Lucerne Performance on Duplex Soil under Mediterranean Climate: Field Measurement and Simulation Modelling

A thesis submitted

by

Muhammad Shafiq Zahid

As fulfilment of the requirements of the degree

of

Doctor of Philosophy

Soil and Land Systems
(Formerly Department of Agronomy and Farming Systems)
The University of Adelaide, Australia

February 2009

Table of Contents

TABLE OF CONTENTS ……………………………………………………………....III
ABSTRACT……………………………………………………………………………VII
DECLARATION…………………………………………………………………..…IX
ACKNOWLEDGEMENTS…………………….……………………………….........X
LIST OF ABBREVIATIONS……………………………………………………...XI
LIST OF FIGURES……………………………………………………………….....XII
LIST OF TABLES…………………………………………………………………XVII

1 GENERAL INTRODUCTION……………………………………………………..1

2 LITERATURE REVIEW…………………………………………………………. .6
2.1 INTRODUCTION……………………………………………………………………6
2.2 GROWTH, DEVELOPMENT AND WATER USE OF LUCERNE…………………...6
2.2.1 GROWTH…………………………………………………………………………7
2.2.2 DEVELOPMENT…………………………………………………………………8
2.2.3 WATER-YIELD RELATIONSHIPS IN LUCERNE…………………………………...9
2.2.4 YIELD COMPONENTS OF LUCERNE…………………………………………...13
2.2.5 ROOT GROWTH……………………………………………………………...18
2.3 LUCERNE SOIL-WATER BALANCE………………………………………………22
2.3.1 DEEP DRAINAGE AND GROUNDWATER RECHARGE UNDER LUCERNE…..22
2.3.2 EVAPOTRANSPIRATION FROM LUCERNE STANDS…………………………...23
2.3.3 WATER USE EFFICIENCY OF LUCERNE…………………………………………25
2.4 LUCERNE AND THE N CYCLE…………………………………………………......27
2.4.1 LUCERNE N2 FIXATION……………………………………………………....27
2.4.2 SOIL NITROGEN FERTILITY FOR LUCERNE PASTURE SYSTEMS…………...31
2.5 AGRONOMIC MANAGEMENT OF LUCERNE…………………………………....33
2.5.1 DEFOLIATION……………………………………………………………….....34
2.5.2 IRRIGATION…………………………………………………………………….38
2.6 SIMULATION OF GROWTH, DEVELOPMENT AND WATER USE IN LUCERNE ……………………………………………………………………42
2.6.1 SIMULATION MODELLING……………………………………………………...42
2.6.2 HISTORY OF GROWTH MODELLING IN LUCERNE……………………………43
2.6.3 APSIM (AGRICULTURE PRODUCTION SYSTEM SIMULATOR)……………… 43
2.7 SUMMARY…………………………………………………………………………...46

3 SEASONAL SHOOT AND ROOT PRODUCTIVITY IN LUCERNE UNDER SEMI-ARID MEDITERRANEAN CLIMATIC CONDITIONS IN RESPONSE TO VARYING WATER SUPPLY DURING SUMMER…………………………47
3.1 INTRODUCTION…………………………………………………………………..47
3.2 MATERIALS AND METHODS……………………………………………………49
3.2.1 EXPERIMENTAL SITE - CLIMATE AND SOIL DETAILS…………………….…..49
3.2.2 TREATMENTS AND DESIGN……………………………………………………51
3.2.3 PLANT MEASUREMENTS………………………………………………………..55
3.2.4 SHOOT DRY MATTER AND GROWTH RATE DETERMINATION……….......56
3.2.5 ROOT MEASUREMENT……………………………………………………………..58
3.2.6 TOTAL NON-STRUCTURAL CARBOHYDRATES (TNC) ESTIMATION……....58
3.2.7 PHYLLOCHRON DETERMINATION………………………………………………58
3.2.8 RADIATION USE EFFICIENCY ESTIMATION (RUE_{SHOOT})…………………….…59
3.2.9 STATISTICAL ANALYSIS……………………………………………………………...59
3.3 RESULTS…………………………………………………………………………...60
3.3.1 CLIMATE DATA 1999-2001………………………………………………………60

3.3.2 LUCERNE SHOOT PRODUCTIVITY AND GROWTH COMPONENTS…………63
3.3.3 ROOT BIOMASS……………………………………………………………...78
3.3.4 TOTAL NON-STRUCTURAL CARBOHYDRATES (TNC)……………………..85
3.4 DISCUSSION………………………………………………………………… 86
3.4.1 LUCERNE DRY MATTER YIELD AND YIELD COMPONENTS………………... 86
3.4.2 LUCERNE ROOTS……………………………………………………………92
3.4.2.1 ROOT:SHOOT RATIO………………………………………………………..94
3.4.3 TOTAL NON-STRUCTURAL CARBOHYDRATES (TNC)……………………..95
3.5 CONCLUSION…………………………………………………………………...96

4 WATER USE AND WATER USE EFFICIENCY OF LUCERNE ON A DUPLEX SOIL UNDER SEMI-ARID MEDITERRANEAN CLIMATIC CONDITIONS IN RESPONSE TO VARYING WATER SUPPLY DURING SUMMER…………...97
4.1 INTRODUCTION……………………………………………………………..97
4.2 MATERIALS AND METHODS………………………………………………98
4.2.1 EXPERIMENTAL SITE - CLIMATE, SOIL, TREATMENTS AND DESIGN……..98
4.2.2 SOIL BULK DENSITY, TOTAL POROSITY AND SATURATION………………..98
4.2.3 SOIL WATER CONTENT (SWC) MEASUREMENT………………………………99
4.2.4 PLANT AVAILABLE WATER CONTENT (PAWC)………………………………100
4.2.5 EVAPOTRANSPIRATION (ET)…………………………………………………… 101
4.2.6 SOIL EVAPORATION…………………………………………………………102
4.2.7 DRAINAGE…………………………………………………………………. 102
4.2.8 WATER USE EFFICIENCY (WUE, WUE_N) AND TRANSPIRATION EFFICIENCY (TE)……………………………………………………………..103
4.2.9 STATISTICAL ANALYSIS…………………………………………………...103
4.3 RESULTS……………………………………………………………………….104
4.3.1 CLIMATE…………………………………………………………………….. 104
4.3.2 SOIL PHYSICAL CHARACTERISTICS…………………………………………105
4.3.3 SOIL WATER CONTENT (SWC) TO ROOTING DEPTH (0-1800 MM)…………106
4.3.4 PLANT AVAILABLE WATER CONTENT (PAWC)…………………………… 110
4.3.5 EVAPOTRANSPIRATION (ET)……………………………………………. 112
4.3.6 SOIL EVAPORATION………………………………………………………… 114
4.3.7 DRAINAGE……………………………………………………………….. 117
4.3.8 WATER USE EFFICIENCY WUE, WUE_N AND TRANSPIRATION EFFICIENCY ………………………………………………………………..118
4.4 DISCUSSION…………………………………………………………………...121
4.4.1 THE DUPLEX CALCAREOUS RED CHROMOSOL AT ROSEWORTHY STORED WATER IN THE 600-1800 MM SOIL PROFILE………………………..121
4.4.2 LUCERNE, IN THE ROSEWORTHY ENVIRONMENT, WAS ABLE TO DRY THE SOIL PROFILE TO 1800 MM…………………………………………...121
4.4.3 IRRIGATED LUCERNE IN THIS ENVIRONMENT ALSO EXTRACTED WATER TO 1800 MM…………………………………………………………….122
4.4.4 ACTUAL ET DRIVEN BY STORED SOIL MOISTURE USE IN THIS ENVIRONMENT…………………………………………………………….…123
4.4.5 POTENTIAL ET IN THIS ENVIRONMENT WAS CONSISTENTLY GREATER THAN ACTUAL ET UNDER RAINFED CONDITIONS BUT NOT NECESSARILY UNDER IRRIGATION…………………………………………….124
4.4.6 DRAINAGE BELOW THE EFFECTIVE ROOTING DEPTH OF 1.8 M WAS NEGLIGIBLE EVEN UNDER IRRIGATION……………………………………..125
4.4.7 WUE WAS LOWEST UNDER RAINFED CONDITIONS AND INCREASED UNDER IRRIGATION……………………………………………………………………125
4.5 CONCLUSION…………………………………………………………………….128

5 SOIL-PLANT N DYNAMICS FOR LUCERNE ON A DUPLEX SOIL UNDER SEMI-ARID MEDITERRANEAN CLIMATIC CONDITIONS & RESPONSE TO VARYING WATER SUPPLY DURING SUMMER…………129
5.1 INTRODUCTION……………………………………………………………129
5.2 MATERIALS AND METHODS………………………………………………..130
5.2.1 EXPERIMENTAL SITE, CLIMATE AND SOIL DETAILS……………………….…130
5.2.2 SHOOT BIOMASS AND N ACCUMULATION…………………………………....130
5.2.3 ESTIMATION OF DEPENDENCE ON N2 FIXATION (NDFA) AND AMOUNT OF N FIXED……………………………………………………......130
5.2.4 SOIL MINERAL N MEASUREMENT……………………………………………...132
5.2.5 STATISTICAL ANALYSIS…………………………………………………………133
5.3 RESULTS…………………………………………………………………….....134
5.3.1 SHOOT N ACCUMULATION………………………………………………………134
5.3.2 NITROGEN FIXATION……………………………………………………………..136
5.3.3 NATURAL ABUNDANCE (δ^{15}N) OF REFERENCE SPECIES AND LUCERNE……………………………………………………………………….136
5.3.4 RELATIONSHIPS BETWEEN SHOOT BIOMASS, N$_2$ FIXED, NDFA AND WATER APPLIED/RECEIVED……………………………………………………..141
5.3.5 SOIL MINERAL N…………………………………………………………………...143
5.4 DISCUSSION……………………………………………………………………...148
5.4.1 SEASONAL N$_2$ FIXATION…………………………………………………….…148
5.4.2 PROPORTIONAL DEPENDENCE ON N$_2$ FIXATION………………………….…149
5.4.3 COMMENTS ON THE ^{15}N NATURAL ABUNDANCE METHOD………………..151
5.4.4 RELATIONSHIP OF AMOUNTS OF N$_2$ FIXED TO GROWTH AND TOTAL WATER USE…………………………………………………………………………151
5.4.5 SOIL MINERAL N DYNAMICS UNDER LUCERNE……………………………...152
5.5 CONCLUSION…………………………………………………………………….154

6 EVALUATION OF THE PERFORMANCE OF APSIM-LUCERNE IN A MEDITERRANEAN CLIMATE ON A DUPLEX SOIL………………………...155
6.1 INTRODUCTION………………………………………………………………….155
6.2 MATERIALS AND METHODS…………………………………………………..156
6.2.1 CLIMATE……………………………………………………………………………156
6.2.2 INPUT DATA………………………………………………………………………...156
6.2.3 MODEL PARAMETERISATION……………………………………………….....157
6.3 RESULTS……………………………………………………………………….…161
6.3.1 MODEL PARAMETERISATION……………………………………………….....161
6.3.2 MODEL PERFORMANCE…………………………………………………………..163
6.3.3 SOIL WATER………………………………………………………………………...174
6.3.4 NITROGEN……………………………………………………………………….…..179
6.4 DISCUSSION……………………………………………………………………….183
6.4.1 MODEL PERFORMANCE…………………………………………………………..184
6.4.2 SOIL WATER………………………………………………………………………...191
6.4.3 NITROGEN…………………………………………………………………………...194
6.5 CONCLUSION……………………………………………………………………..197

7 GENERAL DISCUSSION………………………………………………………198
7.1 INTRODUCTION…………………………………………………………………198
7.2 PRODUCTIVITY OF RAINFED LUCERNE IN A SEMI-ARID MEDITERRANEAN CLIMATE ON A DUPLEX SOIL……………………………198
7.3 PRODUCTIVITY OF IRRIGATED LUCERNE IN A SEMI-ARID MEDITERRANEAN CLIMATE ON A DUPLEX SOIL……………………………201

7.4 APSIM EVALUATION……………………………………………………………...202
7.5 FUTURE RECOMMENDATIONS…………………………………………………204

APPENDICES……………………………………………………………………………206

8.1 APPENDIX A……………………………………………………………………...206

8.2 APPENDIX B……………………………………………………………………..207

8.3 APPENDIX C……………………………………………………………………...208

8.4 APPENDIX D……………………………………………………………………...209

8.5 APPENDIX E………………………………………………………………………210

8.6 APPENDIX F………………………………………………………………………211

8.7 APPENDIX G……………………………………………………………………...212

8.8 APPENDIX H……………………………………………………………………...213

8.9 APPENDIX I……………………………………………………………………….214

8.10 APPENDIX J……………………………………………………………………….215

8.11 APPENDIX K……………………………………………………………………...216

8.12 APPENDIX L……………………………………………………………………...217

8.13 APPENDIX M……………………………………………………………………..218

REFERENCES…………………………………………………………………………224

Abstract

The experimental work reported in this thesis quantified the productivity of lucerne over a two-year period (2000-2001) for a Mediterranean climate at Roseworthy in South Australia (34°32′S, 138°45′E), and determined associated dynamics for water and nitrogen in duplex soil. Shoot growth of dryland lucerne was limited primarily by the pattern and amount of incident rainfall, but high temperature (30-35^{o}C) also constrained summer production. These high summer temperatures induced greater production when irrigation was applied, but under the normally dry summer conditions high temperatures combined with soil water deficit (up to 200mm) caused growth to cease. Thus, shoot dry matter yield under rainfed conditions was 4.9 t ha^{-1} in 2000 (from 7 harvests) and 1.8 t ha^{-1} in 2001 (from 5 harvests) whereas summer irrigation increased yield to 14.9 t ha^{-1} in 2000 (7 harvests) and 7.1 t ha^{-1} in 2001 (5 harvests). Under rainfed conditions the RUE was 0.55 g DM MJ^{-1} PAR$_i$ compared with 1.08 g DM MJ^{-1} PAR$_i$ in the irrigated treatment in 2000, reducing to 0.4 g DM MJ^{-1} for the rainfed and 0.7 g DM MJ^{-1} under limited irrigation in 2001. Lucerne plant population declined from 69 to 20 (plants m^{-2}) in the rainfed treatment and the plants partially compensated for this in 2000 by increasing stem density from 300 to 400 m^{-2} in 2000 although this declined back to 300 m^{-2} in 2001. In all treatments more than 70% of root biomass was in the top 40 cm soil, this was partially due to the vertical distribution of plant available water but also to subsoil constraints to root development below 0.6m. Nevertheless, lucerne was able to extract water and nitrate to 1800 mm soil depth. Large amounts of irrigation (>400mm) over summer (Dec 1999-Mar 2000) increased total soil water content, approaching the drained upper limit; causing a 600% increase in shoot dry matter yield, similarly higher growth rate (71 kg DM d^{-1}) and higher RUE (~1.7 g DM MJ^{-1}), confirming that water availability was the main constraint to lucerne growth. Delayed benefits of summer irrigation, especially in the subsurface treatment, were also observed later (July to October) when lucerne was able to scavenge excess irrigation water and nitrate stored in the 600-1800 mm soil profile, which resulted in increased shoot growth. Drainage below the effective rooting depth was negligible, even under irrigation, confirming that lucerne can dry soil profiles and reduce deep drainage. Average annual water use efficiency was 9 kg DM ha^{-1} mm^{-1} under rainfed conditions compared to ~15 kg DM ha^{-1} mm^{-1} under irrigated conditions. Shoot dry mattter production was closely related to evapotranspiration in all treatments, however, under rainfed conditions losses from evaporation were proportionally higher compared to irrigated treatments. Sub-surface drip irrigation proved superior to surface irrigation using 22% less water compared to surface sprinkler irrigation treatment with comparable yields. Biological N_2 fixation was strongly related to shoot production with 18 to 27 kg N fixed per tonne of shoot dry matter across all seasons and treatments. Dependence on N_2 fixation appeared to be unrelated to soil mineral N concentration and amounts of nitrate in the profile (to 1m) were generally quite low (<35 kg N ha^{-1}).

Soil water dynamics under both rainfed and surface irrigated treatments were adequately simulated by the Agricultural Production System Simulator (APSIM) with RMSD < 10% of the observed means and $R^2 > 0.80$ for the total soil profile (0-2000 mm). Simulation of growth and development was less satisfactory. For example, the RMSD was ~50% of observed mean for shoot biomass ($R^2 = 0.68$) in the rainfed treatment, and 36% ($R^2 = 0.77$) in the irrigated treatment. Overall, simulation of shoot DM production was close to observed values during the growing season (Apr-Nov), however the model was unable to capture the observed shoot yield in response to summer irrigation, with simulated shoot DM 40% less than the observed value in 2000 and 35% less in 2001. N dynamics were poorly simulated under these soil and climate conditions. Amounts of soil mineral nitrogen (kg NO^-_3 -N ha^{-1}) were adequately simulated in rainfed conditions but consistently over-predicted under irrigated conditions. This evaluation of APSIM highlights both good and poor model performance and the analysis indicates the need for caution when applying the model in situations where observed data is scarce. Areas requiring improvements to the model are identified.

Overall this research has improved understanding of the limitations to potential production of lucerne in a Mediterranean environment on duplex soils and shown that APSIM-Lucerne can be used confidently for many applications, particularly soil-water dynamics.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available in all forms of media, now or hereafter known.

Muhammad Shafiq Zahid

February 2009

Acknowledgements

All praise to Almighty "God" who blessed me with capability to complete this study. I would like to thank my supervisors Dr Annie McNeill and Dr Bill Bellotti for their continual support friendship and explanation of the basic principles involved in scientific research. Special thanks also goes to Dr Annie McNeill for practical help in field work and her keen interest in this thesis that enabled me to finish this project successfully. I am indebted to Dr Annie McNeill for providing me financial support to bring me back and complete this manuscript. I am particularly grateful to Dr Bill Bellotti for spending valuable time teaching me APSIM. I pay heartiest gratitude to Prof. David Coventry for providing me insightful direction initially as a co-supervisor, and afterwards continued encouragement that enabled me to complete this project with confidence. I am grateful to Dr. Murray Unkovich for helping me with N_2 fixation aspects of this project. It has been really a team effort from which I have learned a lot and benefited greatly. I am also thankful to Dr. Ian Nuberg, Dr. Gurjeet Gill and all academics for day-to-day help and moral support.

There are many other people that I thank for assistance: David Mathew for financial aspects, and friendship, Anne Mowday for administrative assistance, Penny Day assisted me a lot in field work and lab analysis. I am particularly grateful to Peter Cornelius, Chris Penfold and John Vandeleur for assisting me in field operations. I am particularly thankful to Paul Harris and Brian Glaetzer for their continuous support for computer technicalities. Also grateful thanks to Michele Lorimer for statistical support and advice.

Sincere thanks also to my fellow students Damien Adcock, Michael Cobiac, Eunyoung Choi and Khola Yasmin for their help and friendship.

I would like to give thanks and appreciation to my family, especially my long-suffering wife Naureen for her support and encouragement.

I am indebted to the Australian Agency for International Development (AusAID) for providing me with a scholarship for this research study.

List of Abbreviations

APSIM	Agricultural production system simulator
CLL	Crop lower limit
D	Drainage
d	day
DM	Dry matter
DMY	Dry matter yield
DUL	Drained upper limit
E_s	Soil evaporation
ESW	Extractable soil water content
ET	Evapotranspiration
ET_a	Actual Evapotranspiration
ET_c	Composite Evapotranspiration
ET_p	Potential Evapotranspiration
g	Gram
H	Harvest
ha	Hectare
HB	Harvested biomass
I	Irrigation
kg	Kilogram
LAI	Leaf area index
LC	Lack of correlation
Mg	Mega gram
mg	Milligram
mm	Millimetre
NU	Non unity slope
N	Nitrogen
N_2	Di-nitrogen
NMM	Neutron Moisture Meter
^oCd	Degree days
Pp	Photoperiod
PAWC	Plant available water capacity
PARi	Photo-synthetically active incident radiation
R	Rainfall
RBM	Root biomass
RLD	Root length density
RO	Run off.
RUE	Radiation use efficiency
RMSD	Root mean squared deviation
SB	Squared bias
SBM	Shoot biomass
sla	Specific leaf area
t	Tonne
TE	Transpiration efficiency
TNC	Total non-structural carbohydrate
Tt	Thermal time
VPD	Vapour pressure deficit
WUE	Water use efficiency
yr	Year
ΔS	Change in soil water
$\delta^{15}N$	Delta 15-Nitrogen

List of Figures

Chapter 1

Figure 1.1 Illustration of the structure of this thesis……………………………………………5

Chapter 3

Figure 3.1 Long-term (1949-2001) annual, growing season (Apr-Nov) and summer (Dec-Mar) rainfall for Roseworthy Campus……………………………………………………………..51

Figure 3.2 Randomised Complete Block Design of the lucerne experiment during the study period (Dec 1999-Sep 2001) at Roseworthy Farm site…………………………………………52

Figure 3.3 Water received (mm) through rainfall (presented in line for all treatments) or irrigation (presented in bars) at each growing cycle (H1-H12) from Dec 1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………………55

Figure 3.4 Dry matter yield and shoot residue dry matter at different harvests (H1-H12) during Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………64

Figure 3.5 Cumulative shoot dry matter yield in relation to cumulative water supplied during Dec1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………65

Figure 3.6 Plants and stem populations (m-2) at different harvest (H1-H12) during Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation………………………………………………...67

Figure 3.7 Height, node and leaf number (main stem) at different harvests (H1-H12) during Jan 2000 to Sep 2000 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation………………………………………69

Figure 3.8 Average lucerne stem growth rate (cm day-1) for summer and a winter-spring growing seasons of 2000 at three stages, (A) early shoot, (B) mid-vegetative and (C) maturity, during a growth cycle for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………70

Figure 3.9 Main stem node appearance of during different regrowth for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Arrows indicated points flowering of crop excluded from date set…………………71

Figure 3.10 Phyllochron of lucerne crop measured over different growth seasons from during regrowth cycles from Jan 2000-Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}). Dash lines (----) represent equinox and solstice……………………………………………………………………71

Figure 3.11 Phyllochron of lucerne crop measured over different growth seasons and for each growth cycles against photoperiod on the day of appearance of the first main stem node during regrowth cycles from Jan 2000-Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub})………………………72

Figure 3.12 LAI of lucerne at three stages of crop development, (A) young shoot, (B) mid-vegetative and (C) maturity, during each individual growth cycle (H1-H12) from Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation………………………………………………...73

Figure 3.13 LAI versus accumulated thermal time of during different regrowth cycles for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation……………………………………………………………73

Figure 3.14 Leaf:stem ratio at different harvest (H1-H12) from Jan 2000 to Sep 2000 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………………..74

Figure 3.15 Pattern of LAI development at two different regrowth cycles (a) March 2000, (a-1) June 2000, corresponding PARi interception (b, b-1) and relationship between accumulated PARi and shoot biomass (c, c-1) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………….76

Figure 3.16 Seasonal pattern of shoot radiation use efficiency (RUE_{shoot}) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation from Dec 1999 to Sep 2001. Lines (---) separate different seasons to each other……………………………………………………………………………………77

Figure 3.17 (a) Relationship between shoot radiation use efficiency (RUE_{shoot}) and mean air temperature, and (b) with vapour pressure deficit (VPD) during each regrowth cycle for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation from Dec 2000 to Sep 2000………………………………………77

Figure 3.18 Root biomass (RBM) during 2000-2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………………………………………..79

Figure 3.19 Total root biomass (kg ha-1) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………….80

Figure 3.20 Root length densities in relation to root biomass in different treatments and in different sampling times during Dec1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation……..……………………………………………………………………………84

Figure 3.21 Total non-structural carbohydrates level (%) in taproots of rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation, during 2000-2001……………………………………………………………………85

Chapter 4

Figure 4.1 Pan evaporation and water received (mm) through rainfall or applied as irrigation for each harvest (H1-H12) during the study in rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the two year study period (Dec 1999 to Sep 2001)…………………………………………………104

Figure 4.2 Monthly average vapour pressure deficit experienced at Roseworthy experimental site during the two year study period (Dec 1999 to Sep 2001)………………………………..105

Figure 4.3 Volumetric soil water content (m^3 m^{-3}) on 17/12/1999 and 7/4/2000 for soil profiles indicated by Neutron meter data under (a) rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via (b) surface (I_{surf}) or (c) sub-surface (I_{sub}) irrigation during the two year study period (Dec1999 to Sep 2001)……………………………………………107

Figure 4.4 Total soil water content (mm) in (a) 0-600, (b) 600-1800 and (c) 0-1800 mm soil profiles under rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the two year study period (Dec 1999 to Sep 2001). Error bars represent LSD at (α=0.05) for each growing season…………………..109

Figure 4.5 Plant available water content (mm) in (a) 0-600, (b) 600-1800 and (c) 0-1800 mm soil profiles under rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the study period (Dec1999 to Sep 2001). Error bars represent LSD at (α=0.05) for each growing season……………………….111

Figure 4.6 Comparison between cumulative ET_a estimated during the period Dec 1999 to Sep 2001 by using the water balance equation and the modified composite approach (Ward and Dunin 2001), for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………...113

Figure 4.7 Actual evapotranspiration (bars, ET_a) calculated using the water balance equation and potential evapotranspiration (symbols, ET_p) estimated by (a) Priestley Taylor equation (ET_{PT}) or (b) Modified Priestly Taylor (ET_{MPT}) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………114

Figure 4.8 Measured soil evaporation (Es) from the surface 0-100 mm soil during 15-19 Feb 2001 in rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………115

Figure 4.9 Measured from changes in SWC at 1800-3000 mm soil profile during different measuring times from Dec 1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water via surface (I_{surf}) or sub-surface (I_{sub})……………………………………117

Figure 4.10 Deep drainage (positive values) calculated using a water balance with ET estimated using Priestly-Taylor and for rainfed lucerne (R_{fed}) and lucerne supplied supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the study period (Dec 1999-Sep 2001)…………………………………………………………………………………118

Figure 4.11 Relationship between cumulative amounts of water used with cumulative dry matter yield produced (a) R_{fed} (b) I_{sub} and (c) I_{surf} treatments of lucerne during Dec 1999 to Sep 2001………………………………………………………………………………….. 120

Figure 4.12 Relationship between cumulative amounts of water transpired with cumulative dry matter yield produced in (a) R_{fed} (b) I_{sub} and (c) I_{surf} treatments of lucerne during Dec 1999 to Sep2001…………………………………………………………………………………120

Chapter 5

Figure 5.1 Cumulative shoot N content for the two year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD at α=0.05……………………134

Figure 5.2 Measured δ^{15}N of (a) reference plants (b) lucerne (c) estimated Ndfa (%) and (d) amount of water (mm) applied and/or received as rain fall in R_{fed}, I_{sub} and Isurf treatments during the study period (Dec 1999-Sep 2001) for the 12 sampling times. Error bars represent the LSD at (α=0.05)……………………………………………………………………………137

Figure 5.3 Cumulative shoot N2 fixed and N uptake from soil for the two-year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}f) or sub-surface (I_{sub}) irrigation………………………………...139

Figure 5.4 Shoot N (fixed + uptake from soil) in 12 harvests during the two-years study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation……………………………………...140

Figure 5.5 Relationships between (a) shoot dry matter and N2 fixed (b) Ndfa and N_2 fixed and (c) Ndfa and shoot N for the study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{sub}) or sub-surface (I_{surf}) irrigation……………………………………………………………………………………142

Figure 5.6 Amounts (kg ha-1) mineral soil N (a) 0-400, (b) 400-1000 and (c) 1000-1500 mm soil profiles for the two year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD at (α=0.05)………………………………………………145

Figure 5.7 Soil profile mineral N concentrations (mg kg^{-1}) measured (a) 28 Feb 2000, (b) 9 June 2000 (c) 1 Oct 2000 (d) 20 May 2001 and (e) 8 Oct 2001 for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD at (α=0.05)…………………………………………………………146

Figure 5.8 (a) Seasonal N2 fixed and (b) amounts of soil mineral N in 0-1000 mm soil profile and (c) Ndfa (%) for the two year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD at (α=0.05)………………………………………………147

Chapter 6

Figure 6.1 Relationship between mean day length and thermal time (Tt) during different harvests of lucerne from Dec1999-Sep 2001…………………………………………………163

Figure 6.2 Comparison of observed and simulated date of flowering. Cycle number describes harvest cycle number; negative numbers refer to harvests prior to the main experiment commencing. Simulated values include start and finish dates of flowering…………………..164

Figure 6.3 Observed (◊) and simulated (–) green shoot biomass (kg ha^{-1}) over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) R_{fed} and (b) I_{surf} treatments…………………………... 165

Figure 6.4 Comparison between simulated and observed shoot biomass (kg ha-1) over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) R_{fed} and (b) Isurf treatments…………….. 166

Figure 6.5 Observed (◊) and simulated (–), (a) leaf number, (b) leaf area index in R_{fed} and (c) leaf number and (d) leaf area index in I_{surf} treatment over 12 harvest cycles. 168

Figure 6.6 Comparisons between simulated and observed LAI and leaf number per main stem over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) LAI $R_{\mathbf{fed}}$, (b) LAI $I_{\mathbf{surf}}$, (c) leaf number $R_{\mathbf{fed}}$ and (d) leaf number $I_{\mathbf{surf}}$……………………………………………………………..169

Figure 6.7 Observed (◊) and simulated (–), (a) plant height (b) node number in $R_{\mathbf{fed}}$, and (c) plant height (d) node number in I_{surf} treatments over 11 harvest cycles……………………170

Figure 6.8 Comparisons between simulated and observed plant height and node number over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) plant height $R_{\mathbf{fed}}$ (b) plant height $I_{\mathbf{surf}}$ (c) node number $R_{\mathbf{fed}}$ and (d) node number $I_{\mathbf{surf}}$……………………………………………………171

Figure 6.9 Observed (◊) and simulated (–), (a) leaf weight (b) stem weight in R_{fed} and (c) leaf weight (d) stem weight in I_{surf} treatments over 12 harvest cycles……………………………..173

Figure 6.10 Comparisons between simulated and observed leaf and stem weight over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) leaf wt R_{fed}, (b) leaf wt I_{surf}, (c) stem weight R_{fed} and (d) stem weight I_{surf}…………………………………………………………………………..174

Figure 6.11 Observed (◊) and simulated (–) total soil water in 0-600 mm soil profile for (a) R_{fed} and (b) I_{surf} during Dec 1999 to Sep 2001. Dashed lines (---) represent DUL and CLL………176

Figure 6.12 Observed (◊) and simulated (–) total soil water in 0-2000 mm soil profile for (a) R_{fed} and (b) I_{surf} during Dec 1999 to Sep 2001. Dashed lines (---) represent DUL and CLL... 177

Figure 6.13 Comparison between simulated and observed total soil water (mm) from Dec 1999 to Sep 2001 in (a) R_{fed} 0-600 mm, (b) I_{surf} 0-600 mm, (c) R_{fed} 0-2000 mm and (d) Isurf 0-2000 mm soil profiles……………………………………………………………………178

Figure 6.14 Observed and simulated total nitrogen in green biomass of lucerne (a) R_{fed} and (b) I_{surf} over twelve harvest cycles during Dec 1999 to Sep 2001……………………………...181

Figure 6.15 Observed and simulated N_2 fixed in 12 harvest cycles in (a) R_{fed} and (b) I_{surf} from Dec 1999 to Sep 2001……………………………………………………………………182

Figure 6.16 Cumulative observed and simulated N_2 fixed opting active mode in APSIM-Lucerne ini_file in 12 harvest cycles in (a) R_{fed} and (b) I_{surf} from Dec 1999 to Sep 2001…….183

Figure 6.17 Average of '*swdef_photo'* simulated by APSIM in (a) R_{fed} lucerne and (b) I_{surf} treatments during the study period (Dec 1999 to Sep 2001)…………………………………..188

Figure 6.18 APSIM-Lucerne simulated *green _biomass* (t ha-1), *sw_demand* (mm) and *sw_supply* for irrigated lucerne (I_{surf}) during Dec-99 to Mar-2000……………………………188

Figure 6.19 Existing and proposed modification in water deficit factor for photosynthesis in lucerne…………………………………………………………………………………………189

Figure 6.20 Components of mean squared deviation (MSD) for shoot biomass (SBM) and LAI in R_{fed} and I_{surf} treatments. The three components are non-unity slope (NU), lack of correlation (LC), and squared bias (SB). Root mean squared deviation is % of observed mean in each treatment for SBM and LAI……………………………………………………………...190

Figure 6.21 Components of mean squared deviation (MSD) for 0-600 and 0-2000 mm soil profiles under lucerne in R_{fed} and I_{surf} treatments. The three components are non-unity slope (NU), lack of correlation (LC), and squared bias (SB). Root mean squared deviation is percent (%) of observed means in each treatment for 0-600 and 0-2000 mm soil profiles……………192

Figure 6.22 Cumulative observed and simulated N_2 fixed illustrating the impact of the user specified uptake preference '*active*' or '*fixation*' mode in APSIM-Lucerne for 12 harvest cycles in (a) R_{fed} and (b) I_{surf} from Dec 1999 to Sep 2001……………………………………………195

List of Tables

Table 2.1 Yield (shoot dry matter, t ha^{-1}) for lucerne in different climatic regions under (a) rainfed and (b) irrigated conditions. Yield refers to 1st, 2nd and 3rd year after sowing…………11

Table 2.2 Seasonal shoot dry matter (DM) production (t ha^{-1}) and growth rate (GR, kg ha^{-1} d^{-1}) of highly winter-active lucerne cultivar (Pioneer L69) under Mediterranean climatic conditions in Victoria, Australia……………………………………………………………………………12

Table 2.3 Effect of plant population (m^{-2}) on productivity (t ha^{-1}) in rainfed lucerne for different climatic regions……………………………………………………………………………14

Table 2.4 Reported evapotranspiration rate (mm d^{-1}) in lucerne in different seasons………….24

Table 2.5 Reported water use efficiency (WUE) of lucerne under rainfed and irrigated conditions in Australia and around the world………………………………………………..26

Chapter 3

Table 3.1 Physical and chemical characteristics of the soil determined for various depths at the experimental site used at Roseworthy Farm from Dec 1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation……………………………………………………………………..50

Table 3.2 Parameters measured and the sample size taken in the lucerne experiment for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during Dec 1999 to Sep 2001……………………………………...56

Table 3.3 Details of major agronomic operations carried-out since the plot was sown in June, 1998 and during the experiment period (Dec 1999 to Sep 2001) at Roseworthy Campus……...57

Table 3.4 Monthly rainfall and pan evaporation (mm) from 1999-2001 compared with long-term average (50 years) at Roseworthy Campus Farm Site…………………………………………61

Table 3.5 Monthly maximum and minimum temperature (°C) and Radiation (MJ m^{-2}) at Roseworthy Campus Farm Site from 1999-2001 compared with the 50 years average………..62

Table 3.6 Rate of dry matter accumulation above 5 cm (kg d^{-1} ha^{-1}) in each growing cycle during Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………66

Table 3.7 Proportion of root biomass (%) at various soil depths for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………………………………………...80

Table 3.8 Root length density ($cm^3{}_{root}$ $cm^3{}_{soil}$) at three times during the study period for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………………………...82

Table 3.9 Proportional root length density (%) at various soil depths for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…………………………………………………………………………………...83

Table 3.10 Root:shoot ratio in summer and winter-spring growing seasons (2000) in rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation………………………………………………………………... 84

Chapter 4

Table 4.1 Observed and calculated soil physical characteristics for the 0-3000 mm profile at the experimental site at Roseworthy…105

Table 4.2 Actual evapotranspiration (ET_a) calculated using the Eq. 4.9 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation at various harvests during different growing season (Dec 1999-Sep 2001)…112

Table 4.3 Water applied, actual ET_a, soil evaporation (E_s), transpiration (T_r), dry matter yield (DMY), transpiration efficiency (TE), ET as a percentage (%) of water used and E_s and T_r as % of ET in rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during different growing seasons in the study period (Dec 1999 to Sep 2001)…116

Table 4.4 Water use efficiency in rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation at various harvests cycles during different growing seasons in study period (Dec 1999 to Sep 2001)…119

Table 4.5 Normalised water use efficiency (WUE_n) in rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation at various harvests cycles during different growing seasons in study period (Dec 1999 to Sep 2001)…119

Chapter 5

Table 5.1 Species used as reference plants for estimation of proportional dependence on N2 fixation (Ndfa) by lucerne using the $\delta^{15}N$ natural abundance technique… 132

Table 5.2 Seasonal shoot biomass production (total), shoot nitrogen content, Ndfa (%) N_2 fixed, N uptake from soil, shoot N_2 fixed per tonne of dry matter and per mm of total water use (ET), during four growing seasons in the study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation…135

Chapter 6

Table 6.1 Sample of SILO data used in simulation modelling…156

Table 6.2 Details of actions and commands used in APSIM…157

Table 6.3 Soil water and soil x plant parameters used for APSIM-Lucerne model…159

Table 6.4 Numeric stage codes and phenological stages used in APSIM for new grown and regrowth crop of lucerne…161

Table 6.5 APSIM-Lucerne parameters standard and modified used in final simulation (a) for genotypic thermal time, photoperiod, (b) specific leaf area vs LAI, (c) fraction of translocation and (d) transpiration efficiency coefficient…162

Table 6.6 APSIM-Lucerne parameters for RUE (g DM MJ^{-1}) used in final simulation…163

Table 6.7 Summary of annual production of green biomass (t ha^{-1} y^{-1})…166

Table 6.8 Statistics for goodness-of-fit between simulated and observed for SBM (kg ha^{-1}), LAI and leaf number per main stem (n) in R_{fed} and I_{surf} treatments from Dec 1999 to Sep 2001. Components of mean square deviation (SB, NU, LC) and linear regression (slope, intercept, R^2)…166

Table 6.9 Statistics for goodness-of-fit between simulated and observed for plant height (cm), node (n), leaf weight (g m^{-2}) and stem weight (g m^{-2}) in R_{fed} and I_{surf} treatments from Dec 1999 to Sep 2001. Components of root mean square deviation (SB, NU, LC) and linear regression (slope, intercept, R^2)…………...171

Table 6.10 Statistics for goodness-of-fit between simulated (S) and observed (O) total soil water (mm) in 0-600 and 0-2000 mm soil profile for R_{fed} and I_{surf} treatments from Dec 1999 to Sep 2001. Components of mean square deviation (SB, NU, LC) and linear regression (Slope, Intercept, R^2)………… 176

Table 6.11 APSIM-Lucerne predicted water balance under lucerne in R_{fed} and I_{surf} treatments from Dec 1999 to Sep 2001…………179

Table 6.12 Amounts of observed and simulated nitrate (kg ha^{-1}) in 0-1500 mm soil profile during different sampling time in rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf})…………..180

Table 6.13 Summary of annual amount of N_2 fixed (kg ha^{-1} year^{-1}) in two year study period from Dec 1999 to Sep 2001………… 182