It shows how the use of pasture and its by-products underpins the sustainable delivery of future ruminant livestock production systems and ensures its role in food security. Complementing the previous chapter's concentration on ruminant livestock, Chapter 3 examines plant-animal interactions in grazing systems. These interactions drive system performance. Central to this is the dry matter intake of animals grazing pasture, and the various factors influencing this are reviewed in detail.

Chapter 4 considers the principles of grazing management for sustainable grazing systems. As noted in Chapter 1, grasslands play a key role in soil, water and biodiversity conservation and deliver numerous other ecosystem and cultural services. The chapter defines and discusses key terms and strategies associated with sustainable grazing management and outlines current knowledge regarding major effects of grazing management on above- and below-ground plant responses.

Part 2 Management of grasslands

The second part of the volume reviews key aspects of grassland management, including strategies for sowing, soil health, irrigation and weed control.

Opening Part 2, Chapter 5 examines the planning and sowing of grasslands. The chapter provides an overview of species and cultivar selection, as well as the specific tolerances of different species and cultivars, along with other characteristics. The chapter then moves on to look at initial considerations to be taken into account with the establishment and renovation of grasslands and best practice for the sowing and initial management.

Chapter 6 focuses on grazing systems by providing an overview of grassland management for forage production. In temperate agriculture, grasslands play an important role in the provision of forage for livestock, and appropriate management of grassland is vital to ensure that high quality feed is available. The chapter reviews the short, medium and long term management of grasslands, including stocking rates, the day-to-day management of grazing and harvesting, planning for rotations and silage harvesting, renovation, drainage, reseeding and soil fertility improvement.

Chapter 7 turns to the theme of managing grassland systems to optimise livestock farming. High milk prices have encouraged intensive dairying systems using high inputs of chemical fertilizers, indoor feeding with high amounts of concentrate and imported protein at the expense of grazing. Consequently, grassland acreage has decreased considerably over the last 30 years and European dairy systems have become highly dependent on imported fossil energy and proteins. However, the various roles of grassland in providing regulating and supporting services are now widely recognized and grazing ruminants are highly appreciated by the public. The chapter reviews existing knowledge and tools for developing productive, efficient and environmentally-friendly dairying systems based on grazing and grassland utilisation.

Chapter 8 examines the use of temperate grassland legumes for sustainable animal production. Forage legumes can play a key role here, but their positive environmental and economic effects can only be realized if they also show persistence and yield stability. These are complex traits which depend on the interaction of different biotic and abiotic environmental factors with the genetic background of the sown species/cultivar. The chapter surveys the global cultivation of forage legumes and considers important challenges to achieving persistence and yield stability. It includes a case study on the improvement of persistence in red clover by recurrent selection, and then discusses physiological studies on drought stress tolerance in white clover and broad-leaved birdsfoot trefoil.

Building on the insights of Chapter 8, Chapter 9 looks at efforts to develop new varieties of grasses and legumes. It highlights the challenge plant breeders face in developing high performing forage cultivars that maintain the profitability of temperate grassland farming systems while reducing the environmental footprint and taking account of animal health issues.

The subject of Chapter 10 is the challenge of managing soil health for grasslands. Soil health is a holistic concept that includes all the processes affecting the ability of soil to provide the ecosystem services required from grassland. The primary 'service' provided by grassland is forage for livestock production, but increasingly, scientists recognize a diverse suite of other 'benefits' such as effects on fauna and flora, avoiding off-site impacts, and many aesthetic qualities.

Chapter 11 looks at the management of water resources for grasslands. Grasslands support essential food and fiber production, biodiversity, and water function and other ecosystem services. Planted or native grasslands are typically located on drier, steeper, or less fertile areas of any region. The chapter discusses the topics of water requirements of temperate pastures, monitoring and modeling grassland vegetation and water use, drought monitoring and water resources management in grasslands.

Shifting the focus from the needs of grasslands to dealing with threats to their survival, Chapter 12 examines biological weed control in temperate grasslands. The chapter identifies the constraints to, and opportunities for, the effective biological control of weeds in the world's temperate grasslands.

Picking up issues from Chapters 3 and 4, the subject of Chapter 13 is restoring degraded grasslands. Grazed grasslands are complex ecosystems, and careful and responsible management is essential for their growth and maintenance. The chapter examines the inter-relationship of species, microbial activity, nutrients and environmental factors in restoring and maintaining their health, sustainability and productivity. It also outlines the key factors in restoration of degraded grasslands, such as promoting both the ecosystem's biogeochemical processes and physiological mechanisms in grasses that gradually alter grassland species composition.

The final chapter of the section, Chapter 14, examines advances in remote sensing (RS) for monitoring grassland and forage production. Achieving cheap, appropriate and timely information on vegetation will be essential for sustainable and economically viable management of grassland in the future. RS offers new possibilities to monitor vegetation repeatedly and at large scale. The chapter describes the most important sensor types, reviews recent developments in sensor performance and significant advances for grassland research and practice.

Part 3 Sustainability and wider uses of grasslands

The third and final part of the book considers wider aspects of sustainability such as protecting biodiversity as well as silage processing.

The focus of Chapter 15 is research challenges in adapting grasslands to climate change. Climate change poses many challenges to European grasslands, from droughts, heatwaves and changing precipitation patterns in the south, to warmer winters and wetter summers in the north and increasing frequency of extreme weather events. The chapter reviews the probable impacts of climate change and associated challenges and the adaptiveness of European grassland systems. The chapter includes a number of detailed case studies of climate change impacts and adaptation options from Finland, Italy and Austria and considers the challenges and limitations for climate change mitigation in grasslands and priorities for research.

Chapter 16 looks at issues associated with the protection of biodiversity in grasslands. The chapter summarises the conditions that facilitate biodiversity in permanent and semi-natural grasslands in temperate climates, explaining and giving examples of losses in the biodiversity of managed grasslands in recent decades. It describes some of the main factors influencing biodiversity, leading to discussion of appropriate management measures and how these might be integrated into livestock production systems.

Moving on to new developments in the uses of grasslands, Chapter 17 examines advances in feeding grass silage, the main forage source during indoor feeding periods in many temperate regions. The chapter reviews research on factors affecting nutrient supply from the digestive tract in animals fed a grass silage-based diet and the effects of energy and protein supplementation on production responses, taking into account nitrogen and methane emissions. It also highlights recent developments in the big bale system that has become popular especially in Northern Europe.

Continuing the theme of the use of grasslands for new purposes, Chapter 18 deals with the use of grassland for bioenergy and biorefining. The chapter reviews grassland types, categorizing them according to their potential for biomass production. It details options for the use of grassland biomass, and covers biogas, combustion, pyrolysis and gasification, enzymatic hydrolysis and fermentation to ethanol, and biorefining and future prospects for the use of grassland biomass in bioenergy applications.

The book's final chapter, Chapter 19, looks at the particular challenges associated with organic grassland. After considering the key characteristics of organic grassland, the chapter examines its multifunctionality and specific challenges, offering two detailed case studies which deal with the diversification of organic leys in Great Britain and skylark protection on organic grassland in Brandenburg, Germany.

We would like to express our sincere thanks to the authors. We hope this book contributes to a greater understanding of the complexities involved in managing grassland and a wider appreciation of its great value to society as a whole.

Index

- Abiotic stresses 226–229
- Advances in feeding grass silage
 - effects of ensiling 400–404
 - microbial protein 400–402
 - milk production responses 402–404
 - rumen undegraded protein 402
 - energy value and nutrient supply 398–399
 - overview 397–398
 - round bale silages 415–417
 - silage intake 404–407
 - supplement silage diets 407–410
 - protein 411–415
 - types 410
- Agronomic practices to increase nitrogen levels 330–331
- Alternative biomass 427–431
 - biogas 427–429
 - biorefining 430–431
 - combustion 429
 - enzymatic hydrolysis 430
 - fermentation to ethanol 430
 - pyrolysis and gasification 429–430
- Animal behaviour 62–63
- Animal health and welfare challenges 246–248
- Anti-nutritional factors 46–48
- Australia 164–165
 - CSIRO 165
 - Daily Australia 165
 - Grassland Society of Victoria 164
 - University of Melbourne 164
- Biocontrol improvement 293–297
- Biocontrol integration
 - grazing 298–299
 - herbicides 297–298
- Biodiversity maintenance 387–389
- Biodiversity protection
 - biodiversity maintenance 387–389
 - biodiversity under pressure 382–384
 - critical factors 384–387
 - overview 381–382
 - species-rich grasslands to modern livestock 389–392
- Biodiversity under pressure 382–384
- Bioenergy and biorefining
 - alternative biomass 427–431
 - biogas 427–429
 - biorefining 430–431
 - combustion 429
 - enzymatic hydrolysis 430
 - fermentation to ethanol 430
 - pyrolysis and gasification 429–430
 - biomass quality 426–427
 - overview 425–426
 - prospects for bioenergy 431–432
 - limitations 431–432
 - opportunities 432
- Biogas 427–429
- Biogeochemical cycles 4–10
 - carbon sequestration 4–7
 - nitrogen cycle 7–10
 - soil matter 4–7
- Biogeochemical cycles and biodiversity conservation
 - biogeochemical cycles 4–10
 - carbon sequestration 4–7
 - nitrogen cycle 7–10
 - soil matter content 4–7
 - landscape scale biodiversity conservation 13–18
 - grassland types 14–16
 - mixed crop-livestock 13–14
 - sylvopastoral 13–14
 - overview 3–4
 - plot scale biodiversity 10–13
 - management practices impacts 11–12
 - shaping vegetation affect animal biodiversity 12–13
- Biological control success 293–297
 - effective biocontrol agents 293–296
 - suitable target weeds 296–297
- Biological herbicides 300–311
- Biological weed control
 - classic biological control 286–299
 - biocontrol improvement 293–297
 - biocontrol integration 297–299
 - biological control success 286–293
 - herbicides 300–311
 - S. sclerotiorum* 306–311
 - overview 283–286
 - prospects of weed control 299–300
- Biomass 355–357
 - quality 426–427
- Biorefining 430–431
- Breeding 63–64
- C sequestration fertilization 257–258
- C:N ratio 101–102
- Cadmium 261
- Classic biological control 286–299
 - biocontrol improvement 293–297
 - biological control success 286–293
- Cobalt 260
- Combination of technology 162–164
- Combustion 429
- Compensatory physiological mechanism 328
- Comprehensive species 161–162
- Continuous stocking 94–101
- Cornell University 167

- Cows for temperate-grassland based system 191–193
 - dual purpose breeds 193
 - genetic merit 191
 - ideal cow 193
 - improved cow fertility for efficient dairy 191–192
 - increased milk yield 191
- CSIRO 165
- Cultivar characteristics 145–153
 - establishment and persistence 145–146
 - forage mixtures 151–152
 - growth habitat 146–147
 - seasonal growth profiles 147–151
 - seed quality 153
- Cultivar characteristics database 161–162
- Daily Australia 165
- Data and expertise sharing 162
- Decision support system (DSS) 204–210
 - grazing system over season 207–210
 - herbage intake and milk yield 195–197
- Degraded grassland restoration
 - grassland degradation 334–340
 - effects of fire 340
 - seventy-five years of non-grazing 335–339
 - grazing graminivores 332–333
 - grazing management 333–334
 - twice-over rotation 334
 - initial changes 340–345
 - overview 325–328
 - plant responses to defoliation 327–330
 - compensatory physiological mechanism 328
 - nutrient resource uptake 329–330
 - soil mineral nitrogen threshold level 330
 - vegetative reproduction by tillering 328–329
 - rhizosphere organisms effects on biogeochemical process 331–332
- Degraded grasslands restoration
 - agronomic practices to increase nitrogen levels 330–331
- Dietary diversity 65–66
- DMI control 62–64
 - animal behaviour 62–63
 - breeding 63–64
 - plant selection 63–64
 - sward management factors 62–63
- Drought monitoring methods 274–276
 - early warning systems 275–276
 - remote sensing methods 274–275
 - traditional methods 274
- Dry matter intake 58–62
 - herbage nutritive value 60–62
 - pasture 58–60
- Dynamic farm level 209–210
- Early warning systems 275–276
- Earthworm, indicator of soil health 258
- Effective biocontrol agents 293–296
- Effects of ensiling 400–404
 - microbial protein 400–402
 - milk production responses 402–404
 - rumen undegraded protein 402
- Effects of grazing on soil 101–106
 - C:N ratio 101–102
 - SOC and SON stocks 102–106
 - SOM 101
- Efficacy 309–310
- Energy value and nutrient supply 398–399
- Environment and animal health requirements
 - animal health and welfare challenges 246–248
 - genetic resources 245–246
 - germplasm collection 246
 - interspecific hybrids 245–246
 - new species 245–246
 - greenhouse gas mitigation 243–245
 - nutrient loss 240–243
 - nitrogen leaching 241
 - nitrogen uptake 240–241
 - pasture legume uses 241–243
 - overview 237–238
- Environmental consideration 66–67
- Environmental safety 308–309
- Enzymatic hydrolysis 430
- Establishment and renovation 153–157
 - new plantings 153–154
 - pasture improvement 153
 - seedbed preparation 155–157
 - seeding time 155
 - soil testing 154
- Extended grazing 174
- External content and adaptiveness 368
- Factors affecting soil health 268–269
 - burning 269
 - fertilization 269
 - grazing or biomass removal 268–269
- Feed value of grass 181–182
- Fermentation to ethanol 430
- Forage mixtures 151–152
- Forage production
 - feed value of grass 181–182
 - grazing management 173–177
 - extended grazing 174
 - infrastructure 173–174
 - on/off grazing 174
 - seasonal grazing 175–177
 - tools and decision support systems 174–175
 - multispecies sward for sustainable intensification 202–204
 - N fertilization key role 200–202
 - overview 171–172

- reseeding/sward renovation 177–180
 - methods 177–178
 - species and cultivar choice 179–180
 - time 178–179
- silage 180–181
- stock rate 172–173
- Forage quality 357
- Forage selection key issues 161–164
 - combination of technology 162–164
 - comprehensive species 161–162
 - cultivar characteristics database 161–162
 - sharing data and expertise 162
- Genetic resources 245–246
 - germplasm collection 246
 - interspecific hybrids 245–246
 - new species 245–246
- Genetic variation 310–311
- Germplasm collection 246
- Global climate change impacts 276–277
- Global cultivation 220–221
- Grass budget approach 208–209
- Grass morphology 89–90
- Grassland degradation 334–340
 - seventy-five years of non-grazing 335–339
- Grassland ecosystem future mapping 107–110
 - context-specific solution 107–108
 - grazing tactics 110
 - identify and capture knowledge 109
 - integrate multiple dimensions 108–109
 - plant functional traits 109–110
- Grassland Society of Victoria 164
- Grasslands degradation 334–340
 - effects of fire 340
- Grazing for temperate-grassland based system 193–200
 - feeding concentrate 198–200
 - herbage allowance 194–195
 - herbage availability effects 195–197
 - maximum utilization of grassland 197–198
- Grazing graminivores 332–333
- Grazing management 173–177, 333–334
 - extended grazing 174
 - infrastructure 173–174
 - on/off grazing 174
 - seasonal grazing 175–177
 - tools and decision support system 174–175
 - twice-over rotation 334
- Grazing management concepts 82–89
 - grassland and livestock intensification 82–84
 - grazing methods and management 84–86
 - intensity 86–87
 - sward targets 87–89
- Grazing system over season
 - dynamic farm level 209–210
 - grass budget approach 208–209
 - historical approaches 207–208
- Greenhouse gas mitigation 243–245
- Growth dynamics 89–101
 - below ground responses 96–101
 - continuous stocking 94–101
 - grass morphology 89–90
 - rotational stocking 90–94
- Growth habitat 146–147
- Herbage intake and milk yield 195–197
- Herbage nutritive value 60–62
- Host range 307–308
- Impacts of drought 273–274
- Interspecific hybrids 245–246
- Ireland 165–166
 - The Agriculture and Food Development Authority 165–166
 - Teagasc 165–166
- Landscape scale biodiversity conservation 13–18
 - grassland types 14–16
 - mixed crop livestock 13–14
 - sylvopastoral 13–14
- Lead 260–261
- Leaf morphology 90–91
- Light detection and ranging 355
- Livestock production
 - cows for temperate-grassland based system 191–193
 - dual purpose breeds 193
 - genetic merit 191
 - ideal cow 193
 - improved cow fertility for efficient dairy 191–192
 - increased milk yield 191
 - decision support system (DSS) 204–210
 - grazing system over season 207–210
 - herbage intake and milk yield 204–207
 - forage production 200–204
 - multispecies swards for sustainable intensification 202–204
 - N fertilisation key role 200–202
 - grazing for temperate-grassland based system 193–200
 - feeding concentrate 198–200
 - herbage allowance 194–195
 - herbage availability effects 195–197
 - maximum utilisation of grassland 197–198
 - overview 189–190
- Microbial protein 400–402
- Milk production responses 402–404
- Minerals 42–45
- Monitoring and modelling 270–273
 - soil moisture 271
 - vegetation dynamics 270–271
 - water use 272–273

- New plantings 153–154
- New Zealand 166
- Nutrient loss 240–243, 446–449
 - nitrogen leaching 241
 - nitrogen uptake 240–241
 - pasture legume uses 241–243
- Nutrient resource uptake 329–330
- Nutritional factors 45–48

- Oregon State University 167–168
- Organic grasslands
 - case study 451–453
 - challenges 446–451
 - nitrogen loss 446–449
 - perennial weeds 449–450
 - seed 450–451
 - key characteristics 438–439
 - multifunctionality 440–446
 - biodiversity 444–445
 - crops 441–443
 - environmental impact 445–446
 - livestock 443–444
 - notion 440
 - soil 440–441
 - overview 437–438
- Pasture improvement 153
- Pasture legume uses 241–243
- Penn State University 167
- Perennial weeds 449–450
- Persistence and yield stability for animal production
 - abiotic stresses 226–229
 - global cultivation 220–221
 - overview 219–220
 - red clover persistence 221–226
- Planning and sowing
 - establishment and renovation 153–157
 - new plantings 153–154
 - pasture improvement 153
 - seedbed preparation 155–157
 - seeding time 155
 - soil testing 154
 - forage selection key issues 161–164
 - combination of technology 162–164
 - comprehensive species 161–162
 - cultivar characteristics database 161–162
 - sharing data and expertise 162
 - planning 125–127
 - sowing and initial management 157–161
 - species and cultivar selection 127–129
 - characteristics 145–153
 - tolerances 129–145
 - tool selection review 164–168
 - Australia 164–165
 - Ireland 165–166
 - New Zealand 166
 - United States 166–168
- Plant responses to defoliation 327–330
 - compensatory physiological mechanism 328
 - nutrient resource uptake 329–330
 - soil mineral nitrogen threshold level 330
 - vegetative reproduction by tillering 328–329
- Plant selection 63–64
- Plant-animal interaction
 - DMI control 62–64
 - animal behaviour 62–63
 - breeding 63–64
 - plant selection 63–64
 - sward management factors 62–63
 - dry matter intake 58–62
 - herbage nutritive value 60–62
 - pasture 58–60
 - overview 55–58
 - sward canopy structure 64–67
 - dietary diversity 65–66
 - environmental consideration 66–67
- Plot scale biodiversity 10–13
 - management practices impacts 11–12
 - shaping vegetation affect animal biodiversity 12–13
- Proteins 40–41
 - fibre 37–38
 - lipids 38–40
 - water-soluble carbohydrates 34–37
- Pyrolysis and gasification 429–430

- Recovery from defoliation 91–92
- Red clover persistence 221–226
- Remote sensing advances
 - overview 353
 - technical principles of common sensors 353–355
 - light detection and ranging 355
 - photography 354
 - sensor combinations 355
 - spectrometry and spectral image 354
 - ultrasound 355
 - vegetative characteristics monitored by remote sensing 355–358
 - biomass 355–357
 - forage quality 357
 - species identification and diversity 357–358
- Remote sensing methods 274–275
- Research challenges in adapting climate change
 - case study 369–371
 - external content and adaptiveness 368
 - impacts 367–368
 - limitations and priorities 371–374
 - data 371
 - model capacity 371–372
 - topics and disciplines 372–373
 - transdisciplinary approaches 373–374
 - overview 365–367
- Reseeding/sward renovation 177–180

- methods 177–178
 - species and cultivar choice 179–180
 - time 178–179
- Rhizosphere organisms' effects on
 - biogeochemical process 331–332
- Rotational stocking 90–94
 - leaf morphology 90–91
 - recovery from defoliation 91–92
 - shoot architecture 92–94
- Round bale silages 415–417
- Rumen undegraded protein 402
- Ruminant livestock diet
 - anti-nutritional factors 46–48
 - minerals 42–45
 - nutritional factors 45–48
 - overview 31–34
 - proteins 40–41
 - fibre 37–38
 - lipids 38–40
 - water-soluble carbohydrates 34–37
 - vitamins 42–45
- S. sclerotiorum* 306–311
 - efficacy 309–310
 - environmental safety 308–309
 - genetic variation 310–311
 - host range 307–308
- Seasonal grazing 175–177
- Seasonal growth profiles 147–151
- Seed quality 153
- Seedbed preparation 155–157
- Seeding time 155
- Sensor combinations 355
- Shoot architecture 92–94
- Silage 180–181
 - intake 404–407
- SOC and SON stocks 102–106
- Soil
 - health measurement 254–256
 - mineral nitrogen threshold level 330
 - moisture 271
 - nutrient status 258–259
 - testing 154
- Soil health for grassland production 256–257
- Soil health management
 - C sequestration fertilization 257–258
 - earthworm, indicator of soil health 258
 - overview 253–254
 - soil health for grassland production 256–257
 - soil health measurement 254–256
 - soil nutrient status 258–259
 - trace elements and heavy metals 259–261
 - cadmium 261
 - cobalt 260
 - lead 260–261
- SOM 101
- Sowing and initial management 157–161
- Species and cultivar choice 179–180
- Species and cultivar selection 127–129
 - characteristics 145–153
 - tolerances 129–145
- Species identification and diversity 357–358
- Species-rich grasslands to modern
 - livestock 389–392
- Spectrometry and spectral image 354
- Stock rate 172–173
- Suitable target weeds 296–297
- Supplement silage diets 407–410
 - protein 411–415
 - types 410
- Sustainable grazing management
 - effects of grazing on soil 101–106
 - C:N ratio 101–102
 - SOC and SON stocks 102–106
 - SOM 101
 - grassland ecosystem future mapping 107–110
 - context-specific solution 107–108
 - grazing tactics 110
 - identify and capture knowledge 109
 - integrate multiple dimensions 108–109
 - plant functional traits 109–110
 - grazing management concepts 82–89
 - grassland and livestock intensification 82–84
 - grazing methods and management 84–86
 - intensity 86–87
 - sward targets 87–89
 - growth dynamics 89–101
 - below ground responses 96–101
 - continuous stocking 94–101
 - grass morphology 89–90
 - rotational stocking 90–94
 - overview 79–82
 - targets 106–107
- Sward canopy structure 64–67
 - dietary diversity 65–66
 - environmental consideration 66–67
- Sward management factors 62–63
- Teagasc 165–166
- Technical principles of common sensors 353–355
 - light detection and ranging 355
 - photography 354
 - sensor combinations 355
 - spectrometry and spectral image 354
 - ultrasound 355
- Temperate pastures water requirements 267–268
- The Agriculture and Food Development Authority 165–166
- Tool selection review 164–168
 - Australia 164–165
 - Ireland 165–166

- New Zealand 166
- United States 166–168
- Tools and decision support system 174–175
- Trace elements and heavy metals 259–261
 - cadmium 261
 - cobalt 260
 - lead 260–261
- Traditional methods 274
- Ultrasound 355
- United States 166–168
 - Cornell University 167
 - Oregon State University 167–168
 - Penn State University 167
 - University of California 167
 - USDA-NRSC, 166
- University of California 167
- University of Melbourne 164
- USDA-NRSC 166
- Vegetation dynamics 270–271
- Vegetative characteristics monitored by remote sensing 355–358
 - biomass 355–357
 - forage quality 357
 - species identification and diversity 357–358
- Vegetative reproduction by tillering 328–329
- Vitamins 42–45
- Water resources management
 - drought monitoring methods 274–276
 - early warning systems 275–276
 - remote sensing methods 274–275
 - traditional methods 274
 - factors affecting soil health 268–269
 - burning 269
 - fertilization 269
 - grazing or biomass removal 268–269
 - global climate change impacts 276–277
 - impacts of drought 273–274
 - monitoring and modelling 270–273
 - soil moisture 271
 - vegetation dynamics 270–271
 - water use 272–273
 - overview 265–267
 - temperate pastures water requirements 267–268
- Water use 272–273