

Lincoln University Digital Thesis

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- you will use the copy only for the purposes of research or private study
- you will recognise the author's right to be identified as the author of the thesis and due acknowledgement will be made to the author where appropriate
- you will obtain the author's permission before publishing any material from the thesis.

Water extraction and use of seedling and established dryland lucerne crops

A thesis
submitted in partial fulfilment
of the requirements for the Degree
of Doctor of Philosophy

at
Lincoln University
New Zealand

by
Richard E. Sim

Lincoln University
Canterbury, New Zealand
2014

Parts of this thesis have been accepted for publication in advance of submission of this thesis

From Chapter 4, 5 and 6

Sim, R.E, Moot, D.J., Brown, H.E., Teixeira, E.I. 2012a. Development, growth and water extraction of seedling lucerne grown on two contrasting soil types. In: I. Yunusa (Ed.). "Capturing Opportunities and Overcoming Obstacles in Australian Agronomy". Proceedings of the 16th Australian Agronomy Conference 2012, University of New England, Armidale, NSW The Regional Institute Ltd.

From Chapter 4 and 6

Sim, R.E., Moot, D.J., Brown, H.E., Teixeira, E.I. 2012b. Growth and root:shoot dry matter partitioning in seedling lucerne (*Medicago sativa* L.) differ with sowing date and water availability. In: Proceedings of the 6th International Crop Science Congress, 6-10 August 2012, Bento Goncalves, RS, Brazil. International Crop Science Society.

**Abstract of a thesis in partial fulfilment of the requirements for the
Degree of Doctor of Philosophy**

**Water extraction and use of seedling and established dryland
lucerne crops**

By

Richard E. Sim

The main aim of this research was to refine best management practices for dryland lucerne (*Medicago sativa* L.) crops in relation to crop water extraction. To do this, dryland lucerne was established at Lincoln University, New Zealand in two soils which differed in the plant available water content (PAWC). The low PAWC site (Ashely Dene) had a very stony silt loam soil with ~130 mm of water to 2.3 m. The high PAWC site (Iversen 12) is a deep silt loam soil with ~360 mm of water to 2.3 m. The available water for crop extraction in the establishment year was manipulated by imposing the second treatment, sowing date. This resulted in mean annual dry matter (DM) yields which ranged from 0.4 to 21.5 t DM/ha. A detailed examination of lucerne physiology was undertaken to determine how lucerne extracts water from the soil to explain these yield differences. Mean annual DM production was maximised when lucerne was spring sown in October, with yields of 2.8 t DM/ha at Ashley Dene and 12.1 t DM/ha at Iversen 12. Delayed sowing from December to February reduced the annual yield in the establishment season by 16 kg DM/ha/day at Ashley Dene and 114 kg DM/ha/day at Iversen 12.

Accumulated intercepted radiation explained most ($R^2 = 0.98$) of the differences in DM yield among crops. On average, crops at Ashely Dene intercepted 30% less radiation than those at Iversen 12. Canopy development and expansion determined leaf area index (LAI), and therefore intercepted radiation. Differences in LAI were mainly due to the expansion of individual leaves. The maximum potential leaf area expansion rate (LAER) was 0.011 and 0.016 m²/m²/°Cd for seedling and regrowth crops, respectively. LAER increased 8×10^{-5} per mm² up to an individual leaf area of 150 mm².

Crops in the establishment season displayed an extraction front velocity (EFV) of 14 mm/day when crop water demand was greater than supply. The EFV of second year crops at Ashley Dene doubled to 32 mm/day, to compensate for the low water supply from the soil, however water demand exceeded supply and water stress occurred. Water stress was quantified as transpiration (E_T) in relation to demand (EP_T). Soil evaporation (E_S) was described by the Ritchie model, modified to account for soil drying by crop roots. It explained 84% of the variation in observed soil water content of bare soil. E_T/EP_T was compared to yield forming processes to determine the effect of water stress on crop canopy development, expansion and shoot radiation use efficiency (RUE_{shoot}), expressed as a fraction of a fully water crop ($f_{obs/pred}$). The expansion of LAI was the most sensitive component to water stress which decreased from $f_{obs/pred}$ of 1.0 to near zero when E_T/EP_T was 0.30, compared with $RUE_{shoot} f_{obs/pred}$ which decreased to 0.30. But, because of the exponential relationship between fractional radiation interception and LAI, and also greater below ground partitioning of DM in response to water stress, differences in RUE_{shoot} had the greatest influence on DM yield. RUE_{shoot} for crops grown at Iversen 12 displayed a seasonal pattern, 0.68 g DM/MJ in spring and early summer which decreased to 0.45 g DM/MJ in late summer. RUE_{shoot} was consistently 0.27 g DM/MJ at Ashley Dene.

The effect of grazing management was determined on dryland lucerne DM yield and water use. Grazing the crop canopy reduced transpiration which was proportional to the decrease in intercepted radiation. But, total water use was consistent among grazing managements because E_T and E_S were balanced.

The results presented in this study improve the understanding of lucerne water extraction, which were used to make recommendations for the refinement of best management practices for dryland lucerne crops.

Key words: dryland, evaporation, extraction front velocity, grazing management, leaf area index, lucerne, *Medicago sativa*, photoperiod, phyllochron, radiation interception, radiation use efficiency, transpiration, water stress.

Table of Contents

1	General Introduction.....	1
1.1	Overview of dryland forage production in New Zealand	1
1.2	Potential to increase dryland pasture production	2
1.3	Research objectives.....	3
2	Review of literature.....	6
2.1	Lucerne production in New Zealand.....	6
2.1.1	Overview	6
2.1.2	DM yield	7
2.1.3	Forage quality and animal production.....	7
2.1.4	Defoliation management	8
2.2	Environmental factors that determine lucerne yield	11
2.2.1	Crop growth, development and yield	11
2.2.2	Temperature	12
2.3	Interception of solar radiation by the canopy	16
2.3.1	Leaf area index	16
2.4	DM production and radiation use efficiency (RUE).....	20
2.4.1	Effect of temperature on RUE.....	21
2.4.2	DM partitioning.....	22
2.5	Effect of water limitation on yield	24
2.5.1	Soil water supply.....	24
2.5.2	Water use.....	25
2.5.3	Crop water stress	28
2.6	Establishment.....	31
2.7	Summary	33
3	Materials and Methods.....	34
3.1	Experimental sites.....	34
3.1.1	Site history	34
3.1.2	Soil characteristics	34
3.2	Meteorological conditions	37
3.2.1	Measurements	37
3.2.2	Long-term meteorological conditions.....	37
3.2.3	Rainfall and evapotranspiration during the experiments	38
3.2.4	Temperature and solar radiation.....	41
3.2.5	Vapour pressure deficit and wind run	42
3.3	Agronomic management.....	44
3.3.1	Experimental design and treatments	44
3.3.2	Establishment	45
3.3.3	Soil fertility	46
3.3.4	Weed control	47
3.3.5	Insect control.....	47
3.3.6	Defoliation.....	47
3.4	Calculations.....	49
3.4.1	Meteorological conditions.....	49
3.4.2	Thermal time calculation.....	49
3.5	Statistical analysis	50

4	Lucerne establishment and DM production.....	51
4.1	Introduction.....	51
4.2	Material and methods.....	52
4.2.1	Emergence.....	52
4.2.2	Time to first trifoliate leaf.....	52
4.2.3	Seedling shoot and root biomass.....	53
4.2.4	Shoot yield	53
4.2.5	Seasonal growth rates.....	53
4.2.6	Root biomass.....	53
4.2.7	Validating the base temperature.....	54
4.2.8	Gravimetric soil water content at sowing.....	56
4.3	Results.....	57
4.3.1	Lucerne seedling establishment	57
4.3.2	Annual and seasonal DM yield	63
4.3.3	Root biomass and partitioning	72
4.4	Discussion	79
4.4.1	Establishment	79
4.4.2	DM yield	80
4.4.3	DM yield in relation to sowing date.....	81
4.4.4	Root partitioning	82
4.5	Conclusions.....	85
5	The effect of canopy development and expansion on radiation interception and growth.....	86
5.1	Introduction.....	86
5.2	Materials and Methods.....	87
5.2.1	Canopy development.....	87
5.2.2	Canopy expansion	88
5.2.3	Radiation interception	90
5.2.4	Radiation use efficiency	92
5.2.5	Canopy nitrogen content	93
5.3	Results.....	94
5.3.1	Canopy development.....	94
5.3.2	Canopy expansion	103
5.3.3	Canopy architecture	107
5.3.4	Towards explaining LAER	108
5.3.5	Radiation interception	113
5.4	Discussion	119
5.4.1	Intercepted radiation and DM yield	119
5.4.2	Canopy development.....	119
5.4.3	Canopy expansion	123
5.4.4	Radiation use efficiency and DM yield.....	125
5.5	Conclusions.....	128
6	Soil water extraction and how water limitation affects growth of lucerne....	129
6.1	Introduction.....	129
6.2	Materials and methods	130
6.2.1	Soil water	130
6.2.2	Crop water use.....	133
6.2.3	Patterns of water extraction.....	136

6.2.4	Water use efficiency.....	137
6.2.5	Quantifying the effect of water stress	138
6.2.6	Statistics	139
6.3	Results.....	141
6.3.1	Soil water deficit and plant available water capacity.....	141
6.3.2	Water use and yield.....	152
6.3.3	Water limitations and yield	157
6.4	Discussion	163
6.4.1	Plant available water and water extraction.....	163
6.4.2	DM yield in relation to water stress	167
6.5	Conclusions.....	171
7	Lucerne yield and water use after different defoliation regimes.....	172
7.1	Introduction.....	172
7.2	Material and methods.....	173
7.2.1	Experimental site.....	173
7.2.2	Agronomic management	174
7.2.3	Measurements	177
7.2.4	Statistical analysis	180
7.3	Results.....	181
7.3.1	The effect of grazing management on DM yield, forage quality and water use.....	181
7.3.2	The effect of timing of grazing on DM yield, forage quality and water use	193
7.4	Discussion	204
7.4.1	The effects of grazing management on DM yield.....	204
7.4.2	The effects of grazing management on forage quality.....	208
7.4.3	The effects of grazing management on water use.....	209
7.5	Conclusions.....	212
8	General Discussion.....	213
8.1	Introduction.....	213
8.2	Lucerne establishment and yield.....	213
8.3	Water supply and demand.....	214
8.4	Mechanisms responsible for a reduction in yield under water stress.....	216
8.5	Grazing management	217
8.5.1	Grazing management and water use	218
8.6	Conclusions.....	220
	Appendices	222
	References	254
	Acknowledgments	264

List of Tables

Table 3.1 Monthly long-term means (LTM) from 1960 to 2012 for total solar radiation (R_o), maximum (T_{max}), minimum (T_{min}) and mean (T_{mean}) air temperatures, rainfall, Penman potential evapotranspiration (EP), wind run and vapour pressure deficit (VPD) measured at the Broadfields Meteorological Station, Lincoln, Canterbury, New Zealand.	38
Table 3.2 Total seasonal rainfall, Penman potential evapotranspiration (EP) and maximum potential soil moisture deficit ($PSMD_{max}$) for two growing seasons from 1 July 2010 to 30 June 2012 for Ashley Dene and Iversen 12 at Lincoln University, Canterbury, New Zealand.	39
Table 3.3 Summary of sowing dates for two experiments conducted at Ashley Dene paddock 2MB (Ashley Dene) and Iversen Field paddock 12 (Iversen 12) at Lincoln University, Canterbury, New Zealand.	44
Table 4.1 Final population (plants/m ²), days after sowing (DAS_{50}) and thermal time ($Tt_{50}; ^\circ Cd$) requirement for 50% emergence of lucerne sown in the field at Ashley Dene and Iversen 12 over a range of sowing dates from October 2010 to February 2012 at Lincoln University, Canterbury, New Zealand.	58
Table 4.2 Days after emergence (DAE) and thermal time ($Tt; ^\circ Cd$) requirement for first trifoliate leaf appearance of lucerne sown in the field at Ashley Dene and Iversen 12 over a range of sowing dates from October 2010 to February 2012 at Lincoln University, Canterbury, New Zealand.	62
Table 4.3 Shoot and root plant dry weight (mg) and fractional partitioning of DM to roots (P_{root}) for seedling dryland lucerne at the 2 nd and 6 th trifoliate leaf growth stage at sown Ashley Dene and Iversen 12 from October 2011 to February 2012, Lincoln University, Canterbury, New Zealand.	63
Table 4.4 Total annual (1 July to 30 June) dry matter yields (t/ha) of lucerne sown on 10 dates from October 2010 to July 2012 at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	64
Table 4.5 Root biomass (t DM/ha) of lucerne in its first winter (Year 1: 13 June 2011) and second winter (Year 2: 11 July 2012) sown over a range of dates from October 2010 to February 2011 at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	73
Table 4.6 Shoot and root biomass (t DM/ha) of seedling lucerne at 50% flowering sown over a range of dates at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	74

Table 5.1	Shoot population (shoots/m ²) of lucerne grown at Ashley Dene at the end of each growth period for two seasons, subjected to different sowing dates at Lincoln University, Canterbury, New Zealand.	101
Table 5.2	Shoot population (shoots/m ²) of lucerne grown at Iversen 12 at the end of each growth period for two seasons, subjected to different sowing dates at Lincoln University, Canterbury, New Zealand.	102
Table 5.3	Seasonal accumulated intercepted radiation (R _i ; MJ/m ²) and shoot radiation use efficiency (RUE _{shoot} ; g DM/MJ) for lucerne sown on five dates in the establishment (sowing to June 2011) and year two (June 2011 to July 2012) at Ashley Dene, Lincoln University, Canterbury, New Zealand.	115
Table 5.4	Seasonal accumulated intercepted radiation (R _i ; MJ/m ²) and shoot radiation use efficiency (RUE _{shoot} ; g DM/MJ) for lucerne sown on five dates in the establishment (sowing to June 2011) and year two (June 2011 to July 2012) at Iversen 12, Lincoln University, Canterbury, New Zealand.	116
Table 5.5	Shoot (RUE _{shoot}) and total (RUE _{total}) radiation use efficiency (RUE; g DM/MJ) for lucerne sown on five dates in the establishment (sowing to June 2012) season at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	118
Table 6.1	Maximum soil water deficit (mm) of dryland lucerne measured in the establishment (2010/11) and second (2011/12) growth season at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	142
Table 6.2	Seasonal accumulated water use (WU; mm) and water use efficiency (WUE; kg DM/ha/mm) for lucerne sown on five dates in the establishment (sowing to June 2011) and second year (June 2011 to July 2012) at Ashley Dene, Lincoln University, Canterbury, New Zealand.	154
Table 6.3	Seasonal accumulated water use (WU; mm) and water use efficiency (WUE; kg DM/ha/mm) for lucerne sown on five dates in the establishment (sowing to June 2011) and second year (June 2011 to July 2012) at Iversen 12, Lincoln University, Canterbury, New Zealand.	155
Table 7.1	Cultivars and their dormancy ratings used in two experiments in paddock H7 at Ashley Dene, Lincoln University, Canterbury, New Zealand.	175
Table 7.2	Accumulated DM yield (t DM/ha) of dryland lucerne from June 2011 to 5 December 2011 (Spring DM) and then in total to 13 June 2012 when subjected to three grazing managements at Ashley Dene, Lincoln University, Canterbury, New Zealand.	182

Table 7.3 Maximum soil water deficit (SWD _{max} ; mm), crop water use (E _T ; mm), water use efficiency (WUE; kg DM/ha/mm) and soil evaporation (E _s ; mm) of dryland lucerne from 8 June 2011 to 5 December 2011 subjected to three grazing managements at Ashley Dene, Lincoln University, Canterbury, New Zealand.	186
Table 7.4 Annual dry matter yield (DM; t DM/ha), intercepted total radiation (R _i ; MJ/m ²) and shoot radiation use efficiency (RUE _{shoot} ; g DM/MJ) of dryland lucerne within a rotationally grazed six paddock system from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.	193
Table 7.5 Maximum soil water deficit (SWD _{max} ; mm), crop water use (E _T ; mm), water use efficiency (WUE; kg DM/ha/mm) and soil evaporation (E _s ; mm) of dryland lucerne grown within a rotationally grazed six paddock system from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.	196
Table 7.6 Mean and total annual energy and crude protein content of six dryland lucerne paddocks in a rotationally grazed system over six growth cycles from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.	200
Table 7.7 Date of grazing, DM yield (t DM/ha) and post-grazing residual (t DM/ha), DM consumed (t DM/ha) and utilisation (%) for the first regrowth phase from September to October 2012 for six paddocks within a rotationally grazed system at Ashley Dene, Lincoln University, Canterbury, New Zealand.	202

List of Figures

Figure 1.1 Flow diagram of thesis structure.....	5
Figure 2.1 Monthly growth rate (●) and air temperature (○) for irrigated lucerne from November 1968 to December 1969 at Lincoln University, Canterbury, New Zealand. (Adapted from Hoglund <i>et al.</i> (1974)).....	12
Figure 2.2 Broken-stick threshold model for thermal time (T_t) accumulation at different mean air temperatures as proposed (Moot <i>et al.</i> , 2000).	14
Figure 2.3 Growth rate in relation to mean air temperature (T_{air}) for irrigated lucerne from November 1968 to December 1967 at Lincoln University, Canterbury, New Zealand. (Analysed from data presented in Figure 2.1, adapted from Hoglund <i>et al.</i> (1974)).....	15
Figure 2.4 The relationship between leaf area expansion rate (LAER) and photoperiod (From Teixeira <i>et al.</i> (2009)).	17
Figure 2.5 The relationship between phyllochron (mainstem leaf appearance rate; °Cd) and photoperiod (From Teixeira <i>et al.</i> (2009)).....	18
Figure 2.6 The relationship between total radiation use efficiency (RUE_{total}) of irrigated lucerne grown at Lincoln University, Canterbury, New Zealand (From Brown <i>et al.</i> (2006b)).....	21
Figure 2.7 Fractional partitioning of DM to crown plus taproot in irrigated lucerne crops defoliated on a 42 day rotation in relation to increasing (IPp) and decreasing (DPp) photoperiod (a) and the relationship between 100 mm soil and air temperature grown at Lincoln University, Canterbury, New Zealand (Adapted from Teixeira <i>et al.</i> (2008)).....	23
Figure 2.8 Relative effect on yield forming processes ($f_{dry/irr}$) in lucerne of degree of water limitation (T/T_D) for leaf area index expansion (a), mainstem node appearance rate (b), and radiation use efficiency (c) at Lincoln University, Canterbury, New Zealand (From Brown <i>et al.</i> (2009)).....	29
Figure 3.1 Upper (●) and lower (○) limits of mature lucerne water extraction to 2.3 metres at Ashley Dene (A) and Iversen Field (B) at Lincoln University, Canterbury, New Zealand. Shaded areas and numbers represent plant available water content (Adapted from Moot <i>et al.</i> (2008) and Brown (2004)).	36
Figure 3.2 Monthly rainfall for Ashley Dene (■) and Iversen 12 (■) and Penman potential evapotranspiration (EP; -●-) from 1 July 2010 to 30 June 2012 at Lincoln University, Canterbury, New Zealand.	40

Figure 3.3 Seasonal pattern of potential soil water deficit (PSMD) for two seasons from 1 July 2010 to 30 June 2012 for Ashley Dene (—) and Iversen 12 (—) at Lincoln University, Canterbury, New Zealand. --- marks the long-term mean of maximum PSMD (PSMD _{max} ; 520 mm).	41
Figure 3.4 Mean daily solar radiation (■) and mean daily air temperature for Ashley Dene (—○—) and Iversen 12 (—●—) for monthly periods from 1 July 2010 to 30 June 2012, Lincoln University, Canterbury, New Zealand.	42
Figure 3.5 Mean daily vapour pressure deficit (■) and wind run (—●—) for monthly periods from 1 July 2010 to 30 June 2012. Data were obtained from Broadfields Meteorological Station, Canterbury, New Zealand.	43
Figure 4.1 Number of days (a) and emergence rate (b) to 50% final seedling emergence, and number of days (c) and leaf appearance rate (d) from 50% emergence to first trifoliate leaf of lucerne sown at different times; October (○), November (□), December (△), January (▽) and February (◇) in the field from October 2011 to February 2012 at Ashley Dene (open) and Iversen 12 (closed) at Lincoln University, Canterbury, New Zealand.	55
Figure 4.2 The field emergence of lucerne sown on 10 dates at Ashley Dene (○) and Iversen 12 (●) over two seasons from October 2010 to March 2012 at Lincoln University, Canterbury, New Zealand.	59
Figure 4.3 Gravimetric water content at sowing and daily rainfall (■) for Ashley Dene (○) and Iversen 12 (●) for 10 sowing dates over two seasons from October 2010 to March 2012 at Lincoln University, Canterbury, New Zealand.	60
Figure 4.4 Thermal time to 50% field emergence (Tt ₅₀) in relation to gravimetric water content (GWC) at sowing (0-20 mm) for lucerne sown at Ashley Dene (○) and Iversen 12 (●) from October 2010 to February 2012 at Lincoln University, Canterbury, New Zealand.	61
Figure 4.5 Total annual shoot yield of lucerne sown from October to February at Ashley Dene (○) and Iversen 12 (●) in year one (black; sowing to June 2011 and red; sowing to June 2012) and year two (June 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.	65
Figure 4.6 Yield accumulated within regrowth cycles from 1 October 2010 to 11 July 2012 for lucerne crops sown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.	66
Figure 4.7 Yield accumulated within regrowth cycles from 1 October 2010 to 11 July 2012 for lucerne crops sown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand.	68

Figure 4.8 Linear growth rates of lucerne sown on five dates; SD1 (○), SD2 (□), SD3 (△), SD4 (▽) and SD5 (◇) at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	70
Figure 4.9 Linear growth rate of two year old lucerne crops in relation to increasing (—) and decreasing (---) mean air temperature over the regrowth cycle at Ashley Dene (○) and Iversen 12 (●), Lincoln University, Canterbury, New Zealand.	71
Figure 4.10 Fractional partitioning of dry matter to roots (P_{root}) in relation to photoperiod at emergence for seedling lucerne at 50% flowering over a range of sowing dates at Ashley Dene (○) and Iversen 12 (●), Lincoln University, Canterbury, New Zealand.	75
Figure 4.11 Accumulated shoot (●) and root (○) dry matter yields for lucerne sown on five dates at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	77
Figure 4.12 Fractional partitioning of dry matter to roots (P_{root}) in relation to increasing (●) and decreasing (○) photoperiod at the start of regrowth periods for lucerne grown at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.	78
Figure 4.13 Yield accumulation of lucerne sown on 17 February 2012 at Ashley Dene (○) and Iversen 12 (●) in relation to predicted potential yield of forage kale (····), oats (—) and annual ryegrass (— — —) at Lincoln University, Canterbury, New Zealand.	82
Figure 5.1 Leaf area (cm^2) of seedling (○○) and regrowth (●●) lucerne shoots from Ashley Dene (red) and Iversen 12 (black) measured by LICOR 3100 area meter intact (leaf area _{shoot}) in relation to leaf area of the same shoots when leaf and stem fractions were measured independently (leaf area _{leaf+stem}).	89
Figure 5.2 Leaf area index (LAI) measured non-destructively using the sunscan canopy analyser in relation to LAI measured destructively of seedling (○○) and regrowth (●●) lucerne, grown at Ashley Dene (red) and Iversen 12 (black) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.	91
Figure 5.3 The natural log of solar radiation transmission ($\text{Ln}(R/R_0)$; measured with sunscan canopy analyser) in relation to leaf area index (LAI; measured destructively) of seedling (○○) and regrowth (●●) lucerne, grown at Ashley Dene (red) and Iversen 12 (black) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.	92

Figure 5.4 The number of mainstem (●) and total (○) nodes for seedling lucerne in relation to thermal time accumulation from sowing to 50% flowering grown at Ashley Dene and Iversen 12 after sowing on five dates from October 2011 to February 2012 at Lincoln University, Canterbury, New Zealand.	95
Figure 5.5 The number of mainstem (●) and total (○) nodes for second year lucerne grown at Ashley Dene and Iversen 12 from June 2011 to July 2012 at Lincoln University, Canterbury, New Zealand.	97
Figure 5.6 Phyllochron of mainstem seedling (○) and regrowth (●) lucerne measured from October 2010 to July 2012 at Ashley Dene and Iversen 12 at Lincoln University, Canterbury, New Zealand.	98
Figure 5.7 Phyllochron of seedling (a,c) and regrowth (b,d) lucerne in response to increasing (●) and decreasing (○) photoperiods at the start of each growth period when grown at Ashley Dene (a,b) and Iversen 12 (c,d), Lincoln University, Canterbury, New Zealand.	99
Figure 5.8 The rate of secondary node appearance (branching) in relation to the rate of mainstem node appearance (phyllochron) for dryland lucerne crops grown at Ashley Dene (○) and Iversen 12 (●) in 2011/2012, Lincoln University, Canterbury, New Zealand.	100
Figure 5.9 Leaf area index of lucerne grown at Ashley Dene from five sowing dates over two seasons from October 2011 to July 2012 at Lincoln University, Canterbury, New Zealand.	104
Figure 5.10 Leaf area index of lucerne grown at Iversen 12 from five sowing dates over two seasons from October 2011 to July 2012 at Lincoln University, Canterbury, New Zealand.	105
Figure 5.11 Leaf area expansion rate (LAER) of seedling lucerne sown on five dates (present in red); SD1 (October; ○), SD2 (November; □), SD3 (December; △), SD4 (January; ▽) and SD5 (February; ◇) and subsequent regrowth phases from October 2010 to July 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.....	106
Figure 5.12 Leaf area expansion rate (LAER) of seedling lucerne sown on five dates (present in red); SD1 (October; ○), SD2 (November; □), SD3 (December; △), SD4 (January; ▽) and SD5 (February; ◇) and subsequent regrowth phases from October 2010 to July 2012 at Iversen 12, Lincoln University, Canterbury, New Zealand.	106
Figure 5.13 The relationship between leaf area index and the fractional solar radiation interception (R/R_o) of seedling (○○) and regrowth (●●) lucerne, grown at Ashley Dene (red) and Iversen 12 (black) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.....	107

- Figure 5.14** Leaf area index (LAI) in relation to total leaves per shoot for dryland lucerne grown at Ashley Dene (○□△) and Iversen 12 (●■▲) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand. 108
- Figure 5.15** Leaf area index (LAI) in relation to total number of leaves per m² for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand. 109
- Figure 5.16** Mean leaf size (mm²) for individual regrowth phases in relation to date (a) and mean air temperature (b) for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand. 110
- Figure 5.17** Leaf area expansion rate (LAER) in relation to mean leaf size for individual regrowth phases for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand. 111
- Figure 5.18** Crop nitrogen (N) uptake in relation to shoot yield for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand. 112
- Figure 5.19** Crop nitrogen (N) uptake in relation to leaf area index (LAI) for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand. 113
- Figure 5.20** Relationship between accumulated shoot yield and accumulated intercepted total solar radiation by lucerne crops sown on five dates at Ashley Dene (○) and Iversen 12 (●) for both the establishment (2010/11) and the subsequent growth season (2011/12) at Lincoln University, Canterbury, New Zealand. 114
- Figure 5.21** Shoot radiation use efficiency (RUE_{shoot}) of lucerne sown on five dates; October (○), November (□), December (△), January (▽) and February (◇) at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand. 117
- Figure 5.22** Measured (●) and temperature adjusted (○) shoot radiation use efficiency (RUE_{shoot}) for second year dryland lucerne sown on five dates in the previous season; October (○), November (□), December (△), January (▽) and February (◇) at Iversen 12 from July 2011 to July 2012, Lincoln University, Canterbury, New Zealand. 126
- Figure 6.1** Upper (●) and lower (○) limits of mature lucerne water extraction to 2.3 metres at Ashley Dene (A) and Iversen Field (B) at Lincoln University, Canterbury, New Zealand. Shaded areas and numbers represent plant available water content. 132

Figure 6.2 Comparison of measured (○●) and predicted (—) soil water content (SWC) for the 0-0.2 m soil layer of fallow treatments at Ashley Dene (A, ○) and Iversen 12 (B, ●), Lincoln University, Canterbury, New Zealand.....	135
Figure 6.3 Soil water deficit to 2.3 m from October 2010 to July 2012 for dryland lucerne sown on five dates at Ashley Dene and Iversen 12 Lincoln, University, Canterbury, New Zealand.	143
Figure 6.4 Upper (●) and lower (○) limits of lucerne water extraction measured in the establishment (2010/11) and subsequent (2011/12) year sown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.....	145
Figure 6.5 Upper (●) and lower (○) limits of lucerne water extraction measured in the establishment (2010/11) and subsequent (2011/12) year sown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand....	146
Figure 6.6 Water extraction patterns at five 0.1 m soil layers for a dryland lucerne crop in the second season from August 2011 to July 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.....	148
Figure 6.7 Water extraction patterns at five 0.1 m soil layers for a dryland lucerne crop in the second season from August 2011 to July 2012 at Iversen 12, Lincoln University, Canterbury, New Zealand.	149
Figure 6.8 Time of water extraction (t_c) for each individual soil layer for seedling (a,b) and regrowth (c,d) dryland lucerne at Ashley Dene (○) and Iversen 12 (●) for the 2011/12 season at Lincoln University, Canterbury, New Zealand.....	151
Figure 6.9 Extraction decay constant ($-k_l$) of second year dryland lucerne over a 2.25 m soil profile at Ashley Dene (○) and Iversen (●) in the 2011/12 season at Lincoln University, Canterbury, New Zealand. Error bar represent l.s.d ($P = 0.05$).	152
Figure 6.10 Accumulated shoot yield in relation to accumulated water use for lucerne crops sown on five dates at Ashley Dene (○) and Iversen 12 (●) for both the establishment (2010/11) and subsequent growth season (2011/12) at Lincoln University, Canterbury, New Zealand.	153
Figure 6.11 Water use efficiency of lucerne sown on five dates; October (○), November (□), December (△), January (▽) and February (◇) at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.....	156

Figure 6.12 Transpiration (E_T) from dryland lucerne grown at Ashley Dene (a; ○) and Iversen 12 (b; ●) compared with transpiration demand (EP_T ; —) from June 2011 to July 2012, Lincoln University, Canterbury, New Zealand. Values above each regrowth period quantify transpiration relative to transpiration demand (E_T/EP_T).....	158
Figure 6.13 The mean soil water deficit in relation to the water stress (E_T/EP_T) for individual regrowth cycles of dryland lucerne at Ashley Dene (○) and Iversen 12 (●) Lincoln University, Canterbury, New Zealand.	159
Figure 6.14 Observed phyllochron of dryland lucerne relative to a predicted irrigated crop ($f_{obs/pred}$) in relation to water stress (E_T/EP_T) of crops grown at Ashley Dene (○) and Iversen 12 (●) 2011/2012, Lincoln University, Canterbury, New Zealand.	160
Figure 6.15 Rate of branching (axillary leaves per mainstem node) for dryland lucerne in relation to water stress (E_T/EP_T) of crops grown at Ashley Dene (○) and Iversen 12 (●) 2011/2012, Lincoln University, Canterbury, New Zealand.	160
Figure 6.16 Observed LAER (a) and RUE_{shoot} (b) of dryland lucerne relative to a predicted irrigated crop ($f_{obs/pred}$) in relation to water stress (E_T/EP_T) of crops grown at Ashley Dene (○) and Iversen 12 (●) 2011/2012, Lincoln University, Canterbury, New Zealand.	162
Figure 6.17 Relative effect ($f_{obs/pred}$) on LAER (a) and RUE_{shoot} (b) in lucerne in relation to water stress (E_T/EP_T) in Ashley Dene (○) and Iversen 12 (●) from 2011/2012 redrawn with data from Brown <i>et al.</i> (2009) of dryland relative to irrigated lucerne ($f_{dry/irr}$) from 2000/2002 (■) at Lincoln University, Canterbury, New Zealand.	170
Figure 7.1 Crop mass of dryland lucerne subjected to three grazing managements from 27 September to 5 December 2011; set stocked (△), semi-set stocked (□) and rotationally grazed (○) at Lincoln University, Canterbury, New Zealand.	183
Figure 7.2 Leaf area index of dryland lucerne subjected to three grazing managements from 27 September to 5 December 2011; set stocked (△), semi-set stocked (□) and rotationally grazed (○) at Lincoln University, Canterbury, New Zealand.	184
Figure 7.3 Relationship between accumulated shoot yield and accumulated total intercepted radiation of dryland lucerne subjected to three grazing management treatments from 27 September to 5 December 2011; set stocked (△), semi-set stocked (□) and rotational (○) at Lincoln University, Canterbury, New Zealand.	184

- Figure 7.4** Canopy nitrogen (N) uptake in relation to leaf area index (LAI) of dryland lucerne subjected to three grazing managements from 27 September to 5 December 2011; set stocked (\triangle), semi-set stocked (\square) and rotational (\circ) at Lincoln University, Canterbury, New Zealand. 185
- Figure 7.5** Accumulated crop water use (red), total water use (black) and daily rainfall (\blacksquare) of dryland lucerne subjected to three grazing managements; set- stocked (\cdots), semi set-stocked ($- - -$) and rotational grazing ($—$) from July to December 2012 at Lincoln University, Canterbury, New Zealand. 187
- Figure 7.6** Transpiration (E_T) in relation to intercepted radiation (R_i) accumulated from 1 July to 5 December 2011 for dryland lucerne subjected to three grazing management treatments from 27 September to 5 December 2011; set stocked (\triangle), semi-set stocked (\square) and rotational (\circ) at Lincoln University, Canterbury, New Zealand. 188
- Figure 7.7** Accumulated shoot yield of dryland lucerne from June 2011 to June 2012 subjected to three grazing managements from 27 September to 5 December 2011; set stocked (\triangle), semi-set stocked (\square) and rotational grazed (\circ) at Lincoln University, Canterbury, New Zealand. 189
- Figure 7.8** Soil water deficit to 2.3 m for June 2011 to July 2012 for dryland lucerne subjected to three grazing managements; set stocked (\triangle), semi-set stocked (\square) and rotational grazing (\circ) at Lincoln University, Canterbury, New Zealand. 190
- Figure 7.9** Relationship between accumulated shoot yield and accumulated total intercepted radiation of dryland lucerne from June 2011 to June 2012 subjected to three grazing managements; set stocked (\triangle), semi-set stocked (\square) and rotational grazing (\circ) at Lincoln University, Canterbury, New Zealand. 191
- Figure 7.10** Accumulated shoot yield in relation to accumulated crop water use (E_T) for dryland lucerne from June 2011 to June 2012 subjected to three grazing managements treatments; set stocked (\triangle), semi-set stocked (\square) and rotationally grazed (\circ) at Lincoln University, Canterbury, New Zealand. 192
- Figure 7.11** Accumulated shoot yield of dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 194

- Figure 7.12** Relationship between accumulated shoot yield and accumulated total intercepted radiation of dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 195
- Figure 7.13** Accumulated shoot yield in relation to accumulated water use of dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 196
- Figure 7.14** Transpiration (E_T) in relation to intercepted radiation (R_i) accumulated for dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 197
- Figure 7.15** Transpiration (E_T) in relation to intercepted radiation (R_i) accumulated within regrowth periods for dryland lucerne within a rotationally grazed six paddock system (paddock one shown) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 198
- Figure 7.16** Transpiration per unit of intercepted radiation (E_T/R_i) in relation to mean vapour pressure deficit (VPA) for dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 199
- Figure 7.17** Leaf percentage (a), energy content (MJ ME/kg DM ;b) and crude protein content (CP; c) of dryland lucerne at final harvest in a rotationally grazed system over 6 growth cycles from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand. 201
- Figure 7.18** Energy (GJ ME/ha; \circ) consumption and DM utilisation (\bullet) in relation to DM yield for the first regrowth phase from September to October 2012 for six paddocks within a rotationally grazed system at Ashley Dene, Lincoln University, Canterbury, New Zealand. 203

List of Equations

Equation 1.1	$Y = WU * WUE * HI$	2
Equation 2.1	$Y = R_o * R/R_o * RUE * HI$	11
Equation 2.2	Thermal time (Tt ; °Cd) = $\sum (T_{mean} - T_b)$	13
Equation 2.3	$R/R_o = 1 - \exp(-k * LAI)$	16
Equation 2.4	$RUE = P_n = (P_g - R_T) / R_i$	20
Equation 3.1	$PSMD_i = PSMD_{i-1} + EP_i - rainfall_i$	49
Equation 4.1	$Y(t) = a * \exp(-\exp[-b * (t - m)])$	52
Equation 4.2	$t(DAS_{50}) = m - \ln[-\ln(Y/100)]/b$	52
Equation 5.1	$y = a + c/(-b^{(x-m)})$	89
Equation 6.1	$WU = \min(E_T, EP_T)$	129
Equation 6.2	$SWC = \sum_{bot}^{top} \theta * d$	131
Equation 6.3	$WU = P_R - (SWC_E - SWC_S)$	131
Equation 6.4	$WU_{daily} = (WU/EP) * EP_{daily}$	131
Equation 6.5	$SWD = SWD_i + WU_{daily} - R$	131
Equation 6.6	$E_{S1} = EP * (1 - R/R_o)$ when $\sum E_S \leq U$	133
Equation 6.7	$E_{S2} = \alpha * t^{1/2}$ when $\sum E_S > U$	133
Equation 6.8	$t = [(\sum E_S - U)/\alpha]^2$	134
Equation 6.9	$SWC_t = LL + PAWC \exp(-kl(t-t_c)S_c)$ $S_c = 0$ if $t \leq t_c$	136
Equation 6.10	$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (m_i - s_i)^2}$	139
Equation 7.1	$CP = N\% * 6.25$	179
Equation 7.2	$ME = DOMD * 0.16$	179

List of Abbreviations

Abbreviation	Description	Units
a.i	Active ingredient	
CP	Crude protein	%
DM	Dry matter	t/ha
DL	Critical limiting water deficit	mm
DUL	Drained upper limit	mm ³ /mm ³
EFV	Extraction front velocity	mm/day
EP	Penman potential evaporation	mm
EP _T	Potential transpiration	mm
E _S	Soil evaporation	mm
E _T	Actual transpiration	mm
$f_{obs/pred}$	Observed value/predicted value	dimensionless
GAI	Green area index	dimensionless
HI	Harvest index	dimensionless
k	extinction coefficient	dimensionless
-kl	extraction rate constant	/day
LAER	Leaf area expansion rate	m ² /m ² /°Cd
LAI	Leaf area index	dimensionless
LAI _{crit}	Critical leaf area index	dimensionless
LL	lower limit	mm ³ /mm ³
l.s.d	Least significant difference	
ME	Metabolisable energy	MJ/kg
PAWC	Plant available water content	mm
Pp	Photoperiod	h/day
P _{root}	Fractional DM partitioning	
PSWD	Potential soil water deficit	mm
R/R _o	Fractional radiation interception	dimensionless
R ²	Coefficient of determination	
R _i	Intercepted radiation	MJ/m ²
RMSD	Root mean square deviation	
R _o	Incident radiation	MJ/m ²

Abbreviation	Description	Units
RUE	Radiation use efficiency	g DM/MJ
RUE _{shoot}	Radiation use efficiency for shoot DM	g DM/MJ
RUE _{total}	Radiation use efficiency for total DM	g DM/MJ
SEM	Standard error of the mean	
SWC	Soil water content	mm
SWD	Soil water deficit	mm
SWD _{max}	Maximum annual soil water deficit	mm
T _b	Base temperature	°C
t _c	Extraction start time within an individual layer	date
T _m	Maximum temperature	°C
T _o	Optimum temperature	°C
VPD	Vapour pressure deficient	kPa
WUE	Water use efficiency	kg DM/ha/mm
Y	Yield	t DM/ha

1 General Introduction

1.1 Overview of dryland forage production in New Zealand

New Zealand has a temperate climate (White, 1999) which supports perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) as the main contributors to our pastoral agriculture. These pastures are productive and persistent in areas of high rainfall (>1200 mm) and fertile soils (Brock and Hay, 2001), but unreliable in dryland pastoral systems (Moot, 2012). The central mountain range in both islands, combined with the westerly flows creates a rain shadow on the east coast of ~2.9 M ha which receives ≤ 800 mm of annual rainfall (Brown and Green, 2003). In these regions evapotranspiration exceeds annual rainfall from 300-800 mm, which leads to potential soil moisture deficits (PSMD) between 200 to 500 mm (Salinger, 2003). In the absence of irrigation, water stress conditions develop most summers and pasture production declines when about half of the soil stored plant available water is depleted (Sheaffer *et al.*, 1988). In Canterbury, plant available water generally ranges from 50 to 150 mm/m due to the highly variable, alluvial outwash soils (Webb, 2000). Mills *et al.* (2006) showed in a dryland cocksfoot (*Dactylis glomerata* L.) pasture, yield decreased relative to a fully watered crop by 1.4% per mm beyond a critical deficit of 78 mm. To overcome summer dry conditions the area of land irrigated in Canterbury has increased three fold in the last 30 years to ~360 thousand ha, with the potential for up to 1 M ha to be irrigated (Miller and Veltman, 2004; Moot *et al.*, 2010). Dryland forage production is expected to continue on the hill country where topography limits irrigation and areas on the plains which may be restricted by water availability. However, alternative species and management strategies are required to maximise production in these water limited environments (Moot *et al.*, 2010).

There are several symptoms of dryland pastoral systems failing in these areas. These include; a decline in long term farm profitability, whereby stock production suffers from low quality forage due to invasion of less preferred species (Tozer *et al.*, 2011). Poor stock nutrition which reduces liveweight gains, and lengthens time to sale (Rattray *et al.*, 1987). This impacts on ewe fecundity in the following year, reduces pasture persistence (Clark, 2011; Milne, 2011), which requires constant expensive renewal

(Avery *et al.*, 2008). Successive droughts can lead to negative environmental impacts. For example, failed forage crops may lead to over-grazing of sensitive areas by livestock, exposing the soil surface to wind erosion (Avery *et al.*, 2008). Furthermore, there are predictions for a drier future for these farms. The average increase in surface temperature in New Zealand has been 0.7 °C in the last 150 years which has resulted in the strengthening of westerly wind flow patterns. By 2080 predictions indicate 10% less rain and an increase in PSMD of 20 to 30% in these dry east coast regions (Salinger, 2003). The adaption to a drier environment by dryland pastoral systems has resulted in a need to diversify the traditional ryegrass/white clover pasture to alternative, more suitable species (Milne, 2011; Moot, 2012). Agronomic management strategies are one approach to increase crop productivity when water is scarce (Passioura, 2006). To do this requires an understanding of how crops extract water and how this affects yield. Crop responses to water shortage in relation to environmental conditions needs to be understood as management strategies will depend on specific soil-crop combinations within a farm system.

1.2 Potential to increase dryland pasture production

Where rainfall is insufficient to meet crop demand, the accumulation of yield (Y) is related to water use (WU), described by Equation 1.1. The relationship can be further defined by the dry matter (DM) produced per unit of water transpired (water use efficiency; WUE) and the harvest index (HI), which is the conversion of biomass into usable, usually above ground herbage for forages.

Equation 1.1
$$Y = WU * WUE * HI$$

This relationship implies there is potential to increase yield in a water limited environment through each of these components. Lucerne (*Medicago sativa* L.) is a leguminous, perennial pasture species which is characterised by its deep taproot (White, 1999) and is capable of producing annual yields in excess of 20 t DM/ha under rainfed conditions (Brown *et al.*, 2005a; Teixeira, 2006) and 28 t/ha under irrigation (Hoglund *et al.*, 1974; Brown *et al.*, 2005a). Lucerne's deep taproot gives it greater drought tolerance compared with perennial ryegrass and white clover pastures through greater

access to stored water in the soil profile. For example, on a Wakanui silt loam, a free draining, deep soil, lucerne extracted 328 mm of water to a depth of 2.3 m. In comparison a perennial ryegrass pasture extracted only 243 mm of water to 1.5 m (Moot *et al.*, 2008). The lucerne crop had a WUE of 40 kg DM/ha/mm compared with the perennial ryegrass pasture of 18 kg DM/ha/mm. Together these attributes show lucerne has the ability to both extract more water and use it more efficiently than ryegrass based pastures. Therefore, lucerne as a forage crop is one strategy to increase yield when water is scarce on dryland farms. The physiology of lucerne in relation to water use will be studied in greater detail to allow the refinement of best management practices.

1.3 Research objectives

The main aim of this research was to refine best management practices for dryland lucerne crops in relation to crop water extraction. To do this two field experiments were implemented over two years; 2010/11 and 2011/12. Lucerne was grown under dryland conditions in the same climate, but on two sites which differed in plant available water capacity. The plant available water for seedling crops was manipulated by imposing a second treatment, of sowing date. Sowing date may influence root growth down the soil profile and therefore water available for extraction. The secondary aim was to examine how grazing management affected dryland lucerne yield and water use. To do this, a third and fourth experiment were implemented in 2011/2012 which involved three different grazing strategies, on an established lucerne stand.

This thesis is structured in eight chapters (Figure 1.1). Chapter 2 reviews the literature and focuses on the environmental factors which determine yield potential and physiological reasons for a reduction in yield in relation to water stress. Chapter 3 describes the experimental design and agronomic management and environmental conditions for the first two experiments, which are common to the results in Chapters 4 to 6. Research is divided into four chapters, each with specific objectives.

The objective of Chapter 4 is to establish lucerne crops on five dates from October to February on two sites which differ in plant available water. Seedling emergence will be quantified in relation to temperature and seedbed moisture content to allow comparison

between sites and years. DM yield in the establishment and subsequent year will be compared to determine the sowing date where yield is maximised for both sites. The interaction between the PAWC of the soil and sowing date will combine to produce crops which differ in yield.

The objective of Chapter 5 is to quantify the yield of these crops in relation to environmental variables as management strategies depend on the potential yield of the crop in a specific environment. To do this, yield will be related to intercepted radiation by accounting for canopy development and expansion and the efficiency with which radiation is converted to biomass.

Chapter 6 will examine how the relationships formed in Chapter 5 are influenced by water shortage. To do this, water supply will be quantified to determine water extraction patterns for the crops which differed in yield. Water stress will be quantified as crop transpiration in relation to demand, and relationships developed between the yield forming processes identified in Chapter 5 in relation to water limitation.

Chapter 7 is the final results chapter. The aim of this research is to examine if the timing of DM production can be influenced by grazing the crop at different times, through the manipulation of crop water use. To do this, the crop canopy and the pattern of intercepted radiation will be manipulated by different grazing managements and yield and water use determined.

Overall, this thesis presents a series of results that aim to refine best management practices for dryland lucerne crops in relation to crop water extraction. To do this requires understanding of the physiological drivers of plant growth and development in relation to water limitation, and these are reviewed in Chapter 2.

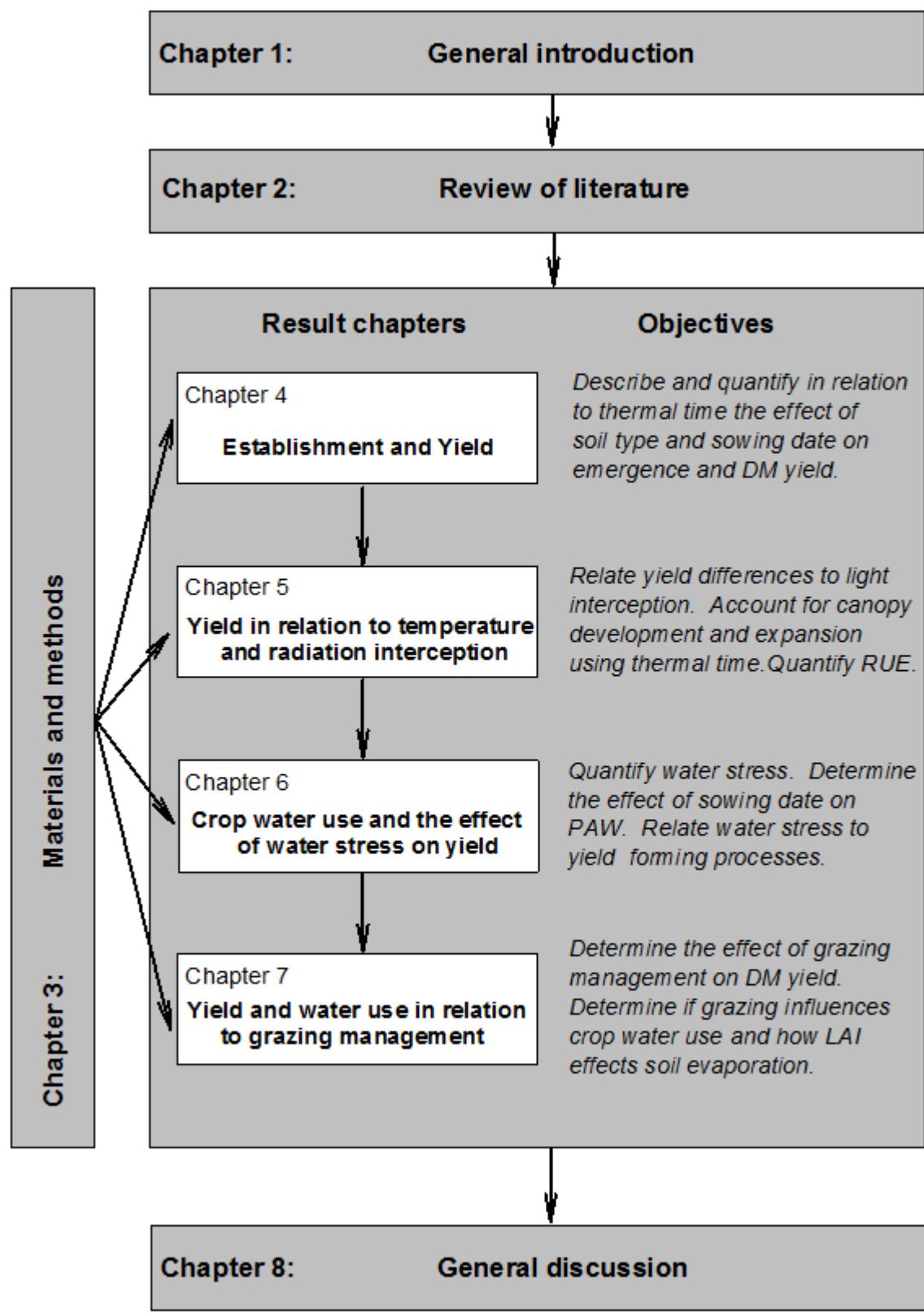


Figure 1.1 Flow diagram of thesis structure.

2 Review of literature

This chapter reviews the current literature on dryland lucerne production and explains why it is a suitable dryland pasture species. It focuses on crop establishment because sowing date is a main treatment of this research. Intercepted solar radiation by the crop canopy is the driver of both crop photosynthesis and transpiration, which contribute to yield. The mechanisms which contributed to the capture and use of radiation will be described and current literature on how temperature and water limitation affects these processes will be reviewed.

2.1 Lucerne production in New Zealand

2.1.1 Overview

The potential of lucerne as a dryland pasture species has been recognised in New Zealand for over 100 years, although the areas sown to lucerne have declined from ~220 thousand ha in mid-1970's (Purves and Wynn-Williams, 1989). The decline has been attributed to insect, and disease pressure and incorrect defoliation management often arising from conflicting requirements of the lucerne crop and grazing livestock (Purves and Wynn-Williams, 1989). Stock performance is maximised when 40-60% of the farm is under lucerne (White, 1982), which requires systemic changes to the farm system in regard to both animal and plant management (Avery *et al.*, 2008). Thus, as stated by Langer (1968), the management of lucerne for optimum yield in a range of soil, climate and defoliation regimes is the most important question. This can be answered and refined through understanding the physiological drivers of lucerne growth (Moot *et al.*, 2003).

In New Zealand, lucerne is promoted as a specialist forage crop. For example, as a high quality pasture for lamb finishing (e.g. McGowan *et al.* (2003)), supplementary feed to integrate into dairy systems (e.g. Rawnsley *et al.* (2013)), and as a conserved forage for feeding during pasture deficits on dryland sheep and beef farms. Exploitation of lucerne's ability to extract water from below the root zone of grass based pastures can reduce drainage (Dolling *et al.*, 2005) which has environmental benefits. For example, Betteridge *et al.* (2007) showed lucerne could be used as a species to mitigate nitrogen

loss from grazed pastures. They reported lucerne yielded 14% more than a ryegrass/white clover pasture and leached 37% less nitrate at 0.6 m depth, although this may further be reduced because lucerne can extract water beyond this depth.

2.1.2 DM yield

Lucerne is grown in a wide range of environments and soil types in New Zealand and therefore reported annual yield ranges from 2.0 to 28.0 t DM/ha/year. The lower yield reported by Musgrave (1977) was for lucerne sown into soil with a pH of 5.5 and seedbed described as ‘rubbly’ which established 21 plants/m². This is below the suggested threshold of 30 to 45 plants/m² to maximise yield (Palmer and Wynn-Williams, 1976; Teixeira *et al.*, 2007a). Lucerne establishment is discussed in Section 2.6. Successful lucerne establishment can increase DM yield three fold relative to poor quality browntop (*Agrostis capillaris*) pastures (Kearney *et al.*, 2010) and lucerne consistently yields ~40% more than grass based pastures in a dryland environment (Iversen and Calder, 1956; Douglas, 1986; Moot *et al.*, 2008). Iversen and Calder (1956) reported an annual yield of 5.1 t DM/ha for lucerne grown on a stony Lismore silt loam, consistent with that in the current research. They found two thirds of the DM production occurred in spring but, compared over five years, lucerne had the lowest coefficient of variability in yield relative to grass based pastures. This suggests stored soil water contributes a larger proportion to yield than that of the shallower rooting pasture species. Lucerne yields increase with greater plant available water. Janson and Knight (1973) reported the yield of lucerne on a stony silt loam with a PAWC of 50 mm/m soil increased from 4.8 to 15.6 t DM/ha when irrigation was applied. Furthermore, Brown *et al.* (2003) consistently grew 20 t DM/ha from a dryland crop on a Wakanui silt loam with PAWC a of 150 mm/m. The physiological basis for yield and how water limitation affects this are discussed in the second part of this review.

2.1.3 Forage quality and animal production

Lucerne is high in metabolisable energy (ME) and crude protein (CP) and stock liveweight gain (LWG) of lambs grazing lucerne has been shown to be double that of grass based pastures in a dryland environment (Ulyatt, 1978; Brown *et al.*, 2006a).

Brown *et al.* (2005a) reported lucerne had relatively stable leaf and stem ME of 11.6 and 9.4 MJ/kg DM, respectively and 29.1 and 11.6% for CP. Forage quality was predominantly driven by the leaf to stem ratio, which decreased as regrowth duration increased due to the lignification of the stem which lowers digestibility (Fletcher, 1976). For example, Allison and Vartha (1973) reported quality could be improved by reducing the regrowth duration from 5 to 4 weeks, noting leaf percentage increased from 55 to 65%. However, increased defoliation frequency lengthens the time the canopy is incomplete which allows germination of weed seeds and can reduce the stand persistence (Palmer, 1982). Hoglund *et al.* (1974) showed weed composition of total DM decreased from 50% to <5% when defoliation was lengthened from pre-bud to flowering. The ability of lucerne to fix atmospheric nitrogen maintains CP of forage in dryland farm systems which often receive little nitrogen fertiliser. Irrespective of regrowth duration, these authors reported annual CP yields of ~2 t/ha, four fold that reported by Mills *et al.* (2006) for a dryland nitrogen deficient cocksfoot pasture. Elliott and Kerse (1974) reviewed on-farm lucerne areas and stocking rate and found farms with >15% of total area in lucerne had an average carrying capacity of 1 stock unit (s.u)/ha higher. Further development of lucerne beyond this attributed directly to 4 to 5 extra s.u per ha, with the recommendation that 40-60% of the farm should be in lucerne to maximise lamb LWG (White, 1982).

2.1.4 Defoliation management

The traditional recommendation for defoliation management of lucerne was to wait until the plant had reached 10% flowering before cutting or grazing (Janson, 1982). This was mainly due to the formation of basal buds which were observed at this time. However, Janson (1975) reported defoliation stimulated bud formation. He showed that in vegetative lucerne two weeks following cutting the crowns had initiated a similar number of new basal shoots as the crop which had been left to flower. When sunlight passes through the canopy it is absorbed by leaves. This alters the quality of light to the underlying layers, in particular the red to far-red (R:FR) ratio decreases, which suppresses growth and development (Hay and Walker, 1989). Peri (2002) used artificial shade to halve the R:FR relative to full sunlight. This resulted in reduced LAI caused by a lower tiller population in cocksfoot. Defoliation returns the R:FR to that of

full sunlight, and induces bud expansion. Frequent defoliation increased the lag period for bud formation, which delayed regrowth. Throughout the year, this lag period resulted in a decline in yield with increasing frequency of defoliation (Vartha, 1973; Hoglund *et al.*, 1974; Teixeira *et al.*, 2007c) and reduced plant population, which favoured ingress of weeds (Palmer, 1982) and decreased stand persistence. For example, Langer and Steinke (1965) reported cutting lucerne every 20 days (6 cuts/year) halved the DM yield compared with cutting every 40 days (3 cuts/year). Hoglund *et al.* (1974) showed yield increased when cutting time was lengthened from bud initiation (10.3 t DM/ha) to first flower (15.6 t DM). Teixeira *et al.* (2007c) reported a similar response, where the decline in yield was proportional to the amount of light intercepted by the canopy. Grazing management has been refined through greater understanding of lucerne physiology and reviewed by Moot *et al.* (2003), and then implemented successfully on-farm (Avery *et al.*, 2008). To reduce the influence of regrowth interval on the current research, defoliation will be standardised across the experiments based on crop phenology (Section 3.3.6).

2.1.4.1 *Continuous grazing*

The literature shows there is generally a reduction in yield and stand persistence when lucerne is continuously grazed. For example, O'Connor (1970) showed yield of lucerne continuously grazed in the spring and summer was 75% less than that which had been intensively grazed for 12 days, on a rotational basis. Janson (1974) reported growth rate was a third for a crop continuously grazed compared with a rotational grazed crop, which resulted in annual DM yields of 13.0 and 18.3 t DM/ha, respectively. The authors noted continuous grazing damaged basal buds which reduced regrowth capacity. The result of this has been recommendations against continuous grazing of lucerne at any time (Janson, 1982; Moot *et al.*, 2003).

Stock selectively graze the leaf and soft stem fractions first which removes apices and interrupts growth. New growth depends on the initiation of new shoots from basal buds which requires the remobilisation of assimilates stored within the taproot and crown (Avice *et al.*, 1996). As grazing pressure increases these new shoots are removed before full expansion, and their contribution to crop canopy and radiation interception

declines. Continuous grazing over a longer term depletes root reserves which increases plant mortality (Teixeira *et al.*, 2007b; Teixeira *et al.*, 2007c). Thus, stocking rate and grazing duration are two key factors which need to be taken into account if set stocking lucerne. O'Connor (1970) continuously grazed lucerne from spring for five months, which depleted perennial reserves and did not allow replenishment during the autumn. Janson (1974) implemented a stocking rate of 30 ewes with 1.3 lambs/ha, feed demand exceeded feed supply and plots were destocked within six weeks of the start of grazing.

Based on the review of grazing management literature and plant growth a more appropriate continuous grazing management regime would be to set stock lucerne at a level to maintain a cover of 2 to 3 t DM/ha. This would allow the expansion of new shoots, maintain the interception of radiation, while reducing light availability to weeds. In a dryland Canterbury environment, a grazing duration of ~3 months is available from spring until the onset of drought in early December. Then the crop is destocked and rotationally grazed in autumn to allow replenishment of perennial DM. To understand how different grazing strategies affect yield, and thus further refine lucerne management practices, yield needs to be quantified in relation to the environment. This requires understanding the physiological drivers of lucerne growth, which are reviewed in Section 2.2.

2.2 Environmental factors that determine lucerne yield

2.2.1 Crop growth, development and yield

Crop yield is the result of plant growth and development (Hay and Walker, 1989). Development is the morphological change of the crop dimensions through distinct events; from germination to maturity. Plant development is driven by temperature and modified by photoperiod (Pp). Brown and Moot (2004) showed that for individual lucerne regrowth cycles the rate of mainstem leaf appearance (phyllochron) occurred at a constant rate in relation to the accumulation of temperature but increased from 37 °Cd in spring, when Pp was 11.4 h, to 60 °Cd when Pp increased to 15.7 h in late summer. Growth refers to the increase in crop DM as the net result of gain through photosynthesis and loss via respiration (Hay and Walker, 1989). Photosynthesis occurs in the chloroplasts, found in crop leaves. During this process incident light energy is used to reduce atmospheric CO₂ and water to produce carbohydrate. The formation of yield, which includes both crop development and growth, can be described by Equation 2.1:

Equation 2.1
$$Y = R_o * R/R_o * RUE * HI$$

Where yield (Y) is the quantity of useable dry matter (DM), which is the result of the quantity of solar radiation (R_o), and the fraction intercepted by the canopy (R/R_o), RUE is the radiation use efficiency of conversion of R/R_o to DM. HI represents the harvest index which is the fraction of total DM available for harvest (Monteith, 1977; Gallagher and Biscoe, 1978). The HI for forage crops, grazed in situ can not be defined by a single index. The ability to harvest DM is a result of utilisation by livestock which is influenced by environmental and agronomic factors (White, 1999). In the current study DM yield is the amount of above ground DM, excluding plant crowns. To be able to explain the effect of water stress on crop yield, it is necessary to understand how environmental factors, temperature and solar radiation, affect potential yield.

2.2.2 Temperature

Plant growth and development rate generally increase with temperature (Monteith, 1972; Gallagher and Biscoe, 1978). Hoglund *et al.* (1974) showed irrigated lucerne grown in Canterbury had a growth rate of 150 kg DM/ha/day during summer when mean air temperature was 18 °C which decreased to 25 kg DM/ha/day in winter when temperature decreased to 5 °C (Figure 2.1).

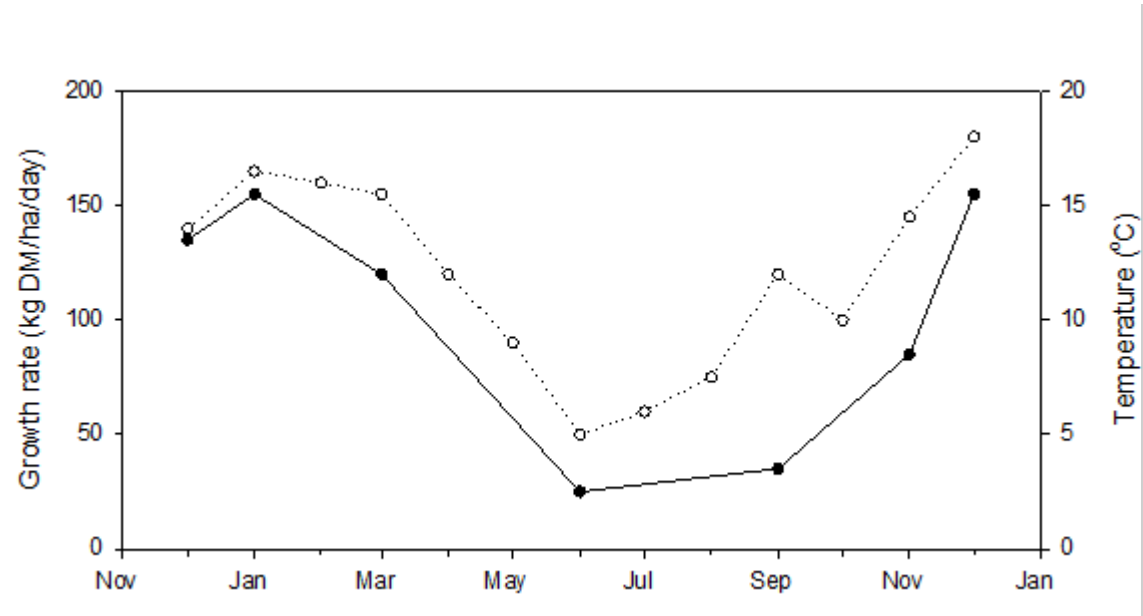


Figure 2.1 Monthly growth rate (●) and air temperature (○) for irrigated lucerne from November 1968 to December 1969 at Lincoln University, Canterbury, New Zealand. (Adapted from Hoglund *et al.* (1974)).

2.2.2.1 Quantifying temperature, thermal time

The effect of temperature on development and growth can be quantified using thermal time (T_t ; °Cd), which allows the comparison of rates between sites and temperature regimes. The calculation of T_t is often based on three cardinal temperatures; generally development rate increases linearly above a base temperature (T_b) to an optimum temperature (T_o) with a linear decrease to a maximum temperature (T_m) (Bonhomme, 2000; Moot *et al.*, 2000). Thermal time is accumulated on a daily basis from the mean daily temperature, less T_b , and can be calculated using Equation 2.2;

Equation 2.2 Thermal time (Tt; °Cd) = $\sum (T_{\text{mean}} - T_b)$

Where, $T_{\text{mean}} = (T_{\text{max}} + T_{\text{min}})/2$

For example, Moot *et al.* (2000) showed white clover germinated in 12 days when soil temperature was 5 °C compared with 4 days when at 15 °C. The rate of germination relative to temperature showed a strong ($R^2 = 0.98$) linear relationship, thus the thermal time for germination was consistent at 57 °Cd ($T_b = 0$ °C). Fick *et al.* (1988) defined the cardinal temperatures for lucerne and suggested the thresholds were; a T_b of 5 °C, T_o of 30 °C and T_m of 40 °C. Moot *et al.* (2001) showed results of lucerne grown in a cool climate that suggested this T_b was too high. Furthermore, Bonhomme (2000) suggested the Tt became non-linear at lower temperatures which is more relevant for crops grown in a temperate environment where T_{mean} is closer to T_b . Moot *et al.* (2001) presented a broken-stick threshold model for lucerne to account for this (Figure 2.2). Tt is zero for temperatures less than the T_b of 1.0 °C, which is consistent with a variety of temperate pasture species (Moot *et al.*, 2000; Monks *et al.*, 2009). Tt is accumulated linearly from T_b until 15 °C at a rate of 0.7 °Cd/°C and then at a rate of 1.0 °Cd/°C until 30 °C. Masiunas and Carpenter (1984) also showed lucerne T_m of 40 °C. The upper threshold is not usually required in our temperate environment because T_{mean} does not exceed T_o . The Tt calculation can further be improved by using diurnal temperature rather than T_{mean} (Jones and Kiniry, 1986). This method calculates Tt at three hourly intervals which are integrated over one day, to get the daily mean value. This model for Tt accumulation will be used in the current research.

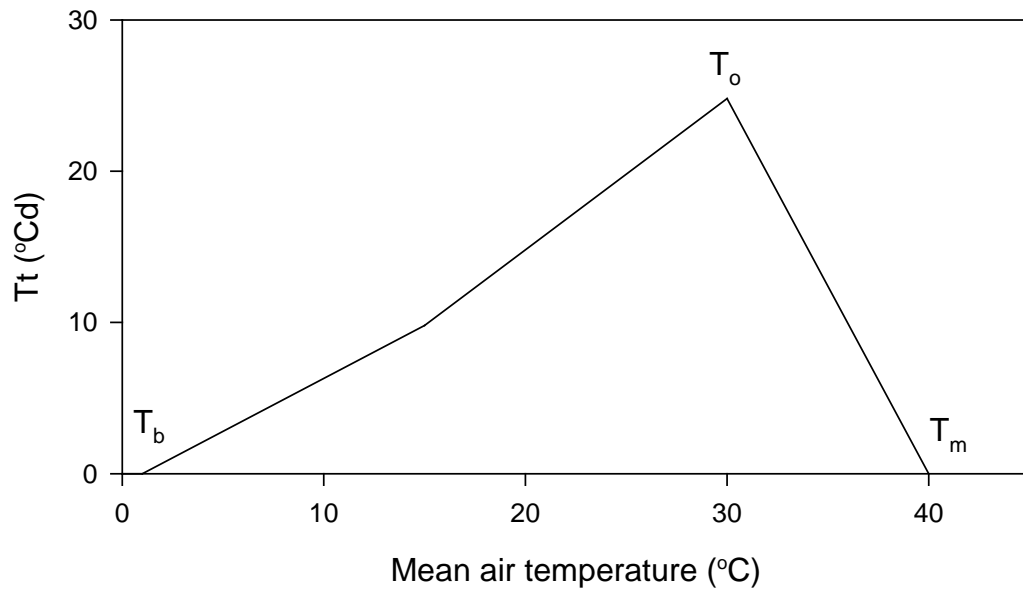


Figure 2.2 Broken-stick threshold model for thermal time (T_t) accumulation at different mean air temperatures as proposed (Moot *et al.*, 2000).

Analysis of the data presented in Figure 2.1 showed temperature explained 85% of the variation in seasonal growth rate of the irrigated lucerne crop (Figure 2.3). Growth rate increased linearly at a rate of 11 kg DM/day/°C when mean temperature increased from 5 °C to 17 °C. Figure 2.3 also demonstrates Bonhomme (2000) point of the non-linear response of growth at temperatures close to T_b and the limitations of determining T_b from linear regression of field data. Yield is determined by the fraction of intercepted solar radiation and its efficiency of conversion into biomass (Equation 2.1). Temperature influences both of these components, which will now be reviewed.

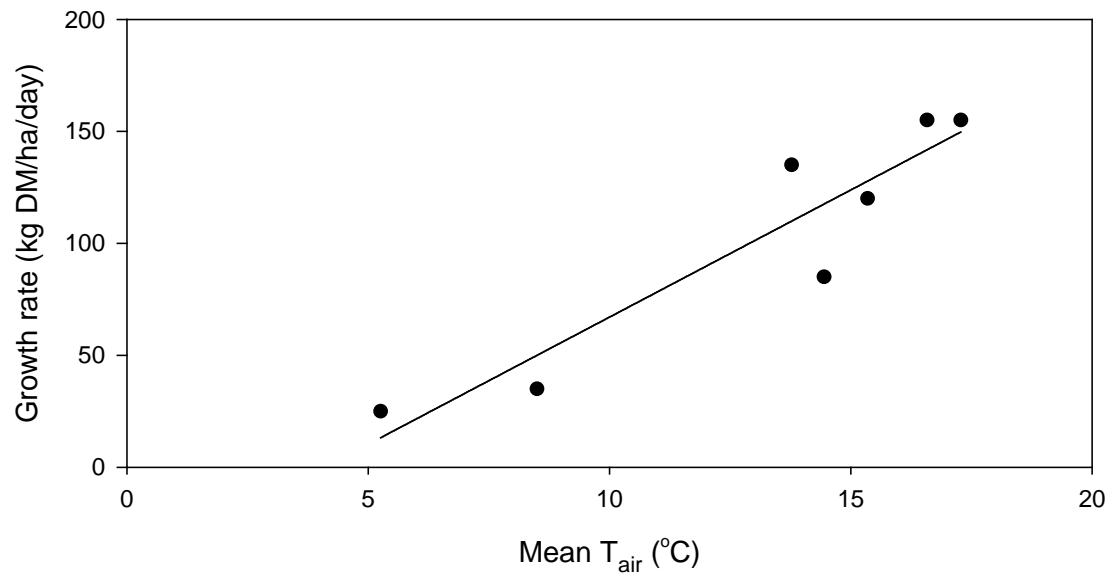


Figure 2.3 Growth rate in relation to mean air temperature (T_{air}) for irrigated lucerne from November 1968 to December 1967 at Lincoln University, Canterbury, New Zealand. (Analysed from data presented in Figure 2.1, adapted from Hoglund *et al.* (1974)).

Note: Linear regression (—): $y = 11.4x - 46.5$, $R^2 = 0.85$.

2.3 Interception of solar radiation by the canopy

Solar radiation is intercepted by the leaves which form the canopy. The amount of light intercepted by the canopy (R/R_o) is a function of the size of the canopy, the leaf area index (LAI; m^2 leaf/ m^2 soil) and the canopy architecture. The canopy architecture is characterised by factors such as; leaf angle, leaf surface properties, thickness, shape and arrangement (Hay and Walker, 1989). The relationship between LAI and R/R_o can be described using the Beer-Lambert law which describes the exponential reduction of light through the canopy, Equation 2.3;

Equation 2.3 $R/R_o = 1 - \exp(-k \cdot LAI)$

Where the extinction coefficient (k) represents the canopy architecture, which is most sensitive to leaf angle, which then regulates the fraction of radiation intercepted by each unit of LAI. Generally, a single extinction coefficient is used to describe the canopy architecture which integrates daily changes in relation to solar elevation (Thornley and Johnson, 2000) and changes in leaf angle throughout the canopy strata. Variation in leaf angle of the lucerne canopy allows more even distribution of light. Keoghan (1982) showed lucerne leaf angle increased from the top to the bottom of the canopy which resulted in increases in k from 0.35 to 1.72, respectively. The author presented a mean k of 0.77 which is consistent with others reported in the literature of 0.70 to 0.93 (Whitfield *et al.*, 1986; Robertson *et al.*, 2002; Varella, 2002; Teixeira *et al.*, 2011; Mattera *et al.*, 2013).

2.3.1 Leaf area index

Leaf area development begins at crop emergence and is determined by the production, expansion and duration of mainstem and axillary leaves (Hay and Walker, 1989). The LAI of a lucerne crop can be determined from mean individual leaf area, number of leaves per mainstem and stem population (Brown *et al.*, 2005b). Brown *et al.* (2005b) and Teixeira *et al.* (2007a) showed for irrigated lucerne grown at Lincoln these LAI components differed between regrowth cycles throughout the year in relation to temperature and photoperiod. The expansion of LAI can be quantified in relation to T_t (Ritchie *et al.*, 1991), which accounts for the influence of temperature on the

components of LAI. Teixeira *et al.* (2007c) reported lucerne grown at Lincoln had an optimum leaf area expansion rate (LAER) of $0.016 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$. The LAER was adjusted to account for seasonal variation as a function of photoperiod (Pp) by a linear decline of $0.0064 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ for Pp below 12.5 h, until zero was reached at 10 h (Figure 2.4).

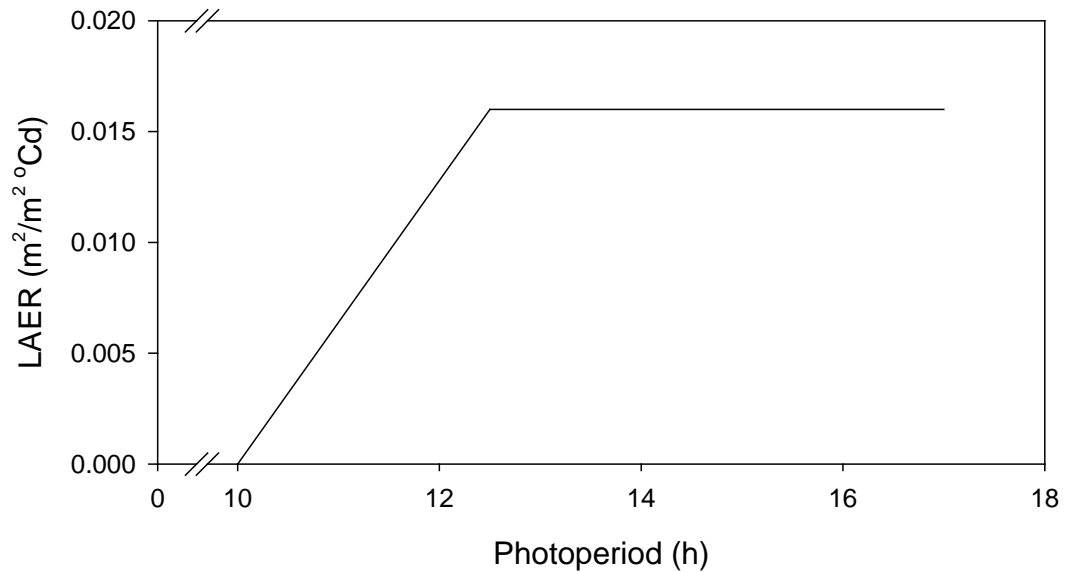


Figure 2.4 The relationship between leaf area expansion rate (LAER) and photoperiod (From Teixeira *et al.* (2009)).

2.3.1.1 Mainstem node appearance

Mainstem node development is the main driver of leaf appearance as it determines the rate of mainstem leaf appearance, which also controls the potential of axillary leaves from the axial buds (Hay and Walker, 1989). The interval between successive mainstem nodes is defined as the phyllochron and quantified using Tt. Brown *et al.* (2005b) reported, in the absence of frost (air $< 0^\circ\text{C}$) or flowering, mainstem node appearance was linear within cycles for regrowth crops ($R^2 > 0.90$). However, the phyllochron differed between 30 to 60°Cd throughout the year, which showed a single phyllochron was inappropriate for lucerne grown in a temperate environment. The most suitable means of describing the seasonal variation in phyllochron is in relation to

photoperiod at the start of each individual regrowth cycle (Moot *et al.*, 2001; Brown and Moot, 2004; Brown *et al.*, 2005b; Teixeira *et al.*, 2007c). Irrigated lucerne grown at Lincoln displays a minimum phyllochron of 34 °Cd for $Pp \geq 12.5$ h which increases to a maximum of 40 °Cd at Pp of 10.5 h (Figure 2.5). Leaf appearance rates are determined by the rate of cell division and expansion at the stem apex (Hay and Walker, 1989) which is driven by assimilate supply. The pattern of seasonal phyllochron follows that of shoot RUE, both decrease during late summer when crops increase partitioning to below ground organs (Teixeira *et al.*, 2007b), which reduces assimilate supply, and possibly the rate of phyllochron expression. Seedling lucerne, defined as the growth phase from sowing to first defoliation has been reported to have a longer phyllochron of 47 °Cd compared with that of regrowth lucerne (subsequent growth phases following the seedling phase) which is consistent with greater partitioning below ground for these crops (Teixeira *et al.*, 2011). It is unknown if a single phyllochron for seedling lucerne is suitable, regardless of sowing date. This will be investigated in the current research, along with the influence sowing date on DM partitioning of seedling crops.

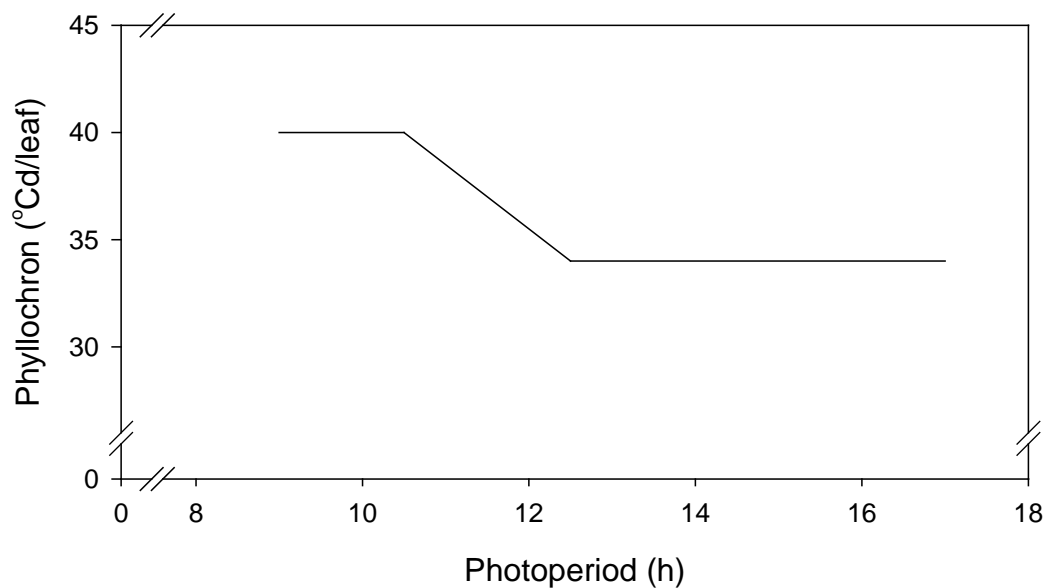


Figure 2.5 The relationship between phyllochron (mainstem leaf appearance rate; °Cd) and photoperiod (From Teixeira *et al.* (2009)).

2.3.1.2 *Branching*

Each mainstem node contains an axillary meristem which has the potential to produce leaves which allows the crop to expand its leaf area exponentially, and increase light interception. Evans and Peadar (1984) reported 17-27% of lucerne shoot yield was derived from branched material, which shows branching is an important contributor towards crop yield. The rate of branching is a development process and can be described in relation to Tt, alternatively branching can be expressed as the relationship between mainstem node number and total node number. For example, Brown *et al.* (2005b) showed in irrigated lucerne grown at Lincoln, branching was initiated after the appearance of about the fifth mainstem node. The rate of branching for spring and autumn regrowth cycles was 2.5 secondary nodes per mainstem node compared with 1.7 for the summer cycles. This difference indicated branch development had a different environmental response or rate of response to that of mainstem node appearance. Juan *et al.* (1993) showed lucerne grown under short Pp (13 h) displayed greater branching than under long Pp (16 h), which is consistent with that shown by Brown *et al.* (2005b). Branching is also dependent on assimilate supply (Hay and Walker, 1989). The reduced branching in summer may be associated with less available assimilate due to greater partitioning of DM below ground (Teixeira *et al.*, 2007b).

2.4 DM production and radiation use efficiency (RUE)

DM production is dependent on the efficiency of conversion of solar energy into assimilate and the partitioning of this assimilate into biomass (Equation 2.1). Radiation use efficiency (RUE) is determined by the slope of the relationship between crop DM and accumulated intercepted radiation (Monteith, 1972, 1977; Sinclair and Muchow, 1999). RUE is a measure of net photosynthesis (P_n); gross photosynthesis (P_g) less total respiration (R_T) in relation to intercepted radiation (R_i), at the crop level (Equation 2.4).

Equation 2.4
$$RUE = P_n = (P_g - R_T) / R_i$$

Photosynthetically active radiation (PAR) occurs within the waveband spectrum of 400 to 700 nm, and is half of the incoming total solar radiation (Monteith, 1972). Solar radiation intensity and duration differs with location and season due to changes in solar angle (Hay and Walker, 1989). Care needs to be taken when defining RUE. RUE can be expressed differently with regard to; DM (total or above ground), band of radiation wavelength (total solar radiation or PAR) and either as intercepted or absorbed radiation. Throughout this research, RUE will be defined by intercepted total solar radiation and reported as shoot RUE (RUE_{shoot}) or total RUE (RUE_{total}).

Varella (2002) showed in field grown lucerne in full sunlight the maximum photosynthesis rate (P_{max}) was reached at a radiation intensity of $\sim 1000 \mu\text{mol m}^{-2} \text{s}^{-1}$, however 95% P_{max} was reached at half this intensity. Solar radiation intensity does not normally limit crop growth in the field for lucerne, a C_3 plant, rather declining temperature does (Hay and Walker, 1989) which parallels solar radiation receipts (Fletcher and Moot, 2007).

RUE_{shoot} is assumed to be constant among annual crops when grown under optimum conditions (Monteith, 1977), which has been shown for individual regrowth cycles for lucerne, however RUE_{shoot} differs seasonally. For example, Thiebeau *et al.* (2011) reported RUE_{shoot} values decreased from 0.9 g DM/MJ in summer to 0.55 g DM/MJ in autumn for lucerne grown in France. Also, Mattera *et al.* (2013) reported RUE_{shoot} varied from 0.6 to 1.1 g DM/MJ over five regrowth cycles for lucerne grown in

Argentina. The three main factors which influence photosynthesis and therefore RUE are nitrogen, temperature and water stress, the latter two are discussed in more detail.

2.4.1 Effect of temperature on RUE

Brown *et al.* (2006b) showed a strong linear increase in RUE_{total} with mean air temperature for irrigated lucerne grown at Lincoln from 0.6 g DM/MJ at 6 °C to 1.6 g DM/MJ at 18 °C, an increase in RUE_{total} of 0.09 g DM/MJ/°C. They presented a framework to account for the effect of temperature on seasonal RUE_{total} (Figure 2.6). This relationship was validated for lucerne grown in the same climate, defoliated on a 42 day cycle (RMSD of 0.2 g DM/MJ) by Teixeira *et al.* (2008) who showed RUE_{total} increased at 0.10 g DM/MJ/°C from 8 to 18°C. Decreases in photosynthesis at temperatures below optimum are associated with a decline in enzyme activity which catalyse reactions in the Calvin cycle (Hay and Walker, 1989). However, Teixeira *et al.* (2008) showed a poor relationship ($R^2 = 0.11$) between air temperature and RUE_{shoot} , because the two components that influence RUE_{shoot} ; RUE_{total} and fractional partitioning of DM to the perennial reserves below ground responded separately to temperature.

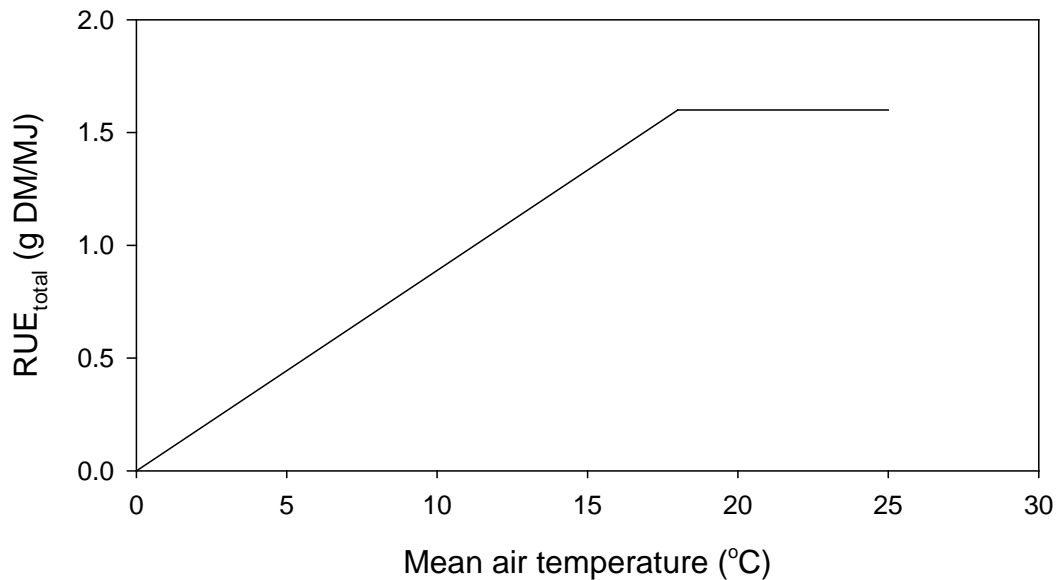


Figure 2.6 The relationship between total radiation use efficiency (RUE_{total}) of irrigated lucerne grown at Lincoln University, Canterbury, New Zealand (From Brown *et al.* (2006b)).

2.4.2 DM partitioning

The carbon allocation strategy of lucerne differs with ontogenetic development which is influenced by environmental factors. During establishment a greater amount of DM is partitioned to the crown and taproot, and shoot growth is compromised. Thiebeau *et al.* (2011) showed seedling and regrowth crops used intercepted radiation equally efficiently, however greater partitioning of assimilate below ground reduced shoot growth for seedling crops. Khaiti and Lemaire (1992) reported the fractional partitioning of DM to the root (P_{root}) for seedling spring sown lucerne in France was 0.65 compared with ~0.2 for the following regrowth cycle. Higher partitioning in seedling crops is linked with slower canopy development rates relative to regrowth lucerne and maximum LAI expansion rates for these crops reported by Teixeira *et al.* (2011) of $0.009 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$, half the rate of regrowth lucerne.

Teixeira *et al.* (2008) reported root DM of regrowth lucerne ranged between 3.5 and 5.5 t DM/ha throughout the growth season, independent of defoliation management. The allocation of DM throughout the season for lucerne grown at Lincoln was described in relation to Pp (Figure 2.7a). During winter and early spring, when daylength is short (<10 h), crops remobilised reserves from the crown and taproot and P_{root} was close to zero. As Pp lengthened, P_{root} increased linearly at a rate of 0.08/h up to Pp of 16.5 h where P_{root} was 0.5, and constant for the remainder of the season. Teixeira *et al.* (2007c) observed a strong positive correlation ($R^2 = 0.76$) between the nitrogen content of root DM and LAER during the early spring period and reported LAER increased ~30% when the nitrogen pool increased from 20 to 60 kg N/ha. Teixeira *et al.* (2008) used the relationship between soil and air temperature ratio ($T_{\text{soil}}/T_{\text{air}}$) and P_{root} which eliminated the hysteresis of the relationship (Figure 2.7b) with Pp. However the lower coefficient of determination ($R^2 = 0.53$) suggested other factors influence DM allocation, which supports Thiebeau *et al.* (2011) who found no significant correlation between $T_{\text{soil}}/T_{\text{air}}$ and partitioning for either seedling or regrowth crops.

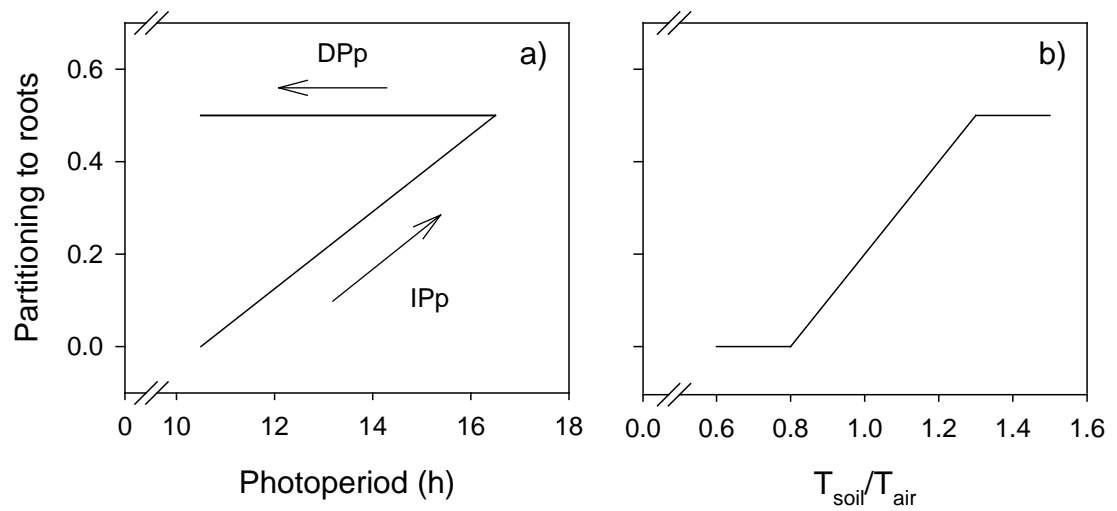


Figure 2.7 Fractional partitioning of DM to crown plus taproot in irrigated lucerne crops defoliated on a 42 day rotation in relation to increasing (IPp) and decreasing (DPp) photoperiod (a) and the relationship between 100 mm soil and air temperature grown at Lincoln University, Canterbury, New Zealand (Adapted from Teixeira *et al.* (2008)).

2.5 Effect of water limitation on yield

Availability of water for growth is often the main factor determining yield and is the most important limiting factor in agricultural systems (Semenov *et al.*, 2009). Lucerne persists during periods of water stress by extracting water from deep within the soil profile to maintain transpiration (Sheaffer *et al.*, 1988). Plants display different strategies for growth under conditions of limited water supply or high evaporative demand, but generally these strategies inevitably reduce yield through the decrease in the capture (R/R_o) and efficiency of use (RUE) of solar energy (Equation 2.1). Crop water use is often calculated as the minimum of the actual crop transpiration (E_T) and the potential transpiration which represents the demand for water from the canopy (EP_T) (Ritchie, 1972; Monteith, 1986). Actual crop transpiration is the result of the supply of water extracted from the soil by the roots, and the potential transpiration is determined by atmospheric conditions, described by potential evapotranspiration (EP) which is regulated by the size of the crop canopy (French and Legg, 1979). The severity of water shortage can be quantified as a ratio of actual transpiration in relation to potential transpiration (E_T/EP_T) (Jamieson *et al.*, 1998; Robertson *et al.*, 2002).

2.5.1 Soil water supply

2.5.1.1 Soil texture

Soil water supply is the result of both soil and root characteristics (Jamieson and Ewert, 1999). Soil texture influences the soil pore size distribution which determines the amount of water the soil can store. The drained upper limit (DUL) and the lower limit (LL) of water extraction by a mature crop which has fully explored all soil moisture to maximum potential rooting depth determines the plant available water capacity (PAWC) (McLaren and Cameron, 1990). Webb (2000) described the two soils in the current research. The Lismore stony silt loam and Wakanui silt loam were derived from similar parent material and soil texture and pore size are comparable, however the PAWC is 50 mm/m for the Lismore and 150 mm/m for the Wakanui. The difference is largely attributed to the shallow (<0.18 m) topsoil and high stone content of the Lismore soil which results in a DUL volumetric water content of ~10% in the sub soil layers compared with ~30% for the Wakanui silt loam. The PAWC in a stony soil is related to

the volume of soil which can store water, which is reduced proportionally to the stone content (McLaren and Cameron, 1990). The PAWC of the soils in the current study will be determined by the maximum amount of water extracted by the crop in the second season. In the establishment season, the amount of extractable water will be determined by the maximum soil water deficit.

2.5.2 Water use

Potential crop water use is influenced by potential evapotranspiration (EP) which summarises complex relationships between environmental factors such as; global radiation, temperature, wind run, and was described by Penman (1948). EP consists of two parts; transpiration by the crop (EP_T) and evaporation of water from the soil surface (E_s). The partitioning of EP between the two is a function of crop canopy cover, and E_s is dependent on soil surface wetness (Ritchie, 1972).

2.5.2.1 Crop water use

Potential crop water use (EP_T) is normally measured when supply is non-limiting and the ratio of EP_T to EP peaks at 1.1 for lucerne (Carter and Sheaffer, 1983b; Brown, 2004) and is reduced in relation to the LAI and canopy cover (French and Legg, 1979). For example, Carter and Sheaffer (1983b) showed actual crop water use (E_T) relative to EP increased exponentially from 0.6 to 1.2 when the LAI of an irrigated lucerne crop increased from ~1.0 to 4.5. An increase in LAI increases the intercepted radiation which provides the latent energy that evaporates water from the stomata within the canopy. For example, Brown *et al.* (2012) showed strong ($R^2 > 0.90$) linear relationships between accumulated E_T and intercepted radiation (R_i), however the slope of the regression differed amongst regrowth cycles throughout the season from 0.10 to 0.27 mm/MJ/m². When E_T/R_i was regressed against mean vapour pressure deficit (VPD) for individual regrowth cycles 75% of the variation was explained. VPD is the difference in the saturated vapour pressure at a given temperature and actual vapour pressure which creates the difference in water vapour concentration between stomata and the external air that drives E_T (Tanner and Sinclair, 1983). When VPD increases,

E_T increases but there is no associated increase in photosynthesis, therefore the water use efficiency (WUE) decreases.

2.5.2.2 *Soil evaporation, E_s*

Water loss from the plant-soil system can continue in the absence of a crop canopy due to soil evaporation (E_s) (Ritchie, 1972). E_s is the loss of water vapour from the soil which largely depends on atmospheric demand and soil wetness. The accuracy of estimating E_s is often disregarded in annual crops because full canopy cover is maintained for a longer duration of the season than in grazed forages (Jamieson *et al.*, 1995a). However, lucerne is repeatedly defoliated throughout the year and Brown (2004) showed lucerne experienced ~100 days per year with incomplete canopy cover. This incomplete canopy cover showed annual E_s from lucerne grown under rainfed and fully irrigated conditions contributed ~30% of total water use. When shelters were used to exclude rainfall, E_s contributed 9% of total water as water loss ceased with the drying of the topsoil. E_s needs to be accounted for in the current study to compare E_T of crops grown on soils with different patterns of leaf area index.

2.5.2.3 *Crop water extraction*

Crop rooting characteristics depend on crop age and soil characteristics (Jamieson and Ewert, 1999). The pattern of water extraction from when the roots reach an individual soil layer can be described by an exponential rate of decline of SWC over time from DUL to LL, known as the 'Monteith Framework' (Passioura, 1983; Monteith, 1986). The rate of extraction is quantified by the extraction rate constant ($-kl$), where the k is the soil dependent diffusion constant (cm^2/day) and l represents root length density (cm/cm^3). The progress of water extraction down the soil profile is the extraction front velocity (EFV; mm/day) and thus differences in the EFV and $-kl$ influence the crop water supply. Brown (2004) validated this relationship for seedling and perennial lucerne crops and showed water extraction of lucerne exhibit a 'top-down' water extraction pattern and water was preferentially extracted via the shortest path. In the establishment year lucerne extracted water to a depth of 1.7 m compared with perennial lucerne to at least 2.3 m and a calculated depth of extraction to 2.7 m. The EFV was

12.5 and 15.6 mm/day for seedling and regrowth lucerne, respectively, and the rate of water extraction was 0.02 to 0.03/day. These parameters were combined to predict the water supply in relation to demand and the subsequent loss in yield when water limitation occurred (Brown *et al.*, 2009). Because the 'Monteith Framework' can only be applied when water demand is greater than supply it is unknown how different water supplies, normally varied by irrigation, influence the above parameters. An alternative is to grow the crops in the same environment, however on soils with similar soil texture which differ in their PAWC, which is a key aspect of the current research.

Janson and Knight (1973) showed the application of irrigation to lucerne on a Lismore stony silt loam in Canterbury increased DM yields three fold. They also observed the fully irrigated crop exhibited water stress and suggested the root system may limit the extraction of water in this soil type. Fick (1984) also noted the potential growth rates of pasture across a wide range of soils in New Zealand were not realised in soils with less than 115 mm of PAWC in the root zone at field capacity. Again, root characteristics were suggested to be the limiting factor in these crops. The root system of lucerne has been described as non-branching relative to annual crops (Sheaffer *et al.*, 1988) which may result in less exploitation of soil by roots searching for water. Dardanelli *et al.* (1997) showed the rate of extraction for lucerne was consistent with that found by Brown *et al.* (2009), however this was a third of that of annual crops such as maize. Rather than an inefficient root system the authors suggested lucerne implemented the strategy to persist by using water conservatively and extract water from depth. Lucerne conservative daily water use of ~3% day (Dardanelli *et al.*, 1997; Brown *et al.*, 2009) of PAWC means 3.6 mm/day can be extracted from soils with 120 mm PAWC in the rooting zone. In Canterbury, summer daily EP often exceeds 5 mm (Jamieson *et al.*, 1995a; Brown *et al.*, 2012) which means crops grown on these soil must display greater EFV and $-kl$, or supply will not meet demand and water stress will occur. Thus, the pattern of water extraction for crops in the present study will be quantified to determine the water supply from these soils.

2.5.3 Crop water stress

2.5.3.1 Quantifying water stress

The plant water status is quantified by the water potential of the leaves (Ψ ; MPa) and is a measure of the turgor pressure of the cells (Gonzalez-Dugo *et al.*, 2010). When the crop is unable to extract water to meet demand, Ψ is decreased. For example, Carter and Sheaffer (1983a) showed the midday Ψ for irrigated lucerne was -1.0 MPa compared with -4.5 MPa for dryland lucerne under extreme water stress. To alleviate water stress the crop reduced LAI which resulted in an 85% decrease in DM yield (Carter and Sheaffer, 1983b). The limitation with defining water stress using Ψ is measurements are time consuming (Gonzalez-Dugo *et al.*, 2010) and are dependent on environmental conditions. For example, Carter and Sheaffer (1983a) showed the diurnal variation of Ψ for irrigated ranged from -0.1 MPa at sunrise to -1.2 MPa at midday, in response to radiation load and as a consequence results were influenced by cloud cover.

An alternative method to quantify water stress is to calculate the degree of stress as an index of transpiration relative to transpiration demand (E_T/EP_T) (Jamieson *et al.*, 1998; Robertson *et al.*, 2002). EP_T is the result of daily EP multiplied by crop cover (French and Legg, 1979). A value of 1.0 shows $E_T=EP_T$, and no water stress. For example, Brown *et al.* (2009) showed the E_T of dryland lucerne became progressively less as the soil dried and was 300 mm less than the fully irrigated crop at the end of the season. The E_T of dryland crops in relation to the fully irrigated crop decreased from ~1.0 in spring to 0.22 by the final regrowth cycle. An increase in water stress caused linear decreases in leaf area expansion, mainstem node appearance rate and RUE_{shoot} , relative to fully irrigated crops (Figure 2.8).

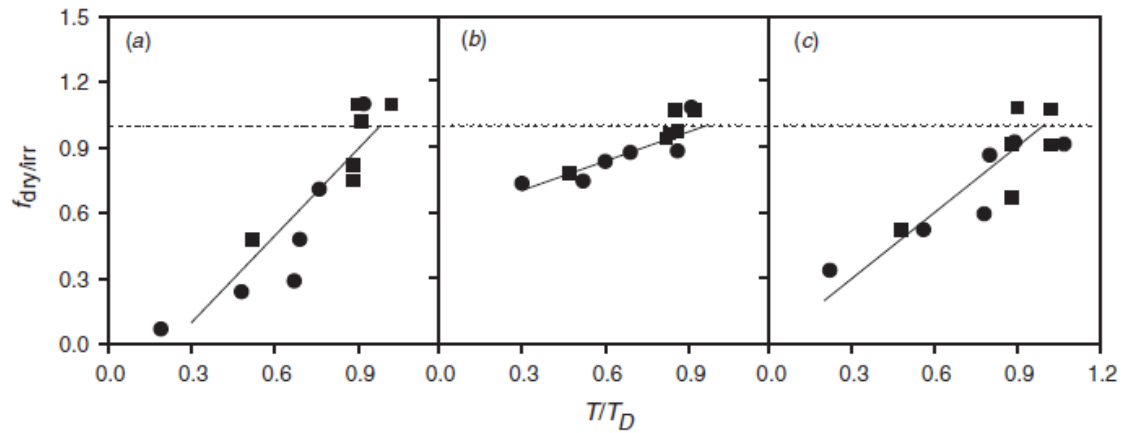


Figure 2.8 Relative effect on yield forming processes ($f_{\text{dry/irr}}$) in lucerne of degree of water limitation (T/T_D) for leaf area index expansion (a), mainstem node appearance rate (b), and radiation use efficiency (c) at Lincoln University, Canterbury, New Zealand (From Brown *et al.* (2009)).

2.5.3.2 Effect of water stress on LAI expansion

As water demand exceeds supply, Ψ declines and leaf cell turgor is reduced, which decreases cell expansion (Hay and Walker, 1989). Plants which lose turgor can be observed to wilt and display folded leaves in a response to reduce radiation interception and heat load. For example, Brown and Tanner (1983) showed a 90% reduction in leaf extension rates as Ψ declined from -1.0 to -2.5 MPa. The components of LAI (Section 2.3.1) display different sensitivity to water stress, generally growth is more sensitive than development (Hay and Walker, 1989). This was shown for lucerne by Brown *et al.* (2009) who showed leaf area expansion rate decreased by 90%, compared with a decrease in phyllochron of 30% relative to a fully irrigated crop when E_T/EP_T decreased from 1.0 to 0.20 (Figure 2.8a and b).

2.5.3.3 Effect of water stress on photosynthesis

During photosynthesis, water and CO_2 are exchanged through a similar pathway. Stomata close during water stress to reduce water loss which reduces E_T , however CO_2 assimilation also declines (Jamieson *et al.*, 1995a; Jamieson, 1999). For example,

Carter and Sheaffer (1983b) showed a linear reduction in leaf conductance from 0.033 m/s to 0.003 m/s when midday leaf water potential declined from a well-watered level of -1.0 MPa to extreme water stress at -4.5 MPa. The threshold of leaf water potential at which stomatal closure is initiated varies from -1.2 to -1.7 MPa (Sheaffer *et al.*, 1988). A reduction in CO₂ assimilation reduces P_{net} and therefore RUE (Equation 2.4). The influence of water stress on RUE_{shoot} of lucerne was shown by Brown *et al.* (2009) who reported a 1:1 decrease in RUE_{shoot} relative to declining E_T/E_{TP} (Figure 2.8c)

Apparent decreases in RUE_{shoot} under water stress may be attributed to DM partitioning. Janson (1982) made the observation lucerne could withstand more frequent defoliation regimes in dry climates. Perennial reserves are associated with crop regrowth and persistence which suggests lucerne crops may respond to water stress by partitioning more assimilate below ground, resulting in a reduction in RUE_{shoot}. The influence on lucerne root growth reviewed by Sheaffer *et al.* (1988) varies. In most cases, absolute root biomass under water stress is less relative to fully watered crops, but increases proportionally to shoot biomass (Durand *et al.*, 1989; Asseng *et al.*, 1998). The effect of PAW on root mass will be examined in the current research.

2.6 Establishment

In New Zealand sowing of lucerne can occur from spring to autumn, which depends on environment conditions such as temperature and soil moisture, as well as weed and pest pressures and other farm management decisions. For these reasons lucerne is generally sown in spring or early summer (Wynn-Williams, 1982). Where establishment failure occurs, the fault usually lies with one or more of the following; time of sowing, lack of moisture, poor consolidation, inoculation failure, early weed competition, early and too frequent defoliation (Elliott and Kerse, 1974). In most cases the earlier the sowing date in spring, the higher the DM yield in the establishment and subsequent year (Justes *et al.*, 2002; Moot *et al.*, 2012). Thiebeau *et al.* (2011) showed delayed sowing from early spring to late summer in France reduced yield of seedling crops by ~60% and yields in the subsequent year by ~25%. When sowing is delayed potential intercepted radiation is reduced, furthermore a larger proportion of growth occurs under declining Pp which means crops experience maximum rates of DM partitioning below ground (Figure 2.7) and shoot yield is further decreased.

Lucerne has a small seed (~2.0 g/1000 seeds) and should be sown <25 mm deep (Wynn-Williams, 1982). However, where moisture may limit germination, seeds can be sown deeper (<35 mm), provided soils are not prone to ‘capping’ which is the formation of a hard cap on the soil surface following the collapse of the soil surface structure after heavy rain, which can inhibit emergence (Tesar and Triplett, 1960). Germination is sensitive to water stress and Triplett and Tesar (1960) reported lucerne emergence stopped in a silt loam and sandy loam soil when soil moisture tension was <-1.0 MPa. Direct seeding minimises soil disturbance and moisture associated with cultivation (Passioura, 2006) and can be used to successfully establish lucerne (Kearney *et al.*, 2010). Regardless of establishment method weed control is essential. Weeds compete for light, moisture and nutrients and the slower leaf area expansion rate of seedling, relative to regrowth lucerne, means establishing crops are more susceptible to invasion by weeds (Palmer, 1982). Under optimal conditions seeding rate is less important, with sowing rates as low as 1.4 kg/ha providing plant densities and DM yield in the first year comparable of crops sown at a rate a magnitude higher (Sims, 1975; Moot *et al.*, 2012). Where populations are established above the threshold to maximise yield of 30- 45 plants/m² (Wynn-Williams, 1982; Teixeira *et al.*, 2007a) self-thinning occurs due to

competition for light by plants. Langer (1968) reported seedlings grown under shade conditions (30% light transmission) experienced a 40% reduction in plant DW. Crops in the present study will be sown from spring to late summer to develop relationships between seedbed temperature and soil moisture content and rate of crop establishment. DM yield in the establishment and subsequent season will be compared to determine the sowing date where yield is maximised for both sites. Furthermore, root biomass will be measured to quantify the observation that lucerne requires up to 12 months to reach maximum production, due to preferential partitioning of DM below ground to build perennial reserves.

2.7 Summary

Based on this review of literature the following conclusions can be made:

- Potential crop yield is the result of intercepted solar radiation and the efficiency with which it is converted into biomass. Temperature affects leaf area expansion and the photosynthetic rate.
- However, shoot yield is also the result of seasonal partitioning of assimilate. The partitioning of DM between the shoot and root fractions can be predicted in relation to photoperiod at the start of an individual regrowth cycle, but may be affected by water stress which needs to be quantified. Partitioning in seedling crops may be influenced by sowing date which will be examined in this study.
- The supply of water can be determined by the rate of water extraction by the root front moving down the soil profile, and the PAWC of the soil. The crop water demand can be determined by the EP, adjusted for canopy cover. It is unknown how the PAWC of the soil effects lucerne EFV, this will be examined.
- Crop water use is the minimum of supply by the roots or demand from the atmosphere. Water stress can be quantified as transpiration demand in relation to supply. Loss of yield can be related to the influence of water stress on the fraction of intercepted radiation and photosynthetic rate.

To answer the main research objectives of the current research, which are to understand water extraction and yield relationships of dryland lucerne, four field experiments will be used. Lucerne crops will be grown on two soils which differ in their PAWC and crop water supply will be further manipulated by the imposition of sowing date treatments. Sowing date will influence root growth and therefore extractable water in these soils. Crop water use will also be manipulated through defoliation treatments of established crops. Unifying relationships between water demand/supply and physiological mechanisms which reduce yield will help refine management to maximise DM yield in these environments.

3 Materials and Methods

The crop establishment part of this research involved two experiments conducted on two sites and over two years from October 2010 to July 2012. This chapter describes both experimental sites and outlines long term and seasonal weather data and agronomic management. Measurements and methods of data analysis are reported in individual chapters.

3.1 Experimental sites

Site one was located at Ashley Dene, Lincoln University's dryland research farm (43°38'S, 172°19'E, 30 m.a.s.l), which is 10 km west of Iversen Field, Site two. The experiment was located at the west end of paddock M2B, a 4.5 hectare area of flat land in the Main Block. Site two was at the Lincoln University Field Service Centre (43°38'S, 172°28'E, 11 m.a.s.l) within a 0.98 hectare area of flat land in Iversen Field paddock 12 (Iversen 12).

3.1.1 Site history

Historically paddock M2B at Ashley Dene has grown lucerne crops from 1982 to 2008. Forage turnip (*Brassica campestris* s.s *napifera*) and annual ryegrass (*Lolium multiflorum*) were sown in February 2008. Following winter grazing the ryegrass was managed as pasture until September 2010 when the site was prepared for Experiment one. Iversen 12 had grown lucerne from 2004 to 2007 followed by forage turnip in 2008 and annual ryegrass from 2009 until the site was prepared for Experiment two.

3.1.2 Soil characteristics

The soil at Ashley Dene, paddock M2B is a Lismore stony silt loam (*Typic Dystrustept* USDA Soil Taxonomy), classified as Typic Orthic Gley soil in the New Zealand Soil Classification (Cox, 1978; Webb, 2003). These soils have a shallow topsoil (0.18 m) containing greater than 8% stones overlaying horizons of coarse gravels in firmly packed sandy loam (Plate 3.1) resulting in a well drained soil profile (Hewitt, 1998). Lismore soils can contain weakly developed dense gravel pans, which vary in thickness

from 50 to 500 mm and generally occur below 0.5 m (McLenaghan and Webb, 2012). These pans can slow the drainage of soil water, creating ‘perched’ water during winter months, resulting in water logged conditions. During neutron probe access tube installation (Section 6.2.1.1) these pans were encountered at ~1.5 m, preventing the 20 tonne excavator pre-spiking access holes. The highly variable nature of these sub-soils meant reinstallation 1 m from the original site was often possible.

The soil at Iversen 12 is a Wakanui silt loam (*Aquic Haplustept*, USDA Soil Taxonomy), classified as a Mottled Immature Pallic soil in the New Zealand Soil Classification and is derived from the same parent material as the Lismore soil (Cox, 1978; Webb, 2003). These soils are formed from greywacke-derived loess and fluvial sediments and typically have 0.3 m of topsoil overlaying horizons consisting of silt to loamy sand to a depth of 2 to 3 m. Gravel was not encountered during neutron probe access tube installation to a depth of 2.3 m (Plate 3.1). Wakanui silt loams are imperfectly drained making them prone to water logging during periods of water surplus in winter as indicated by strong mottling below 0.7 m (Hewitt, 1998).

Plant available water holding capacity (PAWC) of the Wakanui silt loam is about 150 mm/m compared with 50 mm/m in the Lismore stony silt loam (Webb, 2000). Water extraction, indicating lucerne root growth, to at least 2.3 m has previously been shown in both soil profiles with PAWC of 130 mm and 360 mm at Ashley Dene and Iversen 12, respectively (Figure 3.1).

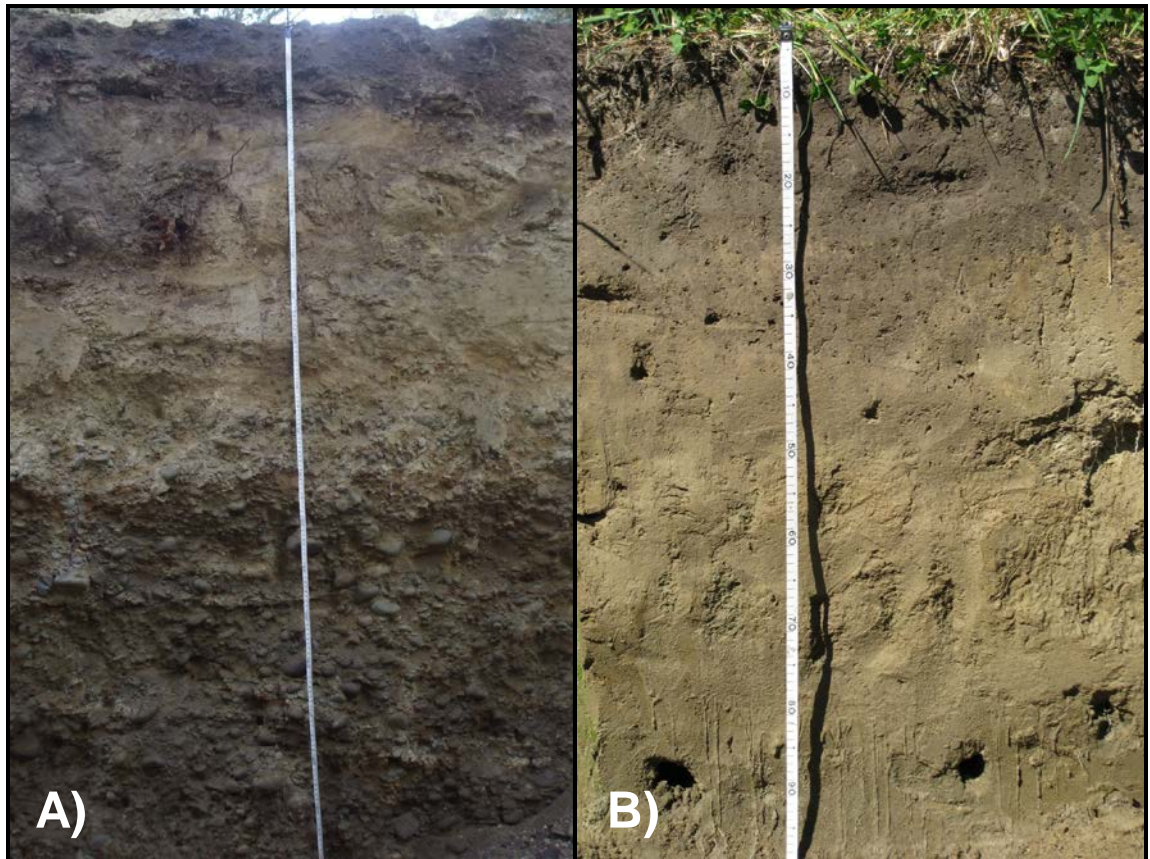


Plate 3.1 Soil profile at Ashley Dene (A) and Iversen 12 (B).

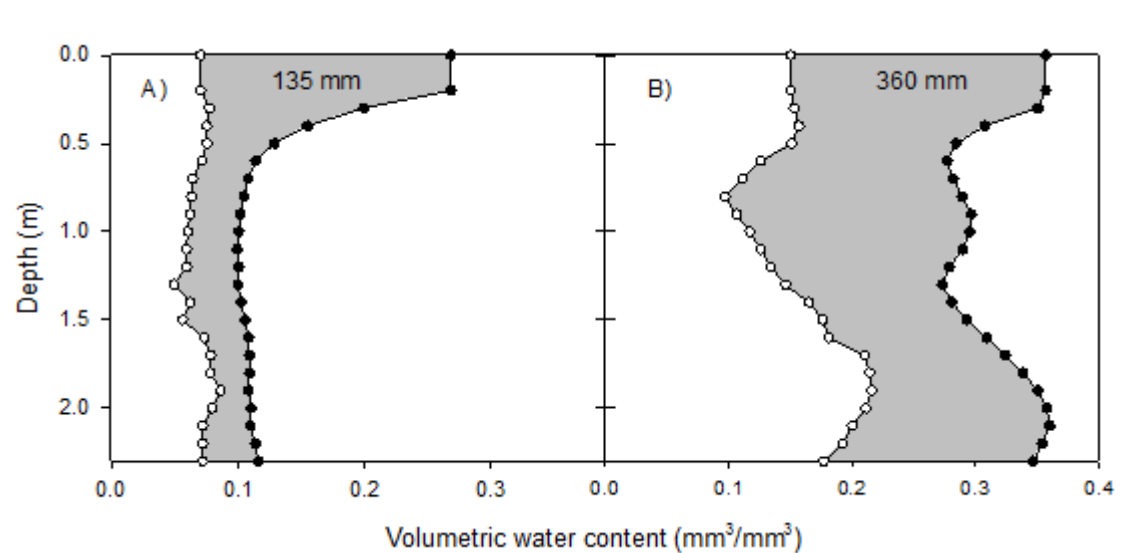


Figure 3.1 Upper (●) and lower (○) limits of mature lucerne water extraction to 2.3 metres at Ashley Dene (A) and Iversen Field (B) at Lincoln University, Canterbury, New Zealand. Shaded areas and numbers represent plant available water content (Adapted from Moot *et al.* (2008) and Brown (2004)).

3.2 Meteorological conditions

3.2.1 Measurements

Rainfall (mm), and air and soil temperature (°C) were recorded at the experimental sites. Air temperature (T_{air}) was measured by a thermistor installed at ~1.5 m above ground, in the middle of the experimental sites. Soil temperature (T_{soil}) was recorded 20 mm below ground level (~sowing depth) from sowing until 50% emergence of the first trifoliate leaf for each sowing over the two years. T_{air} and T_{soil} were measured at hourly intervals by a ‘Hobo 4-channel logger’ (Onset Computer Corporation, Bourne, Maryland, USA). Solar radiation ($\text{MJ/m}^2/\text{d}$), wind speed (m/s), and wet and dry bulb temperatures were recorded at Broadfields Meteorological Station (NIWA, National Institute of Water and Atmosphere Research, New Zealand) 2 km north of Iversen Fields. Measurements were recorded hourly and calculated to daily means.

3.2.2 Long-term meteorological conditions

Long-term mean (LTM) data are for 1960 to 2012. Canterbury’s climate is characterised as cool and temperate with an annual mean temperature of 11.5 °C, ranging from 16.7 °C in January to 6.0 °C in July (Table 3.1). Long-term annual average rainfall is 633 mm which is evenly spread throughout the year. Annual Penman potential evapotranspiration (EP) is 1094 mm which generally exceeds rainfall from September to April resulting in a long-term maximum potential soil moisture deficit (PSMD_{max}) of 520 mm (Figure 3.3).

Table 3.1 Monthly long-term means (LTM) from 1960 to 2012 for total solar radiation (R_o), maximum (T_{max}), minimum (T_{min}) and mean (T_{mean}) air temperatures, rainfall, Penman potential evapotranspiration (EP), wind run and vapour pressure deficit (VPD) measured at the Broadfields Meteorological Station, Lincoln, Canterbury, New Zealand.

Month	R_o MJ/m ² /day	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	Rainfall (mm)	EP (mm)	Wind run km/day	VPD (kPa)
Jan	22.0	22.1	11.3	16.7	50	157	369	1.0
Feb	18.9	21.8	11.2	16.5	43	126	344	0.9
Mar	14.1	20.0	9.7	14.8	52	104	334	0.8
Apr	9.6	17.2	6.8	12.0	53	66	286	0.7
May	5.9	14.1	4.2	9.1	57	46	276	0.6
Jun	4.5	11.3	1.6	6.5	59	34	248	0.5
Jul	5.1	10.7	1.4	6.0	63	37	250	0.4
Aug	7.8	12.1	2.5	7.3	64	53	293	0.5
Sep	12.1	14.5	4.3	9.4	40	76	328	0.6
Oct	17.2	16.7	6.1	11.4	48	110	351	0.7
Nov	21.3	18.6	7.7	13.2	51	133	361	0.8
Dec	22.7	20.6	9.9	15.2	53	152	361	0.9
Annual	13.4	16.6	6.4	11.5	633	1094	317	0.7

3.2.3 Rainfall and evapotranspiration during the experiments

In the 2010/11 year (1 July to 30 June) rainfall was consistent between sites with around 600 mm, slightly below the LTM (Table 3.2). EP was 976 mm, 12% below the LTM. In the 2011/12 year Ashley Dene received 11% more rainfall (645 mm) than Iversen 12 (581 mm) and EP was 16% below the LTM (912 mm), at both sites.

Table 3.2 Total seasonal rainfall, Penman potential evapotranspiration (EP) and maximum potential soil moisture deficit (PSMD_{max}) for two growing seasons from 1 July 2010 to 30 June 2012 for Ashley Dene and Iversen 12 at Lincoln University, Canterbury, New Zealand.

Year	Rainfall (mm)		EP (mm)	PSMD _{max} (mm)	
	Ashley Dene	Iversen 12		Ashely Dene	Iversen 12
2010/11	610	604	976	646	658
2011/12	645	581	912	508	564

Monthly rainfall did not follow the long term distribution pattern, and varied from 113 mm at Ashley Dene during October 2012, to 10 mm during May 2012 at Iversen 12 (Figure 3.2). In most cases, monthly rainfall between the two sites was consistent, although Ashley Dene received about 30% more autumn rainfall than Iversen 12 in 2012. Total monthly potential evapotranspiration followed a similar trend to the LTM each season which increased from a low of 15 mm in June to reach a maximum of 150 mm in January, before decreasing again. In the 2010/11 season potential evapotranspiration exceeded rainfall from September to March. However in the 2011/12 season, potential evapotranspiration continued to exceed rainfall until July, due to 60% less autumn rainfall than the LTM.

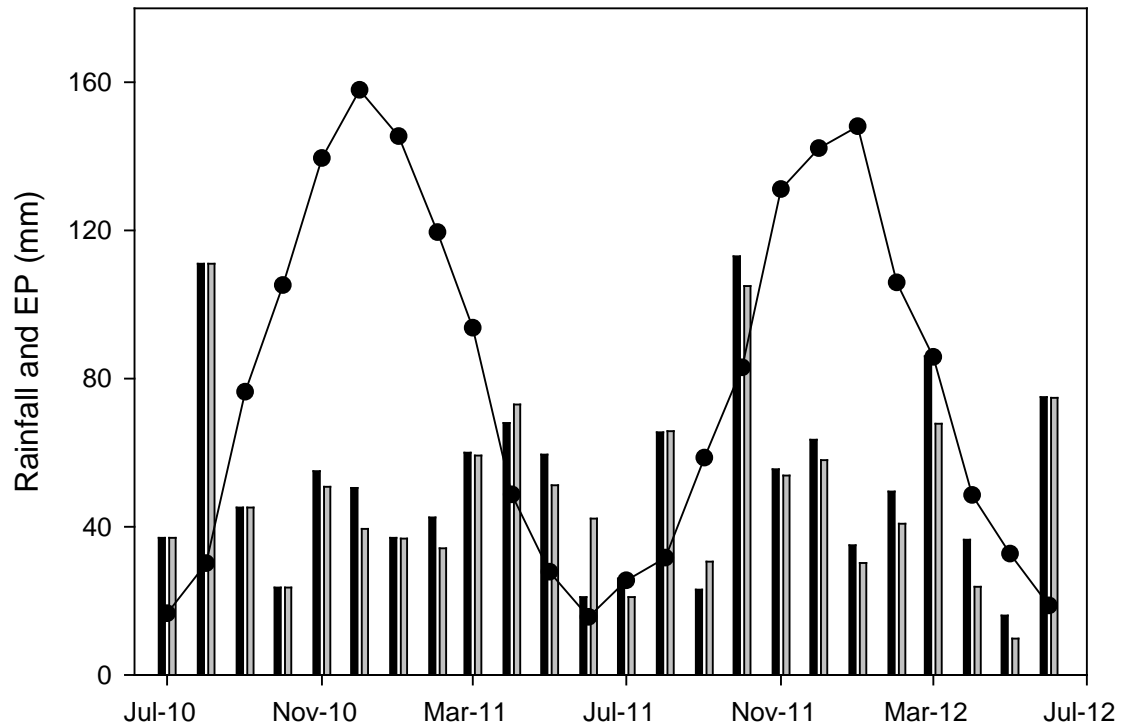


Figure 3.2 Monthly rainfall for Ashley Dene (■) and Iversen 12 (■) and Penman potential evapotranspiration (EP; —●—) from 1 July 2010 to 30 June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Penman potential evapotranspiration data were based on data collected at the Broadfields meteorological station.

The PSMD is associated with both rainfall distribution and potential evapotranspiration. Generally the long-term PSMD begins to increase in September through to a maximum in April/May. In the 2010/11 season the $PSMD_{max}$ was ~650 mm at Ashley Dene and Iversen 12 in late March, 20% higher than the LTM of 520 mm (Figure 3.3). Potential evapotranspiration was 16% lower than average in the 2011/12 season and contributed to the $PSMD_{max}$ being 34% and 15% below the LTM at Ashley Dene and Iversen 12, respectively. Lower than average autumn rainfall extended the $PSMD_{max}$ to early June in 2012. Crops would be expected to suffer yield loss when 50% of PAWC is extracted from the soil (Section 2.5) which would be about 60 and 250 mm for Ashley Dene and Iversen 12, respectively. In a normal season this would occur in the first week of

October for established crops at Ashley Dene and mid-December at Iversen 12. For seedling crops, this would depend on sowing date and pattern of canopy expansion. This will be investigated in the current study.

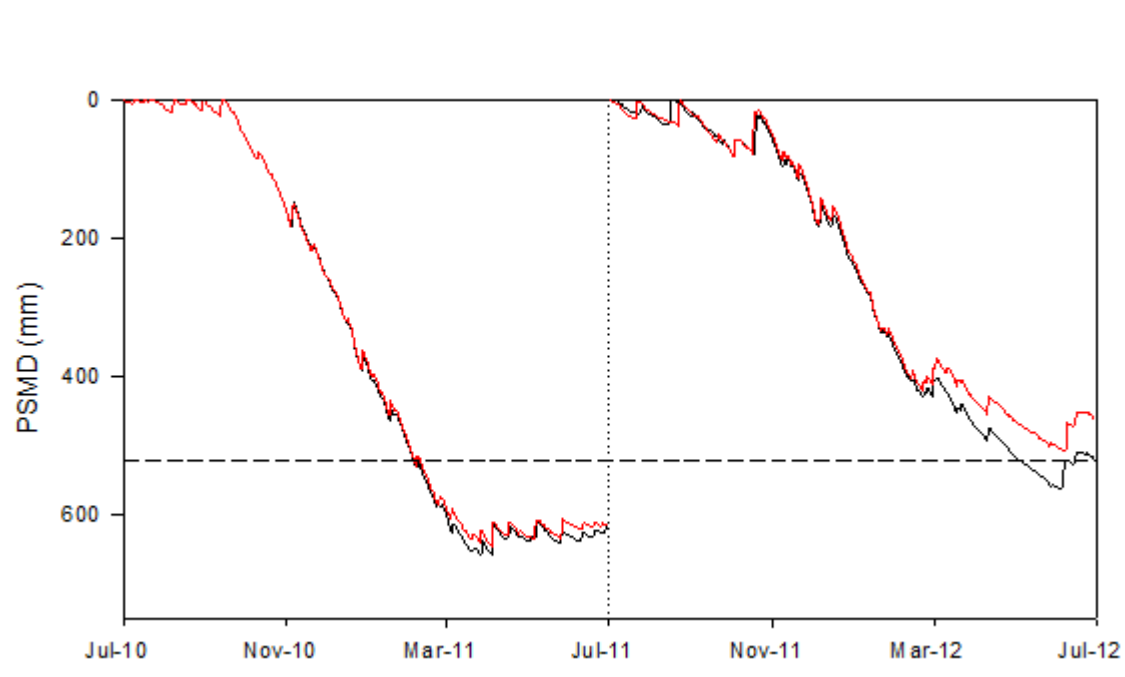


Figure 3.3 Seasonal pattern of potential soil water deficit (PSMD) for two seasons from 1 July 2010 to 30 June 2012 for Ashley Dene (—) and Iversen 12 (—) at Lincoln University, Canterbury, New Zealand. --- marks the long-term mean of maximum PSMD (PSMD_{max}; 520 mm).

Note: Rainfall was collected at experimental sites and Penman potential evapotranspiration was estimated from Broadfields meteorological station.

3.2.4 Temperature and solar radiation

Mean monthly air temperature and total solar radiation followed the long-term trend each season (Figure 3.4). Monthly temperature was highest at Ashley Dene in December 2010 (17.1 °C) and lowest in June at both sites (5.6 °C). Temperatures were consistent between both sites, although from November to February the temperature was elevated by 0.2 °C at Ashley Dene. Temperature extremes over the two seasons were 35.4 °C on 6 February 2011 at Ashley Dene and -6.3 °C on 7 June 2012 at Iversen 12.

Mean daily total solar radiation followed a similar pattern each season and increased from a minimum of 4 to 5 MJ/m²/d in winter to ~22 MJ/m²/d in summer. Yearly average daily solar radiation was 5% higher than the LTM in both seasons. Mean daily total solar radiation was highest in November 2010 (24.6 MJ/m²/d) and lowest in June 2011 (3.9 MJ/m²/d).

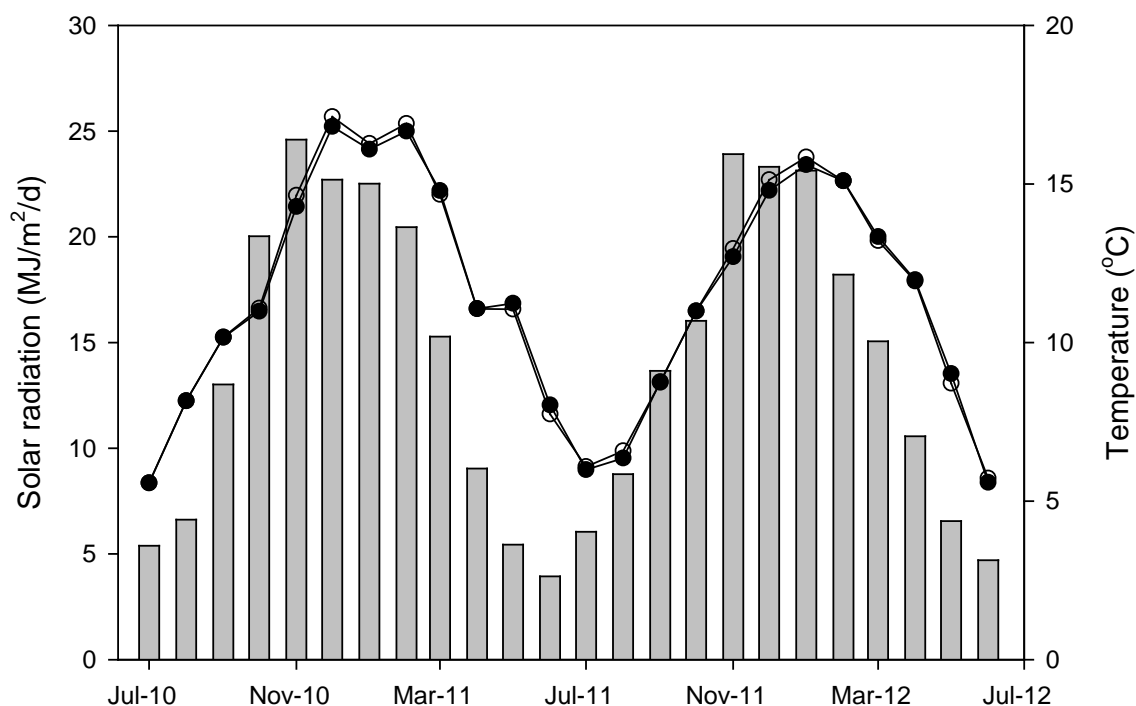


Figure 3.4 Mean daily solar radiation (■) and mean daily air temperature for Ashley Dene (—○—) and Iversen 12 (—●—) for monthly periods from 1 July 2010 to 30 June 2012, Lincoln University, Canterbury, New Zealand.

Note: Solar radiation data collected from Broadfields Meteorological Station and air temperature measured at the experimental sites.

3.2.5 Vapour pressure deficit and wind run

Mean daily vapour pressure deficit (VPD) ranged from 0.4 kPa in winter to 0.8 kPa in January and February (Figure 3.5). Wind run increased from around 250 km/d in July to 400 km/d during the months of summer. Daily wind run range was 40 to 800 km/d.

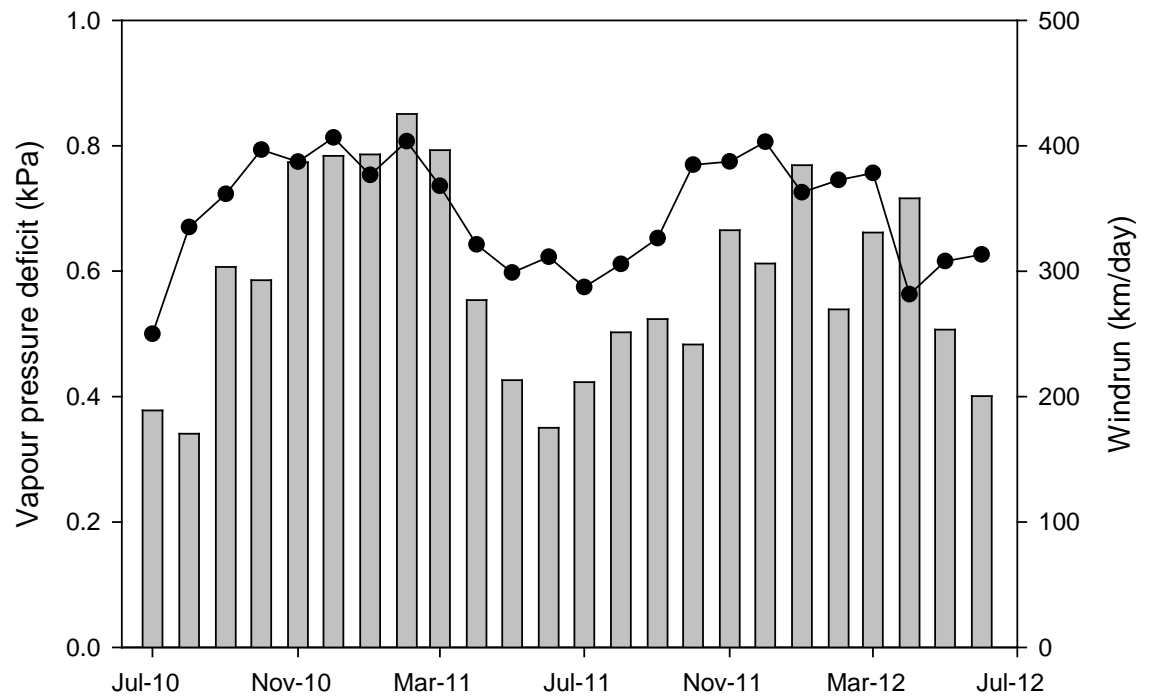


Figure 3.5 Mean daily vapour pressure deficit (■) and wind run (—●—) for monthly periods from 1 July 2010 to 30 June 2012. Data were obtained from Broadfields Meteorological Station, Canterbury, New Zealand.

3.3 Agronomic management

3.3.1 Experimental design and treatments

Experiments at both Ashley Dene and Iversen 12 were identical in their design and setup. The experiments covered an area of 0.63 ha (125 m x 50 m). They were established as a split-plot within a randomised complete block design (Appendix 1). The main-plots were five sowing dates and the sub-plots (4.2 x 7 m) were four methods of rhizobia (*Ensifer meliloti*) inoculation seed treatment, replicated four times. There were further sowing date sub-plot treatments added in the second season with coated seed being sown on five dates similar to that of the previous season. Lucerne was sown monthly from October 2010 until February 2011, which was repeated in the following season (Table 3.3). In the first season the four methods of rhizobia inoculation were; peat, coated and ALOSCA, plus a bare seed control. The objective of those experiments was to examine the effect of sowing date and inoculation method on the establishment and growth of seedling and regrowth crops at Ashley Dene (Wigley, 2011) and Iversen 12 (Khumalo, 2012). This aspect is not part of the current study, and therefore no further data on this were reported here.

Table 3.3 Summary of sowing dates for two experiments conducted at Ashley Dene paddock 2MB (Ashley Dene) and Iversen Field paddock 12 (Iversen 12) at Lincoln University, Canterbury, New Zealand.

Season	Sowing number	Ashley Dene	Iversen 12
2010/11	1	21 Oct	4 Oct
	2	9 Nov	4 Nov
	3	8 Dec	2 Dec
	4	13 Jan	10 Jan
	5	3 Feb	7 Feb
2011/12	6	— 10 Oct —	
	7	— 7 Nov —	
	8	— 9 Dec —	
	9	— 10 Jan —	
	10	— 17 Feb —	

Data presented in this thesis are from one sub-plot treatment, in year one (2010/11), coated seed and from a further five sowing dates in the second year (2011/12). Coated seed contains the rhizobia *Ensifer meliloti*, fungicide against *Pythium* protecting seedlings from ‘damping off’, molybdenum and lime.

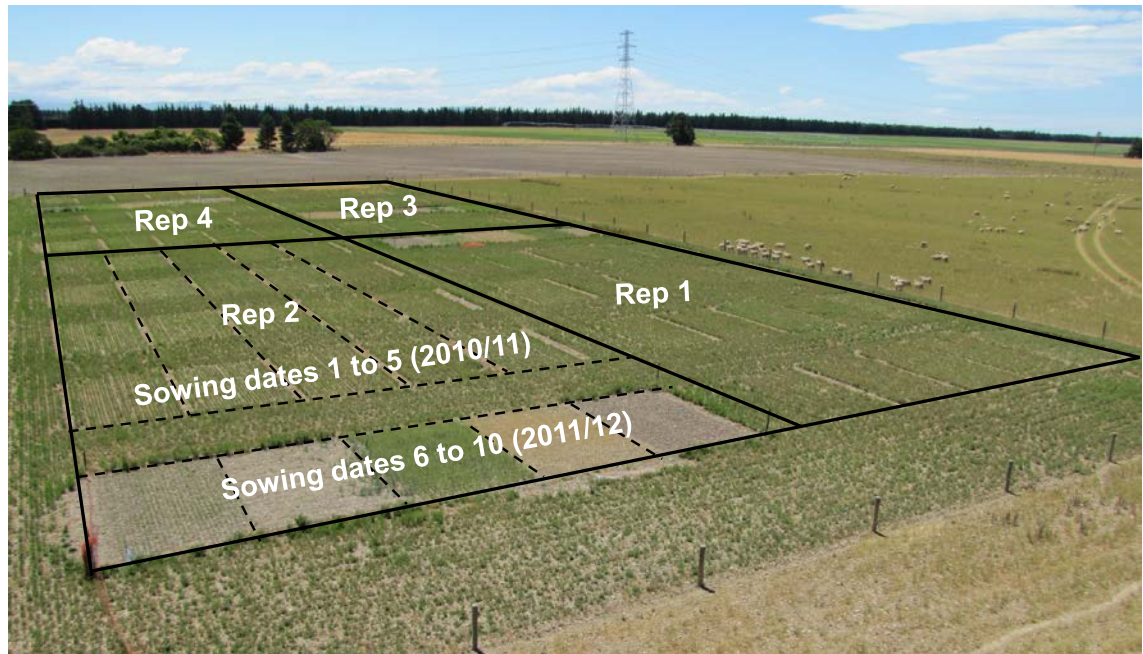


Plate 3.2 Ashley Dene experimental site in January 2012. Dashed lines separate sowing date treatments which run approximately west to east.

3.3.2 Establishment

Ashley Dene was ploughed on 5 September 2010 and cultivated on 14 September 2010. Iversen 12, prepared in a similar way, was ploughed on 1 September 2010, and then harrowed and Cambridge rolled. Fertiliser (Section 3.3.3) and pre-emergence herbicide (Section 3.3.4) were applied. The site was then conventionally cultivated by maxi-till and Cambridge rolled producing a fine, consolidated seedbed. The additional areas to be sown in the second season were grubbed and Cambridge rolled on 3 October 2011 at both experimental sites. A 25 mm rainfall event on 5 October 2011 caused soil compaction and capping so the areas were re-cultivated by maxi-till and Cambridge rolled on 10 October 2011 prior to the first sowing date.

‘Stamina 5’ coated lucerne seed was sown to 20 mm depth at a rate of 16 kg/ha (10.5 kg/ha bare seed) using an Øyjord cone seeder. Crops were sown on five dates, monthly from October 2010, which was repeated in October 2011 at both experimental sites (Table 3.3). For sowing dates 6 to 10 a new seasons line of ‘Stamina 5’ seed was sown, both seed lots had germination over 92%.

3.3.3 Soil fertility

Soil chemical analysis of the topsoil (0-150 mm) was undertaken at the initial experiment setup, prior to each sowing date and at the end of each season during the winter period. The soil analysis results for Ashley Dene and Iversen 12 are displayed in **Appendices 2 and 3**, respectively. Initial soil testing consisted of 16 cores taken randomly across the experimental site and bulked. Other tests consisted of taking 16 cores per sowing date treatment (4 per sub-plot).

The initial soil test at Ashley Dene indicated soil pH, phosphorous (P) and sulphate sulphur [S(SO₄)] were slightly below optimum levels (Appendix 2). To correct this 4 t/ha of lime and 200 kg/ha of superphosphate (0,9,0,11) were applied on 14 September 2010 after ploughing and incorporated with secondary cultivation. At the end of the first season, in June 2011 soil analysis showed P and S(SO₄) and potassium (K) were below optimum levels. On 11 September 2011 300 kg/ha potassic super sulphur (0,8,5,10) was applied to correct these deficiencies. There was concern regarding low K values at Ashley Dene, however reserve soil K test results (TBK; modified boron tetraphenyl method) indicated a very high level (3.1 me/100g). This is consistent with the soils parent material and is expected to supply K to meet the crops demand in this environment (McLaren and Cameron, 1990). The initial soil test at Iversen 12 indicated both P and S(SO₄) were below optimum levels (Appendix 3). To correct these deficiencies 250 kg/ha sulphur super 20 (0,8,0,20) was applied after ploughing on 1 September 2010 and incorporated with secondary cultivation. At the end of the first season, in June 2011 soil analysis showed P was below optimum and on 11 September 2011 200 kg/ha super sulphur 15 (0,9,0,15) was applied to correct this.

3.3.4 Weed control

Following ploughing and before secondary cultivation, sites were sprayed with Treflan (trifluralin; 0.8 kg a.i./ha) on 14 September at Ashley Dene and 1 September at Iversen 12 to control annual grass, *Poa sps*, fathen (*Polygonum aviculare* L.) and chickweed (*Stellaria media* L.). Plots were hand weeded for fathen and shepherd's purse (*Capsella bursa-pastoris* L.) about 1 month after crop emergence for all sowing date treatments. On 8 April 2011 Ashley Dene was hand weeded for horehound (*Marrubium vulgare*) and Californian thistle (*Cirsium arvense* L.) was spot sprayed with Roundup Renew (glyphosate; 1.4 kg a.i./ha). During the first season, the areas which were to be sown in the second season were chemically fallowed to prevent weed invasion and retain soil moisture with applications of Roundup Renew (glyphosate; 1.4 kg a.i./ha) and Buster (glufosinate-ammonium; 1 kg a.i./ha) on 12 January 2011, 8 April 2011 and 15 September 2011. Sowing dates 1 to 5 were sprayed at the end of the first season on 25 August 2011 with Preside (flumetsulam; 0.052 kg a.i./ha) for control of broad leaved weeds, particularly chickweed and spurrey (*Spergula arvensis*) and Gallant (haloxyfop; 0.025 kg a.i./ha) with DC Tron uptake oil (adjuvant) at l/ha for browntop, ryegrass and other grass weeds.

3.3.5 Insect control

Seedling leaf damage caused by springtails (*Bourletilla sps* L.) during crop emergence was controlled by applying Attack (pirimiphos-methyl; 0.475 kg a.i./ha and permethrin; 0.025 kg a.i./ha) to sowing dates 8 and 9 on 29 December 2011 and 22 January 2012, respectively, at both sites.

3.3.6 Defoliation

Defoliation occurred at the end of a regrowth period which was determined based on crop growth stage and time of the year. Seedling crops were defoliated when 50% of marked stems had an open flower. During the autumn months, seedling crops failed to flower and were defoliated when ceiling yield was determined to have been met with the onset of rapid leaf senescence in the lower parts of the canopy. The first spring defoliation of lucerne in its second year occurred when crop height reached 0.35 to 0.40

m to prevent lodging. Subsequent defoliations occurred when 50% of marked stems had a visible flower bud. For one regrowth period during late summer, defoliation was delayed to allow 50% of marked stems to have an open flower. A final defoliation occurred once growth stopped in May/June.

3.3.6.1 *Ashley Dene*

Defoliation management was similar to that of Iversen 12, however because summer moisture stress was more severe at Ashley Dene, defoliation occurred with the onset of drought, regardless of lucerne reproductive stage. Defoliation management resulted in seedling crops being defoliated 1 to 3 times depending on sowing date and second year crops five times (Appendix 4). Seedling crops were defoliated mechanically using a lawn mower with biomass removed and second year crops were grazed with approximately 100 ± 20 ewes for 7 to 10 days. Sheep were removed when residual stem height was ~50 mm to prevent overgrazing and damage to lucerne crowns. Due to preferential grazing, post-grazing residuals of sowing date treatments differed ($P = 0.05$; Appendix 5), therefore plots were mechanically trimmed to ~50 mm to ensure no residual leaf area was transferred to the subsequent regrowth period.

3.3.6.2 *Iversen 12*

Defoliation management resulted in seedling lucerne being defoliated 1 to 4 times depending on sowing date and second year crops 7 times (Appendix 6). All defoliations were undertaken mechanically using a lawn mower with biomass removed from the site, except for the final defoliation in winter of both years when approximately 120 ewes grazed the site for 7 to 10 days. Cutting height was set at ~50 mm to prevent damage to lucerne crowns and maintain a consistent residual throughout the experiment.

3.4 Calculations

3.4.1 Meteorological conditions

3.4.1.1 *Potential Evapotranspiration*

Potential evapotranspiration was calculated daily from hourly weather data from Broadfields meteorological station using Penman evapotranspiration potential (EP) as described by French and Legg (1979).

3.4.1.2 *Potential soil water deficit*

Potential soil moisture deficit (PSMD) was calculated each season (1 July to 30 June) also using the equation presented by French and Legg (1979);

Equation 3.1
$$\text{PSMD}_i = \text{PSMD}_{i-1} + \text{EP}_i - \text{rainfall}_i$$

Where PSMD_{i-1} is the PSMD on the previous day (mm), PSMD was set to zero at the start of each season and was not allowed to exceed zero (i.e. field capacity) and excluded runoff.

3.4.1.3 *Vapour pressure deficit*

Vapour pressure deficit (VPD) was calculated daily as the difference between vapour pressure and saturated vapour pressure at air temperature calculated using wet and dry bulb temperatures obtained from Broadfields meteorological station. Calculations and details are presented in Jenson *et al.* (1990).

3.4.2 Thermal time calculation

Thermal time (T_t , °Cd), was calculated following the method of Jones and Kiniry (1986) from daily mean air temperature using a broken-stick threshold model (Figure 2.2) where T_t is assumed zero below the base temperature (T_b) of 1.0 °C. T_t is accumulated linearly at a rate of 0.7 °Cd/°C up to 15 °C and then at a rate of 1.0 until 30

°C (Moot *et al.*, 2001; Teixeira *et al.*, 2011). This method calculates Tt at three hourly intervals which are integrated over one day.

3.5 Statistical analysis

Statistical analysis was conducted in GENSTAT (version 14.1) (Lawes Agricultural Trust, IACR, Rothamsted, U.K.). Treatments were grouped on year of sowing and experimental site. Data were analysed as a one-way ANOVA in randomised blocks. Means were separated by Fishers protected l.s.d ($P \leq 0.05$) when significant. Linear and non-linear regressions were calculated using the least-squares regression method. Regressions were fitted to individual plot data and coefficients were analysed by ANOVA and means for grouped treatments separated by l.s.d ($P \leq 0.05$) when significantly different.

4 Lucerne establishment and DM production

4.1 Introduction

Annual DM yields of dryland lucerne in Canterbury range from 5 to 20 t DM/ha (Section 2.1.2). The yield difference has largely been attributed to the supply of water (Moot *et al.*, 2008). The water supply is determined by the amount of stored water over the winter within the soil profile, which is available for plant extraction later in the season, and rainfall. Understanding of the soil-plant interactions is required to maximise the capture and use of this limited soil water for managing lucerne for optimal yield. Dryland lucerne experiments were established and grown at Ashley Dene and Iversen 12 at Lincoln University. These locations represent soils with contrasting plant available water content (PAWC), to a depth of 2.3 m of 130 and 360 mm, respectively. The aim was to quantify the yield formation processes for these lucerne crops in response to the environment.

Sowing date was used to create different environmental conditions at establishment. The initial objective was to determine if unifying relationships with temperature and photoperiod could be found that explain the yield forming processes. The second objective was to determine if these relationships were consistent between the two soil types. This was done through measurement of DM production in the establishment and subsequent second growth season. Assessment of below ground DM was undertaken because perennial reserves of lucerne, particularly during the seedling phase, have been shown to be a key determinant of subsequent crop productivity (Teixeira *et al.*, 2007c; Thiebeau *et al.*, 2011).

4.2 Material and methods

This chapter reports the agronomic results of the emergence and growth of lucerne sown at Ashley Dene and Iversen 12 from October 2010 to July 2012. Results include the seedling phase (sowing to 50% flowering) from 20 sowing dates and 92 subsequent regrowth periods over two seasons.

4.2.1 Emergence

Lucerne emergence was defined when both cotyledons were visible and had unfolded (Moot *et al.*, 2000). The number of emerged seedlings was counted from two 1 m long drill rows in each plot. Counts were made every two days until seedling number became constant for three consecutive dates. Gompertz functions (Equation 4.1) were fitted to cumulative seedling emergence number against days after sowing (DAS).

Equation 4.1
$$Y(t) = a * \exp(-\exp[-b * (t - m)])$$

Where Y is the cumulative emergence number of seedlings at time (t ; DAS), a is the final population, and b and m are constants. The number of days (t) to 50% emergence (DAS_{50}) was calculated from the Gompertz function using Equation 4.2 where $Y = 50$.

Equation 4.2
$$t(DAS_{50}) = m - \ln[-\ln(Y/100)]/b$$

4.2.2 Time to first trifoliate leaf

Mainstem node appearance was measured on 40 marked stems per treatment from emergence (10 per replicate). Mainstem node appearance was determined by regression of node number against daily Tt accumulation (Section 3.4.2), which showed a strong positive linear relationship ($R^2 > 0.95$), which allowed time to first leaf appearance to be interpolated.

4.2.3 Seedling shoot and root biomass

Seedling shoot and root biomass was assessed when 50% of the marked seedlings had reached two and six trifoliate mainstem leaves. To do this 10 representative plants were excavated per plot. Shoot and root fractions were separated at ground level. The root fraction included the entire root system.

4.2.4 Shoot yield

Shoot DM production was measured using a single 0.2 m² quadrat, cut just above crown height (~50 mm, to avoid damage to the plants). Measurements were taken systemically each season to avoid re-cutting previously sampled areas. Areas within 1 m of the neutron probe access tubes were also avoided. Following cutting, samples were stored in a cooler at 4 °C and processed within 48 hours. All DM samples were dried in a forced air oven (60°C) to a constant weight. When grazing occurred, post-grazing cuts were taken within 24 hours of removing sheep to determine residuals, and any need for mechanical topping.

4.2.5 Seasonal growth rates

Daily growth rates were calculated by linear regression between accumulated DM against accumulated Tt for each individual growth period to account for seasonal temperature effects and identify environmental effects, other than temperature, that limit production. Growth rate results are presented for the mid-point of each regrowth period.

4.2.6 Root biomass

In the second season (2011/12) sowing dates 6 to 10 were sampled at the end of each regrowth period for crown and taproot (300 mm depth) biomass. At the end of each regrowth period the same 0.2 m² quadrat which was used to measure shoot DM was excavated to 300 mm and crown and taproots removed. Material was placed immediately on ice and stored at 4 °C until processed. Fine root material, which has been shown to contribute <5% to total root biomass, was not measured (Brown, 2004).

Material was washed clean of soil in cold water and taproots counted before partitioning into 3 fractions; i) crown, ii) taproot 0 to 50 mm and iii) 50 to 300 mm. Root biomass for sowing dates 1 to 5 was also measured, at the end of the first and second season.

4.2.7 Validating the base temperature

Emergence and leaf appearance data were used to validate the base temperature. Thermal time for emergence and time to first trifoliate leaf appearance was calculated using air and soil (20 mm) temperatures (Figure 4.1). Regression of these temperatures against rate of development showed weak relationships ($R^2 < 0.50$) with field data, so the temperature selection was based on the physical location of the apical meristem (Angus *et al.*, 1981; Jamieson *et al.*, 1995b). Soil temperature for emergence and air temperature thereafter were used which has been shown to be most suitable with temperate pasture species (Moot *et al.*, 2000; Monks, 2009).

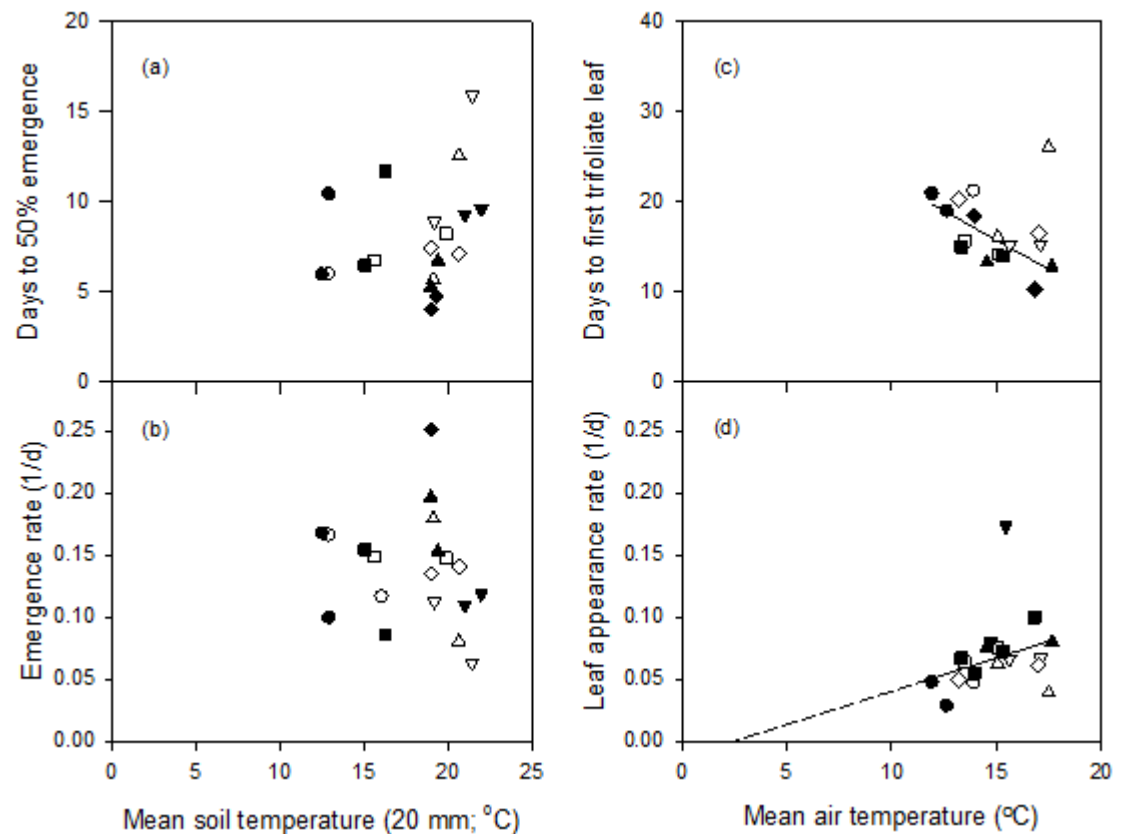


Figure 4.1 Number of days (a) and emergence rate (b) to 50% final seedling emergence, and number of days (c) and leaf appearance rate (d) from 50% emergence to first trifoliate leaf of lucerne sown at different times; October (○), November (□), December (△), January (▽) and February (◇) in the field from October 2011 to February 2012 at Ashley Dene (open) and Iversen 12 (closed) at Lincoln University, Canterbury, New Zealand.

Note: Linear regressions; (c) $y = -1.3x + 35.2$, $R^2 = 0.49$, (d) $y = 0.005x - 0.014$, $R^2 = 0.44$.

There was no apparent relationship between days to 50% seedling emergence (Figure 4.1a) or rate of emergence (Figure 4.1b) and soil temperature during emergence. This means the conditions were not non-limiting and emergence was being regulated by another variable. For example, at a mean soil temperature of 20 °C, time to 50% emergence ranged from 4 to 20 days after sowing. This result suggests analysis of seedling establishment needs to consider other environmental variables which affect

emergence. Field observations suggest soil moisture content at sowing, and subsequent rainfall should also be accounted for. There were weak linear relationships between days for first leaf appearance ($R^2 = 0.49$, Figure 4.1c) and rate of first leaf appearance ($R^2 = 0.44$, Figure 4.1d) against mean air temperature from 12 to 17.5 °C. At a mean air temperature of 12 °C it took 20 days for the first trifoliate leaf to appear, which decreased to 12 days as temperature increased to 17.5 °C. Extrapolation estimated the base temperature to be ~2.5 °C.

These results show data were unsuitable for independent estimation of the base temperature due to the limited temperature range experienced in the field, high minimum temperature (13 °C) and possible curvilinear response of development rate near the base temperature (Angus *et al.*, 1981; Bonhomme, 2000). Therefore, the temperature relationships derived by Teixeira *et al.* (2011) (Section 3.4.2) were used for all thermal time calculations.

4.2.8 Gravimetric soil water content at sowing

Gravimetric water content (GWC) was measured in the top 20 mm of soil at sowing, to indicate seedbed soil water status. From each replicate 20 x 50 g samples were randomly taken and bulked. From this, a sub-sample of ~250 g was dried at 95 °C for at least 48 hours to a constant weight. GWC was calculated inclusive of stone content at Ashley Dene. Stone content was 39±5.8% by weight and did not differ ($P = 0.147$) among treatments. This is greater than the 8% minimum threshold which characterises the Lismore stony silt loam (Section 3.1.2) which shows it is a very stony site. GWC is the weight of soil water per unit weight of dry soil (Kirkham, 2004). The limitation of GWC is that it does not reflect the total water content of the soil which needs to be adjusted for bulk density and stone content i.e. volumetric water content (detailed in Section 6.2.1). The objective of this measurement is to indicate the level of soil wetness at sowing and relate this to the rate of germination, therefore GWC measurements of the soil fraction where the seed is located is suitable.

4.3 Results

4.3.1 Lucerne seedling establishment

4.3.1.1 *Final populations and time to 50% emergence*

The cumulative field emergence of lucerne seedlings was described by Gompertz curves ($R^2 \geq 0.95$; Figure 4.2) for each sowing date at both experimental sites. The final seedling emergence differed ($P < 0.05$) among sowing dates for Ashley Dene in 2010/11 and at Iversen 12 in 2011/12 (Table 4.1). At Ashley Dene final emergence ranged from 215 plants/m² in the December 2010 sown lucerne, to 370 plants/m² in the October 2010 sown crop. Based on a sowing rate of ~450 seeds/m², this represents 50 to 80% emergence.

The number of days from sowing to 50% emergence (DAS₅₀) differed ($P < 0.05$) with sowing date ranging from 4 to 16 days (Table 4.1). The thermal time requirement for 50% emergence ranged from 60 °Cd to 250 °Cd. The lowest Tt requirement which may indicate non-limited conditions occurred in the October 2011 sown crop, at both sites. Generally, time to 50% emergence decreased with later sowing, as soil temperatures increased with rate of emergence maximised at around 20 °C. As mentioned in Section 4.2.7, these results suggest temperature was not the only environmental influence on emergence.

Table 4.1 Final population (plants/m²), days after sowing (DAS₅₀) and thermal time (Tt₅₀; °Cd) requirement for 50% emergence of lucerne sown in the field at Ashley Dene and Iversen 12 over a range of sowing dates from October 2010 to February 2012 at Lincoln University, Canterbury, New Zealand.

Sowing date	<u>Ashley Dene</u>			<u>Iversen 12</u>		
	Population	DAS ₅₀	Tt ₅₀	Population	DAS ₅₀	Tt ₅₀
October 2010	368 _a	9 _b	119 _b	317	10 _{ab}	109 _b
November	242 _b	8 _b	126 _b	330	12 _a	159 _a
December	215 _b	13 _a	205 _a	344	7 _c	78 _c
January 2011	289 _{ab}	9 _b	138 _b	328	9 _b	156 _a
February	372 _a	7 _b	119 _b	391	4 _d	72 _c
P	<0.05	<0.05	<0.05	ns	<0.001	<0.05
SEM	44.1	1.0	15.1	26.3	0.7	8.6
October 2011	225	6 _c	59 _d	198 _b	6 _b	59 _b
November	253	7 _{bc}	85 _c	301 _a	7 _b	78 _b
December	288	6 _d	91 _c	273 _{ab}	5 _b	85 _b
January 2012	204	16 _a	251 _a	263 _{ab}	10 _a	169 _a
February	296	7 _c	115 _b	341 _a	5 _b	76 _b
P	ns	<0.001	<0.001	<0.05	<0.05	<0.05
SEM	34.9	0.8	3.8	27.4	0.9	14.6

Note: Sowing date treatments were given in Table 3.3. Thermal time accumulated using soil temperature (T_b = 1 °C; 20 mm) as per Teixeira *et al.* (2011). Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

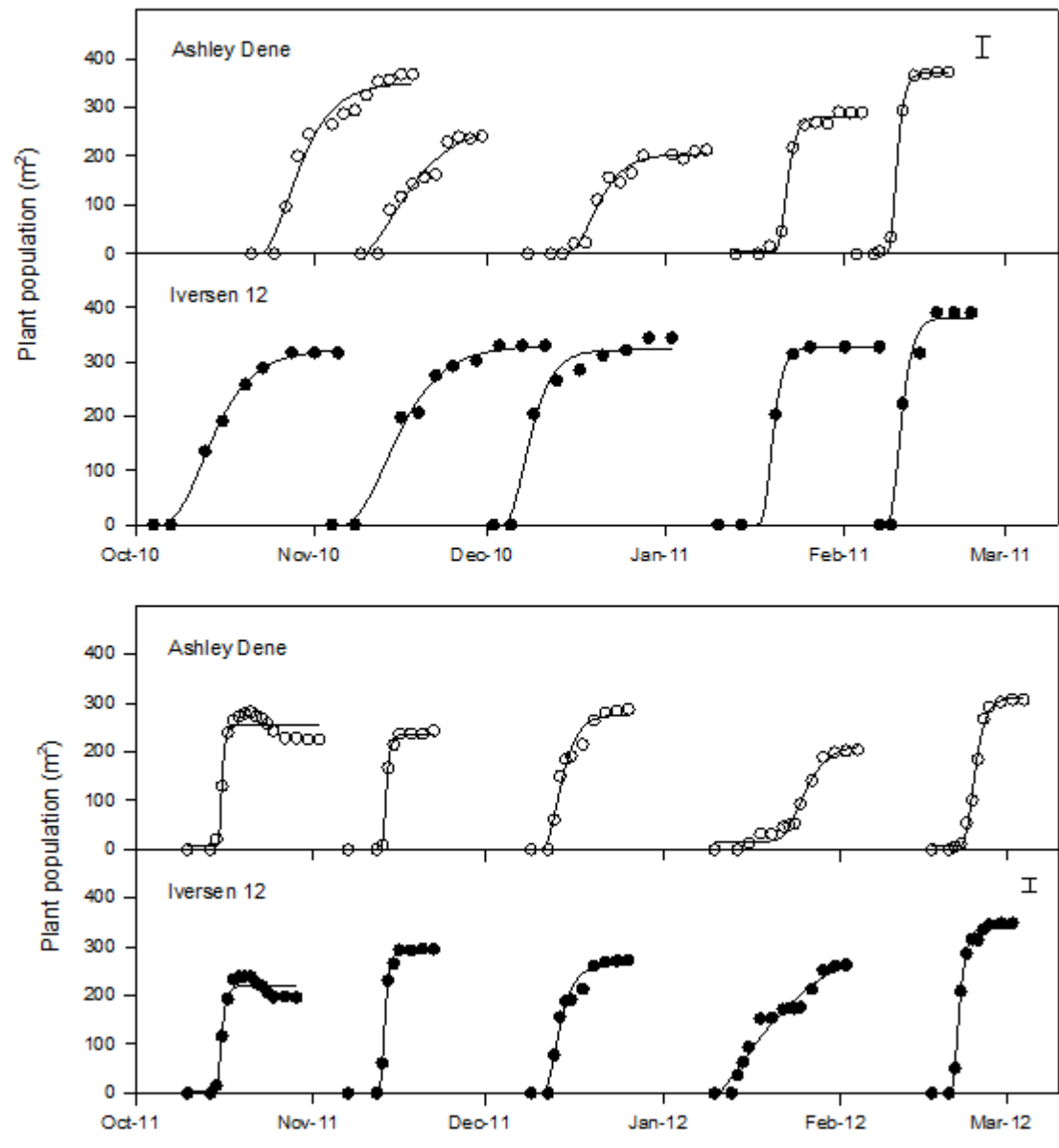


Figure 4.2 The field emergence of lucerne sown on 10 dates at Ashley Dene (○) and Iversen 12 (●) over two seasons from October 2010 to March 2012 at Lincoln University, Canterbury, New Zealand.

Note: Error bars represent l.s.d ($P = 0.05$) for the final emergence population where sowing date treatments were different. Sowing date treatments were given in Table 3.3. Gompertz functions (Equation 4.1) are described in Appendix 7.

4.3.1.2 Soil moisture content at establishment

With later sowing dates GWC tended to decrease from ~15% in early spring to 10% in summer (Figure 4.3). Ashley Dene usually had lower GWC than Iversen 12 and therefore germination was dependant on rainfall at this site. Rainfall of 15 to 20 mm occurred after sowing, except for the December 2010 sowing at Ashley Dene which resulted in germination being delayed by about two weeks (Figure 4.2). Seedling senescence occurred during the October 2011 sown crops at both sites due to a ~60 mm rainfall event resulting in soil capping which caused a reduction of about 10% in final emerged populations (Figure 4.2).

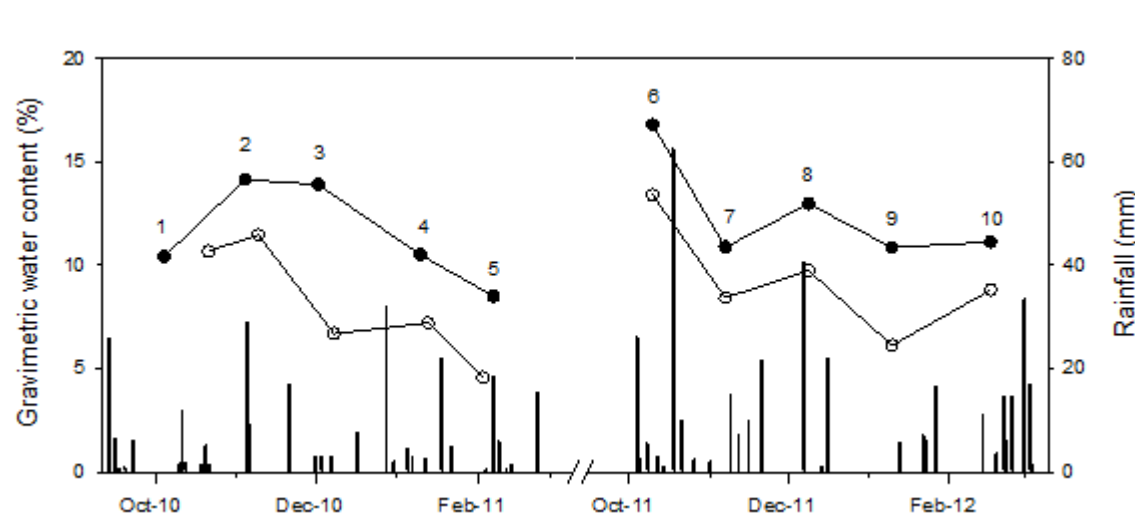


Figure 4.3 Gravimetric water content at sowing and daily rainfall (■) for Ashley Dene (○) and Iversen 12 (●) for 10 sowing dates over two seasons from October 2010 to March 2012 at Lincoln University, Canterbury, New Zealand.

Note: Numbers represent sowing date treatments which are detailed in Table 3.3.

The thermal time requirement for 50% emergence showed a moderate exponential relationship in relation to GWC at time of sowing (Figure 4.4) with an R^2 of 0.74. The relationship showed a requirement of ~90 °Cd when the GWC was greater than 9%. Tt for emergence increased exponentially to ~250 °Cd when the soil dried to a GWC of ~6%.

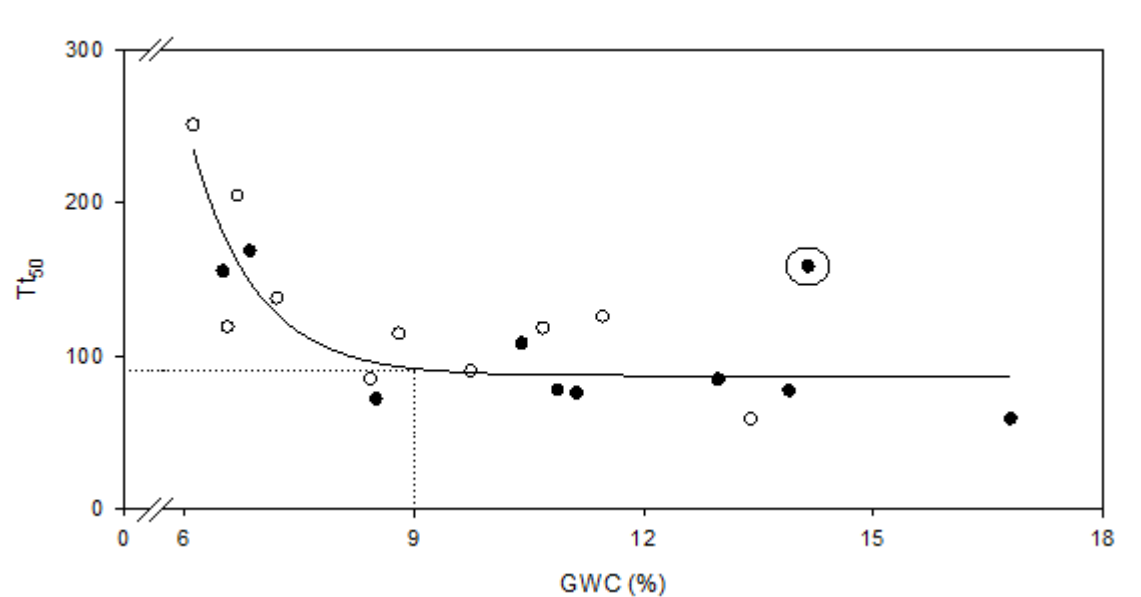


Figure 4.4 Thermal time to 50% field emergence (Tt_{50}) in relation to gravimetric water content (GWC) at sowing (0-20 mm) for lucerne sown at Ashley Dene (○) and Iversen 12 (●) from October 2010 to February 2012 at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using soil temperature ($T_b = 1\text{ }^{\circ}\text{C}$; 20 mm) as per Teixeira *et al.* (2011). Form of the regression: $y = 87.3 + 2.2 \times 10^5 e^{-1.19x}$, $R^2 = 0.74$. Circled data point was excluded from regression as heavy rainfall resulted in soil capping and delayed final emergence.

4.3.1.3 Time to first trifoliate leaf

Time to first trifoliate leaf was analysed from 50% emergence, as the time from sowing to emergence was inconsistent between treatments. The number of days to first trifoliate leaf ranged from 6 days when sown in January to 35 days when sown in October at Iversen 12 (Table 4.2). Tt requirement ranged from 66 to 330 $^{\circ}\text{Cd}$ for the same sowing dates, although the Tt requirement was more consistent for first leaf appearance relative to emergence, with 50% of treatment means within the pooled standard error of the mean of 190 $^{\circ}\text{Cd}$.

Table 4.2 Days after emergence (DAE) and thermal time (Tt; °Cd) requirement for first trifoliate leaf appearance of lucerne sown in the field at Ashley Dene and Iversen 12 over a range of sowing dates from October 2010 to February 2012 at Lincoln University, Canterbury, New Zealand.

Sowing date	<u>Ashley Dene</u>		<u>Iversen 12</u>	
	DAE	Tt	DAE	Tt
October 2010	21 _b	235 _b	35 _a	329 _a
November	14 _c	169 _c	14 _b	160 _{bc}
December	26 _a	353 _a	13 _{bc}	177 _b
January 2011	15 _c	194 _{bc}	6 _d	66 _d
February	16 _c	204 _{bc}	10 _b	139 _c
P	<0.001	<0.001	<0.001	<0.001
SEM	1.3	16.7	1.0	10.3
October 2011	21 _a	190 _{bc}	21 _a	178 _a
November	16 _b	204 _a	15 _b	143 _b
December	16 _b	182 _c	13 _b	141 _b
January 2012	15 _b	187 _c	13 _b	152 _b
February	20 _a	200 _{ab}	18 _a	190 _a
P	<0.001	<0.001	<0.001	<0.05
SEM	0.3	13.3	0.9	10.6

Note: Sowing date treatments were given in Table 3.3. Thermal time accumulated using air temperature ($T_b = 1\text{ }^{\circ}\text{C}$) as per Teixeira *et al.* (2011). Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

4.3.1.4 Seedling shoot and root biomass

Seedling biomass assessments were made when crops were at the 2nd and 6th trifoliate leaf stage (Table 4.3). Seedlings at Ashley Dene were 40% smaller than those at Iversen 12, at the 2nd trifoliate leaf stage. By the 6th trifoliate leaf stage seedling at Ashley Dene were 55% smaller.

Table 4.3 Shoot and root plant dry weight (mg) and fractional partitioning of DM to roots (P_{root}) for seedling dryland lucerne at the 2nd and 6th trifoliate leaf growth stage at sown Ashley Dene and Iversen 12 from October 2011 to February 2012, Lincoln University, Canterbury, New Zealand.

Site	2 nd Trifoliate leaf			6 th Trifoliate leaf		
	Shoot	Root	P_{root}	Shoot	Root	P_{root}
Ashley Dene	15.0 _b	3.7 _b	0.20 _b	53.4 _b	15.6 _b	0.23 _a
Iversen 12	25.3 _a	4.6 _a	0.15 _a	117.4 _a	23.6 _a	0.17 _b
P	<0.001	<0.001	<0.001	<0.001	<0.05	<0.001
SEM	0.82	0.24	0.008	8.73	2.23	0.10

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

4.3.2 Annual and seasonal DM yield

4.3.2.1 Total annual DM yield

At Ashley Dene, yield was greatest ($P<0.001$) in the establishment season (sowing to June 30th) when lucerne was sown from October to December, yielding 2.5 t DM/ha compared with 0.5 t DM/ha when sown in February (Table 4.4). In the second season, sowing date in the previous establishment season affected yield ($P<0.05$), with DM production again greatest from the October to December sown lucerne yielding 7 t DM/ha, compared with the later sowing dates yielding 6 t DM/ha, or ~15% less.

October and November sowing of lucerne had the greatest ($P<0.001$) yield in the establishment season at Iversen 12 producing 12 t DM/ha compared with 2 t DM/ha when sowing was delayed until February (Table 4.4). There was a sowing date effect ($P<0.001$) in the following regrowth season for these crops, with the October and December sown lucerne yielding 20.4 t DM/ha, compared with 15.8 t DM/ha for the January and February sown lucerne, or ~20% less.

Table 4.4 Total annual (1 July to 30 June) dry matter yields (t/ha) of lucerne sown on 10 dates from October 2010 to July 2012 at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Sowing date	<u>Ashley Dene</u>		<u>Iversen 12</u>	
	Establishment	Year 2	Establishment	Year 2
October 2010	2.4 _a	6.7 _{ab}	12.0 _a	21.5 _a
November	2.4 _a	7.6 _a	8.0 _b	19.1 _b
December	2.2 _a	6.4 _{ab}	8.5 _b	19.4 _{ab}
January 2011	1.6 _b	5.8 _b	3.7 _c	16.6 _c
February	0.6 _c	5.7 _b	2.6 _d	14.9 _c
P	<0.001	<0.05	<0.001	<0.001
SEM	0.17	0.60	0.50	1.01
October 2011	3.1 _a		12.1 _a	
November	2.5 _a		12.8 _a	
December	2.7 _a		8.4 _b	
January 2012	1.5 _b		5.8 _c	
February	0.4 _c		1.1 _d	
P	<0.001		<0.001	
SEM	0.29		0.50	

Note: Sowing date treatments were given in Table 3.3. Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

Annual shoot yield decreased at both sites when sowing was delayed from October to February, in both the establishment year and the subsequent season (Figure 4.5). Annual shoot yield decreased by 5 kg DM/ha and 60 kg DM/ha per day at Ashley Dene and Iversen 12, respectively, when sowing was delayed from October to mid-December. Delayed sowing beyond mid-December decreased yield by 16 kg DM/ha and 114 kg DM/ha per day at Ashley Dene and Iversen 12, respectively. Sowing date continued to affect annual yield in the subsequent season. At Ashley Dene, the yield loss was consistent with that of the first year crops. At Iversen 12, the response in second year crops decreased compared with the establishment year, with a loss of 50 kg DM/ha/day from delayed sowing.

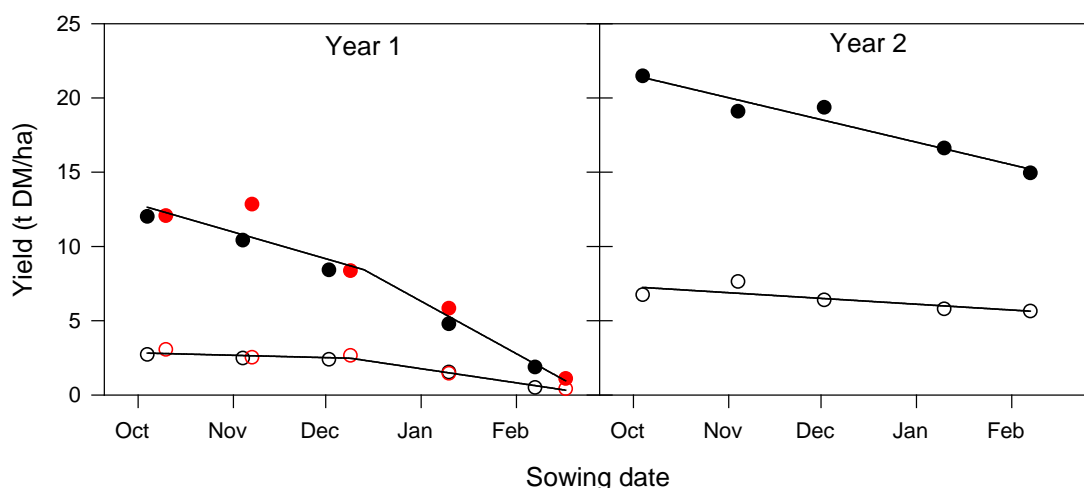


Figure 4.5 Total annual shoot yield of lucerne sown from October to February at Ashley Dene (○) and Iversen 12 (●) in year one (black; sowing to June 2011 and red; sowing to June 2012) and year two (June 2011 to June 2012 at Lincoln University, Canterbury, New Zealand).

Note: Regressions; Ashley Dene; Year one $y = -5x < 8$ December, $-16x > 8$ December, $R^2 = 0.97$. Year 2 $y = -15x$, $R^2 = 0.61$. Iversen 12; Year one $-60x < 13$ December, $-114x > 13$ December, $R^2 = 0.96$. Year 2 $y = -49x$, $R^2 = 0.93$.

4.3.2.2 Seasonal DM yields for Ashley Dene

Seasonal DM accumulation in the establishment and subsequent growth season from sowing dates 1 to 5 at Ashley Dene are displayed in Figure 4.6. The greater ($P < 0.001$) yield from earlier sowing in the establishment season came from the number of subsequent regrowth periods following the seedling phase. October and November sown crops had three regrowth periods, compared with only one for the February sown crop. During the establishment season, final yields attained for individual regrowth phases were consistently around 1 t DM/ha, regardless of the time of year.

In the second season five regrowth phases were achieved which differed ($P < 0.05$) in DM yield. The spring cycles had the highest yields of 2.1 t DM/ha and 1.7 t DM/ha for the first and second cycle, respectively. The third cycle from December to February yielded 0.7 t DM/ha and 1.5 t DM/ha was grown in the fourth regrowth phase, however it was evident yields plateaued in early April. The final growth phase resulted in 0.5 t DM/ha with the onset of ground frosts in early May and snow in June.

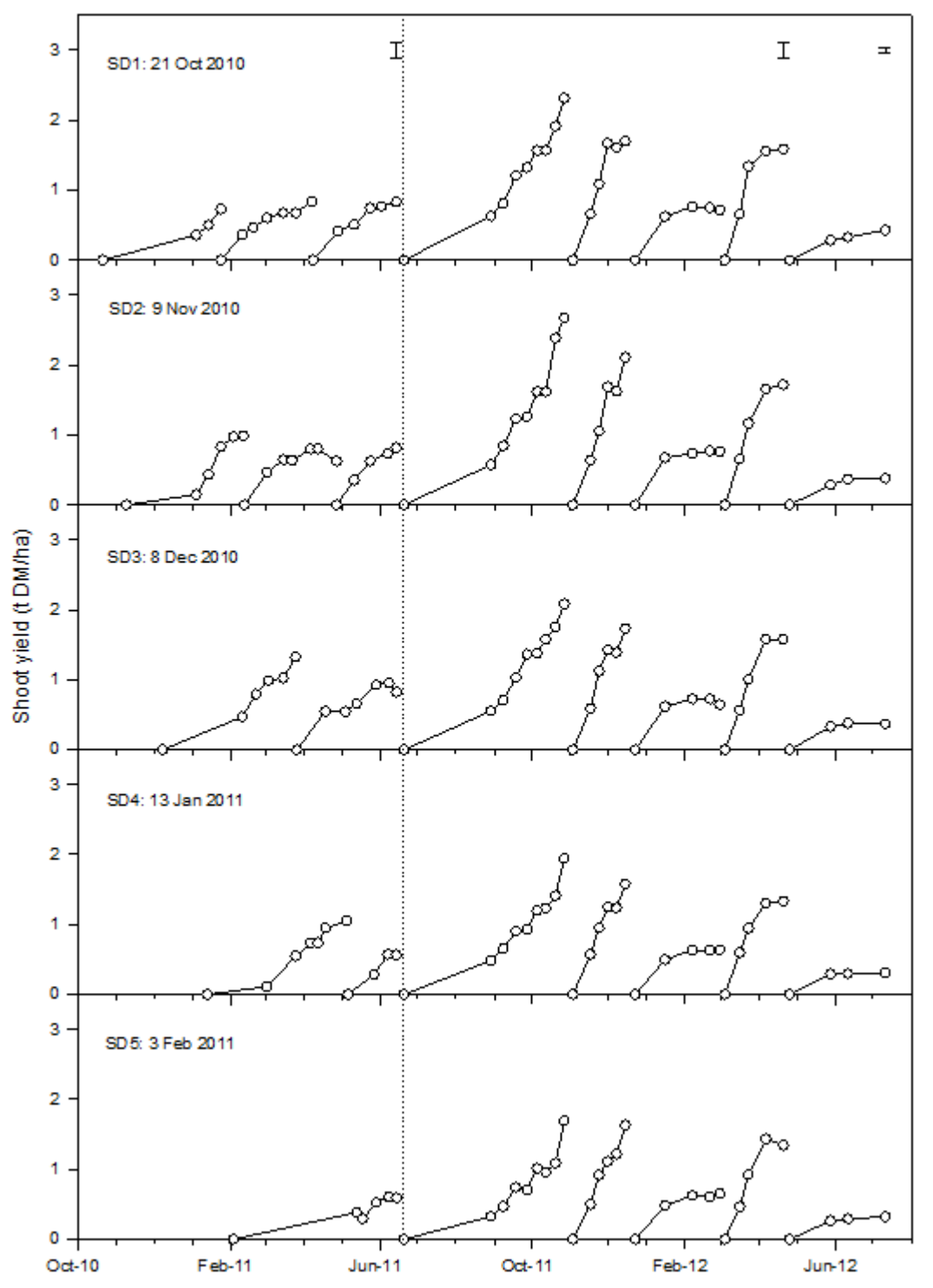


Figure 4.6 Yield accumulated within regrowth cycles from 1 October 2010 to 11 July 2012 for lucerne crops sown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Error bars represent l.s.d ($P = 0.05$) for the final harvest in each regrowth cycle where sowing date treatments were harvested on the same day and were different. Dotted line denotes end of first season.

4.3.2.3 *Seasonal DM yields for Iversen 12*

The pattern of seasonal DM accumulation for the establishment and following season for Iversen 12 sowing dates 1 to 5 is displayed in Figure 4.7. Similarly to Ashley Dene, the greater ($P<0.001$) yields attained from sowing earlier in the establishment year were attributed to the total number of growth cycles achieved within the season. The October and November sown lucerne resulted in four cycles of different yields ($P<0.05$), the seedling phase yielded 3.2 t DM/ha, which was reduced to 1.5 t DM/ha by the fourth regrowth cycle. The February sown lucerne resulted in one meaningful growth cycle, of 3.0 t DM/ha.

In the second season, 7 regrowth phases were managed with yields from 4.5 t DM/ha for the first two spring regrowth periods down to 0.5 t DM/ha for the last. The greater ($P<0.001$) annual yield for sowing dates October to December compared with that of sowing dates January and February was attributed to greater ($P<0.05$) final DM yields in regrowth cycles 1, 4,5 and 6 of year 2 of about 25%.

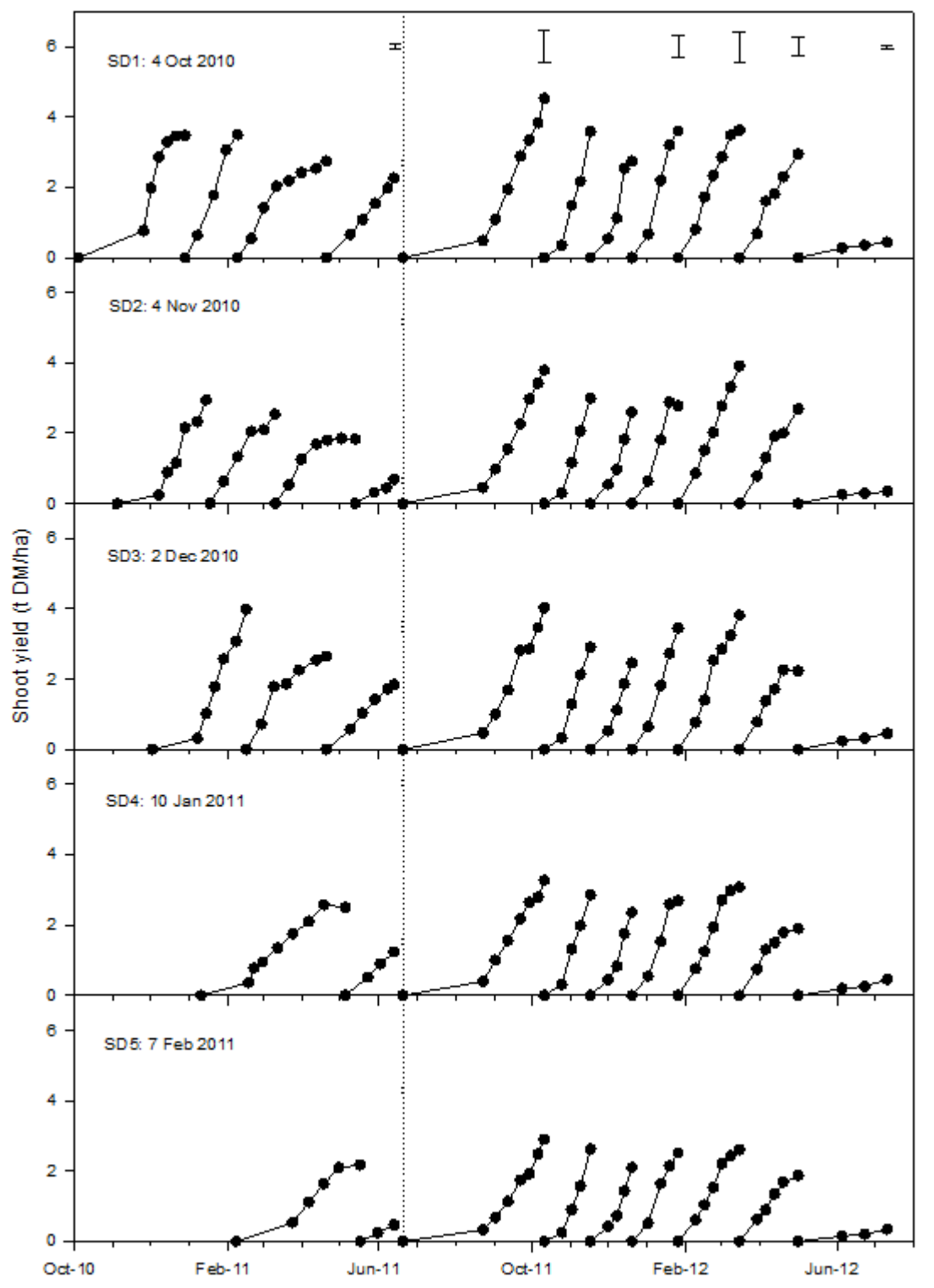


Figure 4.7 Yield accumulated within regrowth cycles from 1 October 2010 to 11 July 2012 for lucerne crops sown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Error bars represent 1 s.d ($P = 0.05$) for the final harvest in each rotation where sowing date treatments were harvested on the same day and were different. Dotted line denotes end of first season.

4.3.2.4 *Seasonal dry matter accumulation rate*

The seasonal pattern of DM accumulation rate is shown in Figure 4.8 for sowing dates 1 to 5 in the establishment and subsequent growth season for both Ashley Dene and Iversen 12. Consistent growth rates of less than 2.5 kg DM/°Cd during the establishment season at Ashley Dene reflect the low final DM yields of about 1 t DM/ha for individual regrowth periods. In comparison, at Iversen 12 growth rates showed a seasonal pattern with 7.5 kg DM/°Cd in summer decreasing to 3.0 kg DM/°Cd by late autumn.

In the second season, lucerne at both sites displayed a linear increase in growth rates from winter reaching a maximum rate in the second regrowth cycle in November of 4 and 9.5 kg DM/°Cd at Ashley Dene and Iversen 12, respectively. At Ashley Dene growth rates decreased to 0.8 kg DM/°Cd in mid-summer, before increasing to 2.9 kg DM/°Cd. In comparison, at Iversen 12, following the peak in growth rates, there was a steady decrease of 40% in growth rates down to 5.7 kg DM/°Cd in April. The onset of frosts in early May resulted in growth rates of 1 kg DM/°Cd at both sites.

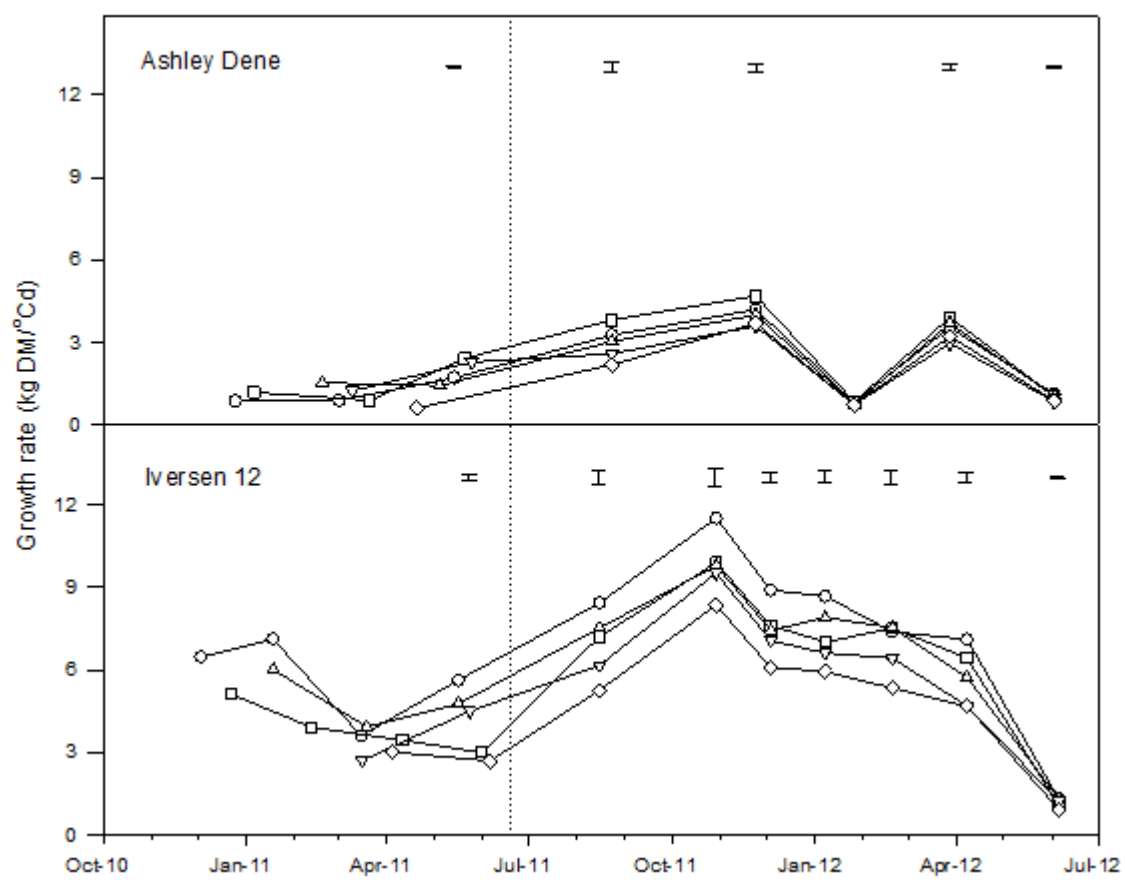


Figure 4.8 Linear growth rates of lucerne sown on five dates; SD1 (○), SD2 (□), SD3 (△), SD4 (▽) and SD5 (◇) at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1\text{ }^{\circ}\text{C}$) as per Teixeira *et al.* (2011). Error bars represent 1 s.d ($P = 0.05$). Individual values for each regrowth period displayed in Appendix 8 and Appendix 9.

4.3.2.5 Growth rate in relation to temperature

Linear growth rates for sowing dates 1 to 5 in the second season in relation to mean air temperature for each regrowth period are displayed in Figure 4.9. Growth rate differed ($P < 0.001$) at the same mean air temperature depending on the direction of temperature change. For example, when mean air temperature was $12.5\text{ }^{\circ}\text{C}$ at Iversen 12, growth rate when temperatures were increasing in October was $9.8\text{ kg DM}/^{\circ}\text{Cd}$ compared with when temperatures were decreasing in April of $5.8\text{ kg DM}/^{\circ}\text{Cd}$. Growth rates at Ashley

Dene displayed a similar pattern, albeit at a lower level. However, lucerne grown at Ashley Dene experienced its lowest growth rate of 0.8 kg DM/°Cd when mean temperature was at its highest of 16 °C. There was also a decrease in growth rate when temperatures were increasing at Iversen 12 during summer regrowth cycles 3 and 4. This result suggests temperature was not the only factor affecting DM production rate.

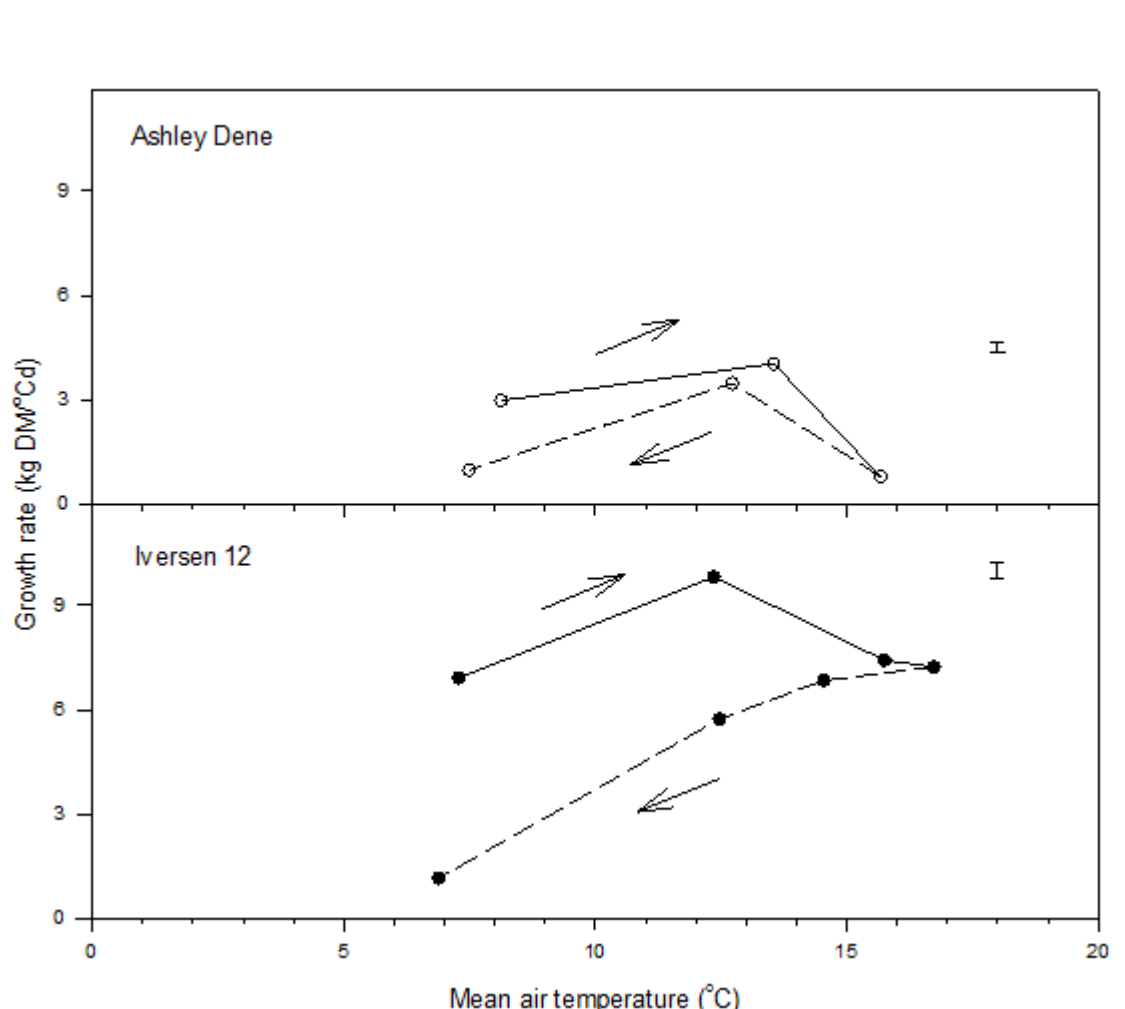


Figure 4.9 Linear growth rate of two year old lucerne crops in relation to increasing (—) and decreasing (---) mean air temperature over the regrowth cycle at Ashley Dene (○) and Iversen 12 (●), Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1\text{ }^{\circ}\text{C}$) as per Teixeira *et al.* (2011). Error bars represent 1.s.d ($P = 0.05$). Arrows indicate direction of temperature change. Individual values for each regrowth period displayed in Appendix 8 and Appendix 9.

4.3.3 Root biomass and partitioning

Both the annual DM production, particularly in the second season, and the seasonal growth rate patterns suggest the partitioning of DM to below ground fractions could be important to explain the above ground DM results.

4.3.3.1 *Root biomass matter of one year old lucerne stands*

Root biomass at the end of the establishment season was influenced ($P<0.001$) by sowing date (Table 4.5). At Ashley Dene, the greatest root mass was observed in the lucerne sown from October to December with a biomass of 1.9 t DM/ha, compared with that from the February sown lucerne with 0.6 t DM/ha. At Iversen 12, root biomass was greatest from the November and December sown lucerne with a biomass of 5.3 t DM/ha compared with that from the February sown lucerne with 1.1 t DM/ha.

4.3.3.2 *Root biomass of two year old lucerne stands*

Sowing date in the establishment season also influenced ($P<0.05$) root mass at the end of the second season (Table 4.5). At Ashley Dene, greatest root mass was observed from lucerne sown in October and November with of 4.7 t DM/ha compared with 3.7 DM t/ha, or 23% less from the other sowing dates. At Iversen 12, root biomass was greatest from October to January sowings with a biomass of 6.7 t DM/ha compared with the February sowing with a yield of 5.7 t DM/ha, or 16% less.

Table 4.5 Root biomass (t DM/ha) of lucerne in its first winter (Year 1: 13 June 2011) and second winter (Year 2: 11 July 2012) sown over a range of dates from October 2010 to February 2011 at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Sowing date	<u>Ashley Dene</u>		<u>Iversen 12</u>	
	Year 1	Year 2	Year 1	Year 2
October	2.18 _a	4.84 _a	4.34 _b	6.74 _a
November	1.99 _a	4.61 _{ab}	5.70 _a	6.61 _a
December	1.65 _{ab}	4.05 _{bc}	4.88 _{ab}	6.74 _a
January	1.23 _b	3.52 _c	3.17 _c	6.89 _a
February	0.59 _c	3.40 _c	1.13 _d	5.67 _b
P	<0.001	<0.05	<0.001	<0.05
SEM	0.19	0.24	0.30	0.23

Note: Sowing date treatments were given in Table 3.3. Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

4.3.3.3 *Root biomass partitioning in seedling lucerne*

Shoot and root DM yields of seedling lucerne (sowing to 50% flowering) were influenced ($P<0.05$) by sowing date (Table 4.6). Maximum shoot yield was from November and January sown crops with 4.5 t DM/ha grown in Iversen 12, in comparison at Ashley Dene maximum shoot yield was from December and January sown crops with 1.2 t DM/ha. Shoot yield showed a similar seasonal pattern at both sites with both early and late sowing incurring high yield penalties.

Root biomass showed a similar seasonal pattern to that of shoot yield, however the ratio at which DM was partitioned to the root fraction (P_{root}) differed ($P<0.001$) in Iversen 12 (Figure 4.10). Spring sown crops that emerged at a photoperiod of about 14.5 hours showed a P_{root} of 0.32. This increased to 0.50 for the mid-season sowing which emerged at the maximum photoperiod of about 16.5 hours. As photoperiod decreased

from 16.5 h to 14.5 P_{root} remained constant at about 0.50. The average P_{root} of 0.53 was not significantly different ($P = 0.063$) at Ashley Dene across sowing dates.

Table 4.6 Shoot and root biomass (t DM/ha) of seedling lucerne at 50% flowering sown over a range of dates at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand

Sowing date	<u>Ashley Dene</u>		<u>Iversen 12</u>	
	Shoot	Root	Shoot	Root
October	0.9 _b	0.9 _{ab}	2.6 _b	1.2 _a
November	0.9 _b	1.1 _{abc}	4.5 _c	3.2 _b
December	1.4 _c	1.2 _{bc}	3.3 _b	3.5 _b
January	1.1 _{bc}	1.5 _c	4.5 _c	4.1 _b
February	0.4 _a	0.6 _a	1.1 _a	1.1 _a
P	<0.05	<0.05	<0.001	<0.001
SEM	0.12	0.17	0.32	0.39

Note: Sowing date treatments were given in Table 3.3. Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

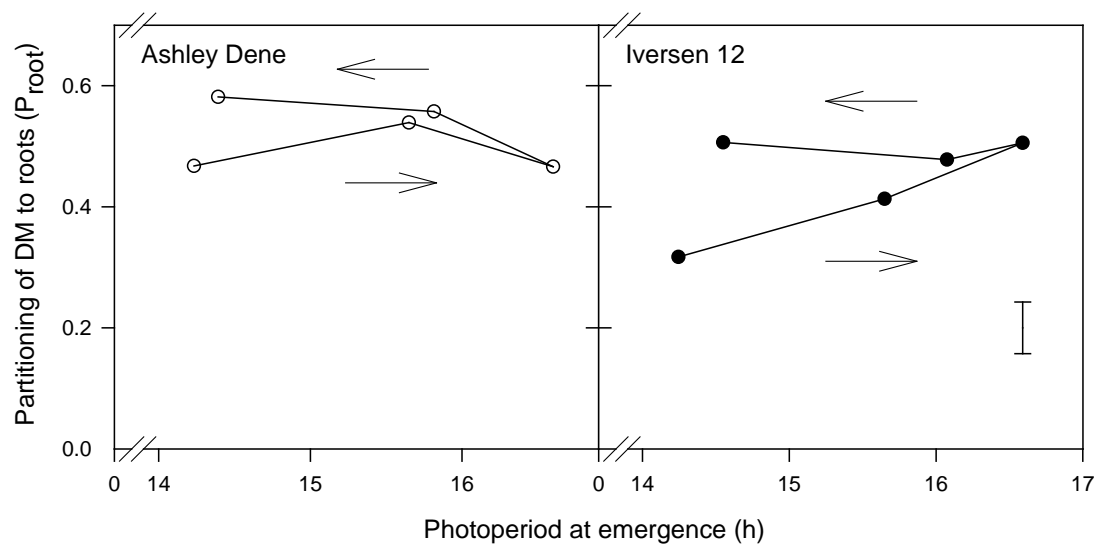


Figure 4.10 Fractional partitioning of dry matter to roots (P_{root}) in relation to photoperiod at emergence for seedling lucerne at 50% flowering over a range of sowing dates at Ashley Dene (○) and Iversen 12 (●), Lincoln University, Canterbury, New Zealand.

Note: Error bars represent l.s.d ($P = 0.05$) where significantly different. Arrows indicate direction of photoperiod change.

4.3.3.4 *Shoot and root dry matter accumulation in first year lucerne*

DM accumulation for the establishment season for sowing dates 6 to 10 at Ashley Dene and Iversen 12 are displayed in Figure 4.11. Greater ($P<0.001$) annual shoot DM yield when sowing earlier is largely attributed to the number of regrowth periods achieved within the season. Final yields for each regrowth cycle at Iversen 12 ranged from 4.5 t DM/ha for summer regrowth periods down to 0.5 t DM/ha at the end of the season, compared with Ashley Dene yields which were consistently around 1 t DM/ha.

Root biomass accumulation at Ashley Dene was greatest ($P<0.05$) in the October sown lucerne by the end of the season with 2.8 t DM/ha. In comparison, at Iversen 12, root mass displayed a linear increase up to about 5 t DM/ha by the third regrowth cycle, which then became constant until the end of the season. The timing of this plateau of root biomass differed among the sowing dates.

DM was partitioned to the root at Ashley Dene during the establishment year at a consistent ratio of ~0.50 and this was not influenced by Pp ($R^2<0.05$) (Figure 4.12). In comparison, at Iversen 12 DM partitioning displayed a strong relationship ($R^2 = 0.88$), with a change in Pp of one hour either increasing or decreasing the P_{root} by ~0.10 depending on the direction of Pp change. For example, as Pp increased from 14 to 16.5 h the P_{root} increased from 0.30 to 0.50. Lucerne which initiated regrowth under decreasing Pp conditions experienced decreasing P_{root} at 14.5 h of 0.30 to 0 at about 12 h.

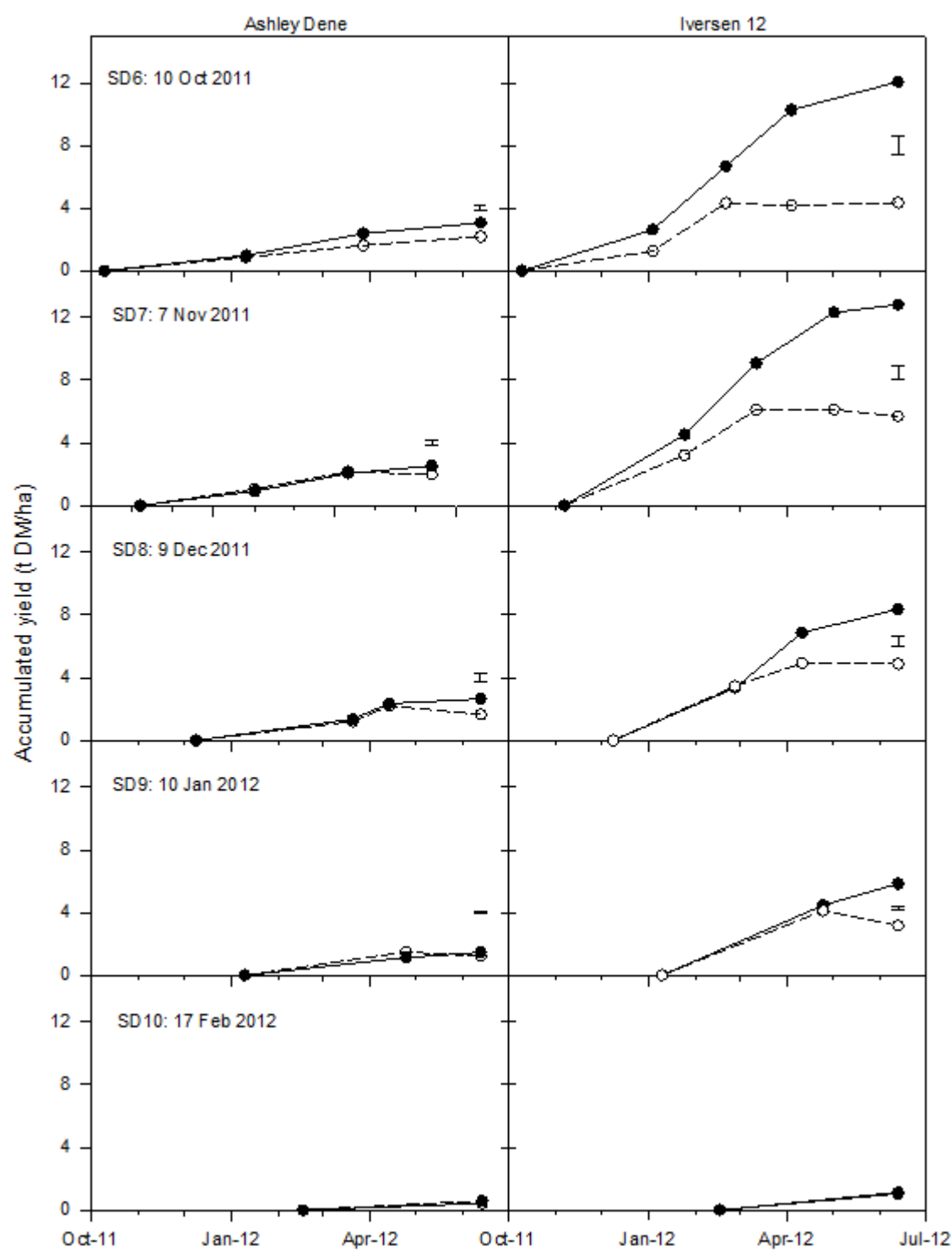


Figure 4.11 Accumulated shoot (●) and root (○) dry matter yields for lucerne sown on five dates at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Error bars represent l.s.d ($P = 0.05$) where significantly different within a treatment.

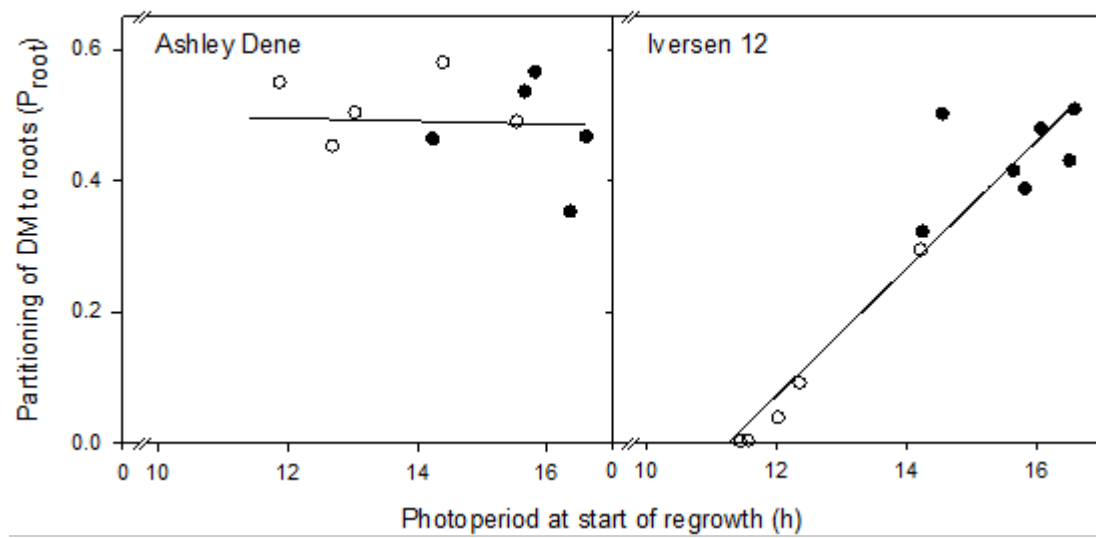


Figure 4.12 Fractional partitioning of dry matter to roots (P_{root}) in relation to increasing (●) and decreasing (○) photoperiod at the start of regrowth periods for lucerne grown at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Linear regressions; Ashley Dene $y = -0.002x + 0.51$, $R^2 = <0.05$, Iversen 12 $y = 0.096x - 1.08$, $R^2 = 0.88$.

4.4 Discussion

Crops were all successfully established. Sowing date affected seasonal DM production in the establishment year and also the subsequent season. Maximum DM yield was attained from early spring sown crops which maintained higher daily growth rates in the following season.

4.4.1 Establishment

Lucerne establishment is not considered to have been affected by sowing date. This is because all sowing date treatments achieved a population >200 seedlings/m² within a month after sowing (Figure 4.2). At populations above ~ 45 plants/m² annual yield is unlikely to be affected (Palmer and Wynn-Williams, 1976; Teixeira *et al.*, 2007a), as at the populations attained, self-thinning is highly likely. This was shown by Moot *et al.* (2012) who reported regardless of sowing rate within normal practices (Section 2.6), half of the sown seed established, which resulted in self-thinning of populations to achieve a stand of 80 plants/m² after 6 years.

The high rate of final establishment was attained despite a large range in time to emergence which ranged from 60 to 250 °Cd (Table 4.1). Seed emergence is a complex physiological process, largely determined by temperature and water potential of the seedbed (Watt *et al.*, 2011). There was a moderate relationship ($R^2 = 0.74$) between gravimetric water content (GWC) at sowing and thermal time requirement for emergence which showed a requirement of about 90 °Cd when GWC was above 9% (Figure 4.4). This was overestimated as the minimum requirement was shown to be 60 °Cd (Table 4.1). A limitation of these data is that the GWC is from the time of sowing and the change in soil moisture due to soil drying and rainfall during the establishment phase, which was up to 16 days (Table 4.1) is not accounted for. However, this variability is common in practical situations, where sowing depth, soil moisture, and seedbed consolidation can interact to produce stands with poor emergence and insufficient plants for maximum yield to 60% seed emergence (Triplett and Tesar, 1960). Nevertheless, the result is consistent with a range of temperate pasture species (Angus *et al.*, 1981; Moot *et al.*, 2000), but needs to be quantified in a similar experimental design, where moisture is non-limiting. To quantify the effect of soil

moisture content on emergence a hydrothermal time model can be used (Watt *et al.*, 2011). This accounts for both temperature and water potential of the seedbed during the establishment phase and may explain these variables, however most of the studies are restricted to controlled environment situations (Watt *et al.*, 2011).

The conservation of soil moisture when sowing is fundamental for rapid and even plant emergence in a dryland environment. This is important because, although the Tt of lucerne emergence is similar to other pasture species, seedling biomass accumulation is slow, and the time to first grazing is delayed, making it vulnerable to weed invasion (Teixeira *et al.*, 2011; Moot *et al.*, 2012). Furthermore, final stand population may be dependent on initial emergence rather than final population, due to self-thinning of smaller plants which emerge later (Triplett and Tesar, 1960). To reduce moisture loss from the seedbed prior to sowing, primary and secondary cultivation should occur in advance, to allow moisture lost from this process to be recharged before sowing (Busari *et al.*, 2013). Soil moisture can be conserved further by direct drilling which reduces soil disturbance and consolidation of the seedbed following sowing which reduce soil water evaporation and improve seed emergence (Triplett and Tesar, 1960; Unger and Stewart, 1983; Passioura, 2006). Because all crops were successfully established, the most productive sowing date will be identified through DM production, which will be discussed in relation to soil type and sowing dates (Section 4.4.2).

4.4.2 DM yield

4.4.2.1 DM yield in relation to soil type

The two soil types created four fold differences in annual DM yield. The likely reason for the difference in yields between the two sites is related to the soil profile (Section 3.1.2) which influences the amount water available for growth (Section 2.5.1). Plant available water needs to be quantified to further explain crop yield differences between the two sites and will be described in Chapter 6. Mean annual yield of lucerne in the establishment year sown at Ashley Dene was 1.9 t DM/ha, compared with 7.5 t DM/ha at Iversen 12 (Table 4.4). This yield difference was maintained in the second season, mean annual yield at Ashley Dene was 6.2 t DM/ha, compared with 18.3 t DM/ha at

Iversen 12, or a three fold difference. These results showed that the main objective of these experiments which was to create crops which differed in yield was achieved (Section 1.3). Yields attained are consistent with reported literature. Brown *et al.* (2003) reported a five year mean yield of dryland lucerne of 20 t DM/ha in a field adjacent to Iversen 12. Dryland yields were below that of irrigated crops which exceed 25 t DM/ha (Brown *et al.*, 2000), which suggests yields in the present study were limited by water. Reported annual yields at Ashley Dene range from 6 to 15 t DM/ha (Moot *et al.*, 2008; Stocker, 2011).

4.4.3 DM yield in relation to sowing date

To maximise DM yield lucerne should be spring sown. October sown crops yielded on average 3 t DM/ha and 12 t DM/ha at Ashley Dene and Iversen 12, respectively (Table 4.4). DM yield in the establishment year was reduced by 16 kg/ha/day at Ashley Dene and 114 kg/ha/day at Iversen 12, when sowing was delayed from mid December to February (Figure 4.5). The formation of yield (Section 2.2) implies crops sown earlier experience longer canopy duration, intercept more radiation throughout the season and therefore would be expected to incur greater DM accumulation. This was shown with up to three regrowth cycles in the October sown crops compared with only one from the February sown crops. These components will be quantified for the crops in Chapter 5.

The lower DM yields from later summer sown crops suggest an alternative animal feed source should be considered. This is the result of a lack of autumn and winter growth from lucerne, further compounded by increased partitioning below ground when crops emerge under decreasing Pp. For example, the February sown crops partitioned ~50% of total DM below ground (Table 4.6) and experienced growth rates of <3 kg DM/°Cd (Figure 4.8). This resulted in shoot yields from sowing to June of 0.5 and 1.9 t DM/ha at Ashley Dene and Iversen 12, respectively, (Table 4.4). Alternative species with greater cool season growth which provide a single or multi graze option in winter when lucerne growth is minimal and should not be grazed (Moot *et al.*, 2003) include forage oats (*Avena sativa*), kale (*Brassica oleracea*), or annual ryegrass (*Lolium multiflorum*) (de Ruiter *et al.*, 2009; Martini *et al.*, 2009; Chakwizira *et al.*, 2011). Yield was predicted for these crops using temperature driven leaf area expansion rates to

determine intercepted radiation, which was converted to yield using constant radiation use efficiencies for the crops (parameters detailed in Appendix 10). The alternative species had potential yields of 7.2 t DM/ha for kale, 5.7 t DM/ha for oats and 4.7 t DM/ha for annual ryegrass, or three times that of the lucerne crops when sown late February (Figure 4.13). These alternative species are more appropriate to be sown at this time, and lucerne should be sown the following spring.

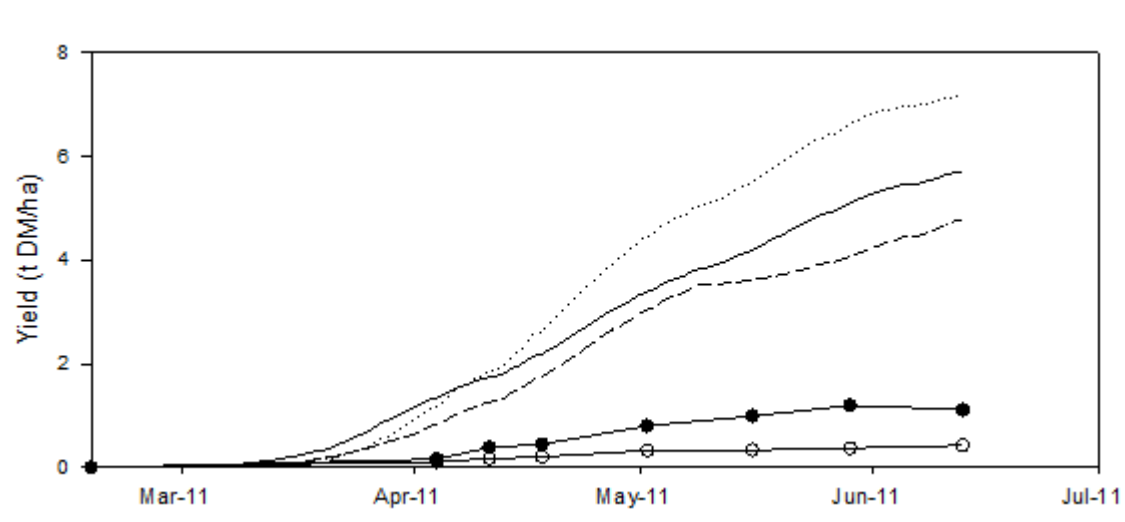


Figure 4.13 Yield accumulation of lucerne sown on 17 February 2012 at Ashley Dene (○) and Iversen 12 (●) in relation to predicted potential yield of forage kale (·····), oats (—) and annual ryegrass (---) at Lincoln University, Canterbury, New Zealand.

Note: Model parameters are detailed in Appendix 10.

4.4.4 Root partitioning

The current partitioning framework presented in Figure 2.7, appears to be overridden by crop ontogeny when crops are establishing and when under stress. There was a difference in the response of root partitioning of seedling and regrowth lucerne between Ashley Dene and Iversen 12 in response to sowing date and site. This suggests a single environmental predictor of partitioning, for example P_p is inappropriate. Root partitioning will be discussed for seeding and regrowth crops.

4.4.4.1 *Seedling lucerne*

Seedling lucerne did not display constant DM partitioning below ground which suggests a single P_{root} value was inappropriate for seedling growth. The P_{root} of seedling lucerne grown at Iversen 12 was described by P_p at the start of the growth period by a similar seasonal pattern to that of mature lucerne (Figure 2.7), albeit at higher levels. For example, the P_{root} of the spring sown crop was 0.32 when P_p was 14.5, this increased to 0.50 at the longest P_p of 16.5. Partitioning in regrowth crops is associated with different rates of phenological development, for example mainstem node appearance rates (Teixeira *et al.*, 2011). Therefore it is expected the physiology of seedling lucerne will change with sowing date. This is not reported in the literature and will be examined in Chapter 5.

Seedling lucerne grown at Ashley Dene did not show the same seasonal variation, which suggests crop ontogeny when under water stress overrides the environmental signals which regulate partitioning. The P_{root} of seedling crops was maintained at 0.53 for all sowing dates (Figure 4.10). The higher level of partitioning at Ashley Dene shows that shoot growth may have been compromised to maintain root growth in response to water stress, which suggests the root fraction was a stronger sink for assimilate. However, although the P_{root} was higher at Ashley Dene, the absolute DM partitioned below ground during the seedling phase was ~0.7 t DM/ha at Ashley Dene compared with 2.6 t DM/ha at Iversen 12.

4.4.4.2 *Regrowth lucerne*

These results show the establishment phase, where P_{root} is maintained at >0.40 was not only limited to seedling lucerne. This challenges the suggestion defoliation triggers lucerne to change its behaviour from seedling to regrowth crop phases where P_{root} is under the control of P_p (Thiebeau *et al.*, 2011). Rather it appears to be controlled by absolute root biomass. Lucerne crops in the establishment year continued to maintain high ratios of partitioning below ground until a root mass of 4 to 5 t DM/ha (Figure 4.11). Furthermore, this was shown in the second season, where late sown crops preferentially partitioned more DM below ground to satisfy this apparent root biomass requirement, which mostly explained the annual yield differences. For example, at

Iversen 12 the early sown crop had an annual DM yield in the second season of 21.5 t DM/ha compared with 15.8 t DM/ha for the late sown crops (Table 4.4). However, the late sown crops partitioned 2.5 t DM/ha below ground more than the early sown crop (Table 4.5), which explains part of the shoot yield difference. This apparent level of desired root biomass supports other studies of lucerne grown at Iversen Field (Brown, 2004; Teixeira, 2006) and Ashley Dene (Speedy, 2012).

Partitioning data described in this study are absolute root biomass and do not account for loss of DM due to root respiration. Root respiration may represent a significant proportion of DM, which could change the partitioning results presented. The relationship presented in Figure 4.12 showed partitioning did not remain constant after the longest day, which differs from the current framework (Figure 2.7) where fractional partitioning is maintained at 0.50 until winter. This is because the framework accounts for root respiration by calculating root biomass from a temperature adjusted RUE_{total} of 1.6 g DM/MJ (Figure 2.6), less the observed RUE_{shoot} , therefore the remainder is attributed to below ground partitioning. This showed root maintenance was up to 0.035 g/g/day (Teixeira *et al.*, 2009). In autumn the root mass of these crops was ~5 t DM/ha, however the absolute amount of DM partitioned below ground within each regrowth cycle, which were ~70 days, was ~0.2 t DM/ha, therefore root respiration may contributed significantly to total DM.

Results from this chapter showed lucerne DM yield is maximised when sown in early spring, despite being successfully established in late summer. The interaction between soil type and sowing date produced crops which differed in yields. Shoot yield was further influenced by the partitioning of DM among these crops. To further explain the yield differences of these crops the environmental factors that determine lucerne yield will be investigated (Section 2.2). The effect of water stress, particularly for crops at Ashley Dene is evident. Water stress will be quantified in Chapter 6, to further explain relationships between crop yield and intercepted radiation identified in Chapter 5.

4.5 Conclusions

Based on the results from this chapter the initial aim of the experiment to establish and grow contrasting lucerne crops on two sites which differed in plant available moisture was achieved with DM yields of 7 and 20 t DM/ha being achieved from lucerne in its second year from Ashley Dene and Iversen 12, respectively.

Based on these results the following conclusions can be made:

- Lucerne establishment was not affected by sowing time. All treatments established >200 plants/m². Rate of establishment was driven by temperature but regulated by available moisture. Thermal time requirement for emergence showed a requirement of about 90 °Cd when GWC was above 9%.
- Lucerne DM yield during the establishment season was greatest when sown from October to December at Ashley Dene and October to November at Iversen 12 with yields of 2.5 and 12 t DM/ha being achieved, respectively.
- Sowing date in the establishment season affected the annual DM yield in the subsequent season which was most prominent on the high yield potential site, Iversen 12. Sowing later than December reduced DM yield 23%, from 20.4 to 15.8 t DM/ha.
- Yield differences between sowing dates were partially explained by DM allocation between above and below ground fractions. Root partitioning of total DM $>40\%$ was maintained until ~ 5 t/ha was reached at Iversen 12.

The following chapter aims to describe these results with regard to crop radiation interception and its efficiency of use by quantifying canopy development and expansion processes.

5 The effect of canopy development and expansion on radiation interception and growth

5.1 Introduction

In Chapter 4 actual DM yield ranged from 0.4 to 21.5 t DM/ha due to differences in sowing date and PAWC of the soil types. Crop yield is the result of plant development and growth, where growth is the product of available total solar radiation (R_o), multiplied by canopy interception by green leaves (R/R_o) and its conversion to biomass (radiation use efficiency; RUE) as indicated in Equation 2.1 (Monteith, 1977; Gallagher and Biscoe, 1978).

Whether the yield differences reported in Chapter 4 resulted from differences in radiation interception and/or RUE, will be quantified in this chapter. Crop development is described by the rate of leaf appearance, both mainstem and axillary (branching) which leads to the formation of a crop canopy (Section 2.3.1). The ability of the crop to expand this canopy is quantified as leaf area index (LAI) and is a measure of leaf area per unit of ground area, which along with canopy architecture, drives crop radiation interception (Equation 2.3). RUE is quantified in terms of both shoot (RUE_{shoot}) and total (RUE_{total}) DM (Section 2.4).

5.2 Materials and Methods

The experimental design and management details were presented in Chapter 3, with results for crop establishment and DM presented in Chapter 4. Materials and methods specific to the objectives to quantify canopy development, canopy expansion and radiation interception of these lucerne crops are detailed below.

5.2.1 Canopy development

5.2.1.1 *Mainstem node appearance*

Mainstem nodes were measured on 10 marked stems per plot during the seedling phase and 5 marked stems during subsequent regrowth periods. Stems were selected on different plants with an intentional bias to mark taller, dominant stems which have been shown to account for >80% of shoot yield (Teixeira *et al.*, 2007a), and because shorter stems often senesce as the canopy develops. Stems were marked within 7 days of defoliation and measurements were taken every 3 to 7 days until the end of each regrowth period. Nodes were counted from the base of the stem up to the last fully expanded leaf (3 visible leaflets), and secondary nodes were recorded.

5.2.1.2 *Secondary nodes*

The number of secondary nodes (axillary leaves) was counted on the marked mainstem. Only leaves which were >50% green were counted and counts were made up to the point of leaf senescence, *i.e.* maximum total number of leaves.

5.2.1.3 *Phyllochron*

The phyllochron, or rate of mainstem node appearance ($^{\circ}\text{Cd}$), was calculated by regressing mainstem node number against accumulated thermal time for each regrowth period. Thermal time was accumulated using air temperature ($T_b = 1^{\circ}\text{C}$) as described in Section 2.2.2.1. Phyllochron was displayed in relation to photoperiod at the start of the growth period or at emergence for seedling crops. This differs from Brown (2004) who averaged photoperiod over the entire growth cycle. The limitation of the latter approach is that it does not discriminate between differences observed in development

rate at similar photoperiod but either side of the longest day. Monks (2009) found development rate (time to flowering) in annual clovers was determined by the duration and direction of photoperiod, rather than the absolute photoperiod.

5.2.1.4 Number of Stems

The number of stems was counted from each 0.2 m² quadrat harvested for DM (Section 4.2.4). Results presented are from the final DM harvest for each regrowth period.

5.2.2 Canopy expansion

5.2.2.1 Leaf area index

Crop leaf area index (LAI; m²/m²) was calculated using specific leaf weight (SLW; g DM/m² LAI) from a sub-sample of 20 shoots passed through a leaf area meter (LICOR 3100; Licor Inc. Lincoln, USA). Shoots were laid flat with leaves spread apart and passed through the belt meter.

This method systemically underestimated leaf area mainly due to leaves overlapping around the apex of the shoot and thus it was further calibrated. To calibrate, samples of 20 shoots were passed through the leaf meter, then the leaves were removed from each stem and both were separately passed back through the area meter. Regression of both leaf area measurements showed the initial method underestimated leaf area and measurements were therefore multiplied by 1.30 to correct this (Figure 5.1). The calibration process was repeated 91 times on five occasions throughout the season which showed the correction factor was consistent ($R^2 = 0.99$) between seedling and regrowth lucerne and across the two experimental sites.

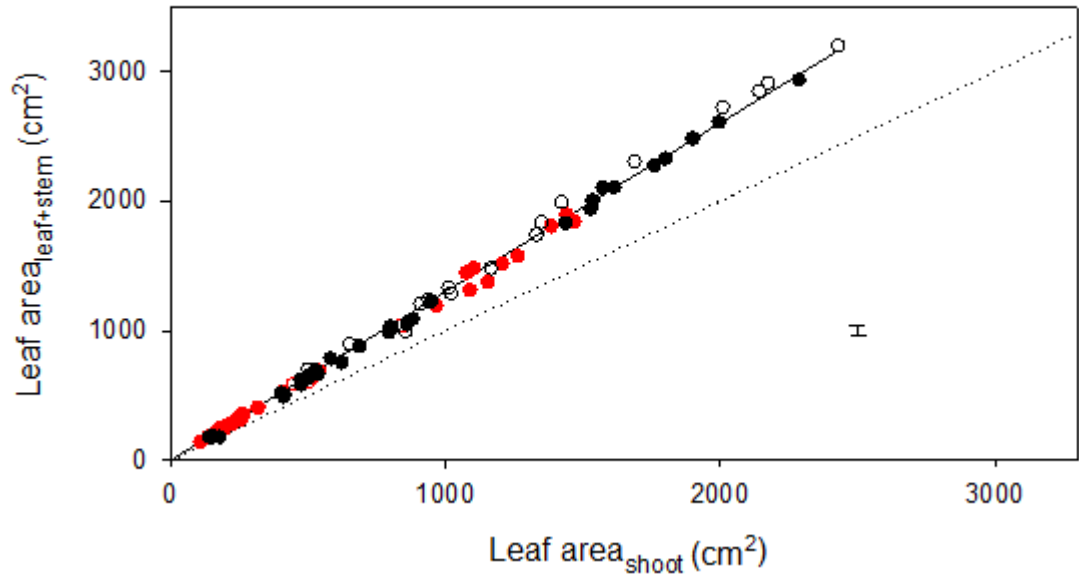


Figure 5.1 Leaf area (cm^2) of seedling ($\circ\circ$) and regrowth ($\bullet\bullet$) lucerne shoots from Ashley Dene (red) and Iversen 12 (black) measured by LICOR 3100 area meter intact (leaf area_{shoot}) in relation to leaf area of the same shoots when leaf and stem fractions were measured independently (leaf area_{leaf+stem}).

Note: linear regression (—) $y = 1.30x$; $R^2 = 0.99$, 1:1 Line (\cdots). Error bar represents one SEM.

5.2.2.2 Leaf area expansion rate

LAI was regressed against Tt accumulation to determine the rate of leaf area expansion (LAER; $\text{m}^2/\text{m}^2/^\circ\text{Cd}$). Tt was accumulated (Section 3.4.2) from emergence for seedling crops and the subsequent day following defoliation for regrowth crops. Daily LAI was determined from fitted logistic curves that estimated the sigmoidal shape of leaf area expansion over time for each growth period (Equation 5.1).

Equation 5.1
$$y = a + c/(-b^{(x-m)})$$

Where a is the lower asymptote, c is the upper, b depends on the values of y , m is the time of maximum LAI and x is accumulated thermal time.

5.2.2.3 *Linear leaf area expansion rate*

Coefficients from the fitted logistics did not allow suitable comparisons between treatments to explain LAER in relation to independent variables. Therefore, linear LAER was calculated as the slope of the linear regression between LAI against Tt, which allowed comparison with relevant literature (e.g. Teixeira *et al.* (2011)). The LAER was then plotted against the mean date of each regrowth cycle to observe seasonal pattern.

5.2.2.4 *Mean leaf size*

The total number of leaves/m² was regressed against LAI to determine the mean leaf size. Total leaf number was the sum of mainstem and axillary leaves per mainstem (Section 5.2.1.1 and 5.2.1.2) multiplied by stem number (Section 5.2.1.4). Stem number was counted when DM assessment was taken, weekly during spring and summer and fortnightly in autumn and was <7 days from date of leaf counts. LAI was determined for the date of leaf count from the logistic models of seasonal LAI (Section 5.2.2.2).

5.2.3 **Radiation interception**

5.2.3.1 *Radiation interception*

The amount of light intercepted by the canopy (R/R_o) was calculated as a function of LAI and canopy architecture (k) using Beer's law (Equation 2.3). The amount of intercepted radiation (MJ total radiation/m²) was calculated daily using the LAI from the fitted models (Section 5.2.2.2) and k (Section 5.2.3.2), which was multiplied by daily incident radiation (R_o) and summed for each growth period.

5.2.3.2 *Extinction coefficient (k)*

The value of k was determined from the negative slope of the regression between the natural log of canopy radiation interception, $\ln(R/R_o)$ and LAI, measured independently. R/R_o was measured directly, non-destructively using a Sunscan plant canopy analyser system (Delta-T Devices Ltd, Burwell, Cambridge, England). For this,

incident and transmitted radiation measurements were made. Eight below and above canopy readings were taken per plot, perpendicular to drill rows. Measurements were taken during stable light conditions within two hours either side of solar noon. The analyser settings for the leaf absorption parameter was set at 0.95. Readings were taken on 25 occasions at both Ashley Dene and Iversen 12 throughout the second season (July 2011 to June 2012) measuring both seedling and regrowth lucerne.

Sunscan LAI readings were regressed against destructive LAI measurements (Section 5.2.2.1) which showed an overestimation of LAI calculated from the Sunscan canopy analyser of 18% (Figure 5.2). This reinforced the need for destructive sampling, particularly when measuring incomplete canopies, for seedling lucerne and crops grown on the stony site at Ashley Dene.

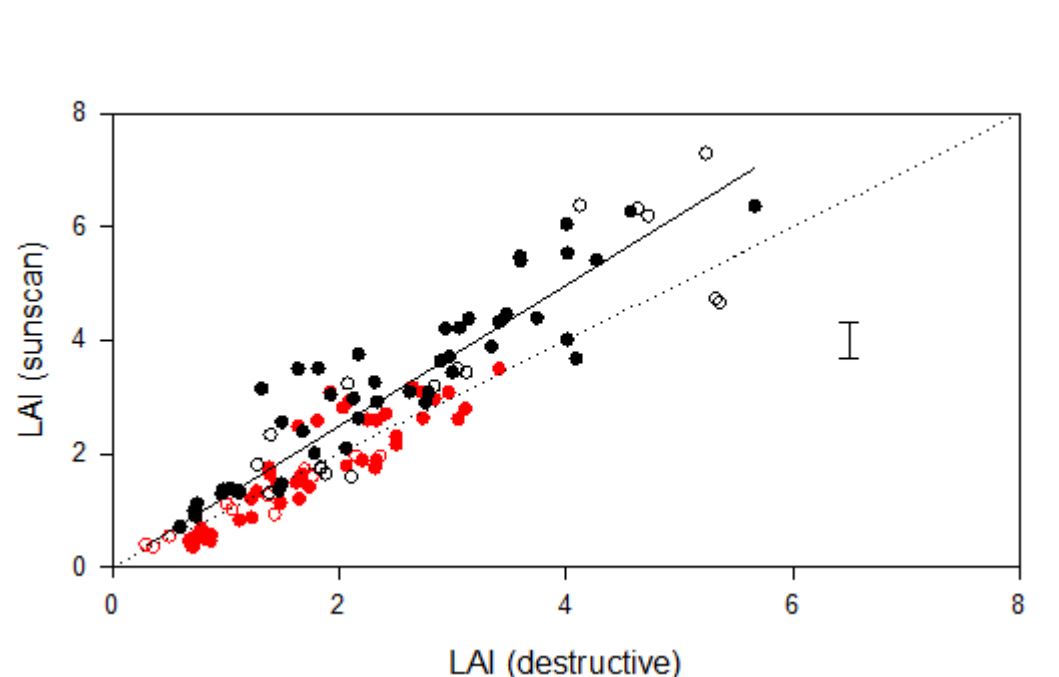


Figure 5.2 Leaf area index (LAI) measured non-destructively using the sunscan canopy analyser in relation to LAI measured destructively of seedling (○) and regrowth (●) lucerne, grown at Ashley Dene (red) and Iversen 12 (black) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: linear regression (—) $y = 1.18x$; $R^2 = 0.85$, 1:1 Line (···). Error bar represents one SEM.

The regression of $\ln(R/R_0)$ in relation to LAI showed a consistent ($R^2 = 0.86$) k value of 0.89, (reported as positive number) between seedling and regrowth lucerne at both experimental sites (Figure 5.3), which was used in Equation 2.3 to calculate intercepted radiation.

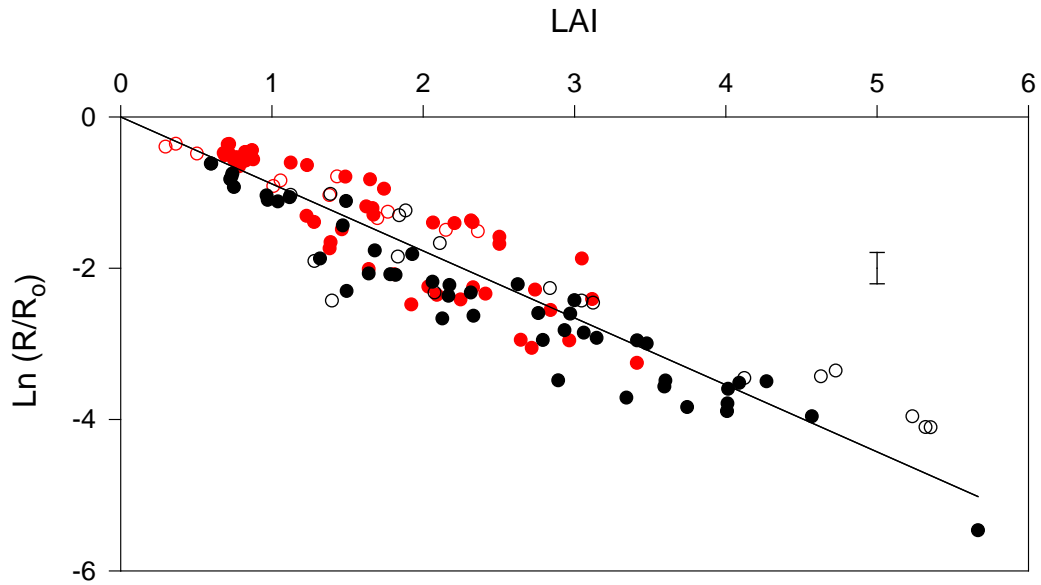


Figure 5.3 The natural log of solar radiation transmission ($\ln(R/R_0)$; measured with sunscan canopy analyser) in relation to leaf area index (LAI; measured destructively) of seedling (\circ) and regrowth (\bullet) lucerne, grown at Ashley Dene (red) and Iversen 12 (black) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: linear regression (—) $y = 0.89x$; $R^2 = 0.86$. Error bar represents one SEM.

5.2.4 Radiation use efficiency

Radiation use efficiency (RUE; g DM/MJ intercepted total solar radiation/m²) was calculated from the slope of the regression of accumulated intercepted radiation against accumulated DM for each regrowth period. RUE is presented in terms of above ground DM (RUE_{shoot}) and total DM (RUE_{total}). RUE_{total} includes DM from; shoot, crown and 300 mm of taproot. The regressions were not forced through the origin because during the early stages of regrowth, reserves can be mobilised from the root mass and allocated

to the above ground fraction (Teixeira, 2006). RUE results are presented for the mid-point of each regrowth period.

5.2.5 Canopy nitrogen content

Nitrogen content was determined for each growth cycle from the final DM harvest. Analysis was conducted on the sub-sample of representative shoots used for determining LAI (Section 5.2.2.1). Samples were ground to pass through a 1 mm sieve (Cyclotec Mill, USA) and near infrared spectroscopy (NIR; Foss NIR Systems 5000 Rapid Content Analyser), calibrated using wet chemistry for lucerne forage was used to determine nitrogen content.

5.3 Results

5.3.1 Canopy development

5.3.1.1 *Seedling lucerne mainstem node appearance*

Mainstem node number increased linearly in relation to accumulated Tt for seedling lucerne crops (Figure 5.4). The rate of increase in node number was constant for each sowing date ($R^2 > 0.93$), however the slope of the regressions changed ($P < 0.001$) with sowing date (Appendix 11), which indicates the phyllochron was constant in Tt but regulated by other variables. At Ashley Dene, the phyllochron was 54 °Cd for lucerne sown in October but increased to 78 °Cd for December sown crops, and then decreased to 62 °Cd for February crops. Crops sown at Iversen 12 displayed a linear increase in phyllochron with sowing date from 37 °Cd in October to 58 °Cd when sown in February.

5.3.1.2 *Seedling lucerne branching*

The number of nodes on the mainstem increased exponentially ($R^2 > 0.98$) for all seedling crops, once branching was initiated, shown as when the total number of nodes exceeded the number of mainstem nodes. This consistently occurred between the 4th and 5th mainstem node (Figure 5.4). The rate of increase in the total number of nodes was not different between sowing dates at Ashley Dene ($P = 0.052$), however it followed a similar seasonal pattern to that of crops at Iversen 12. The November and December sown crops increased the total number at the fastest rate ($P < 0.001$). Total nodes were counted until the onset of leaf senescence, which resulted in crops at Ashley Dene growing a maximum of ~25 leaves compared with up to 40 leaves at Iversen 12.

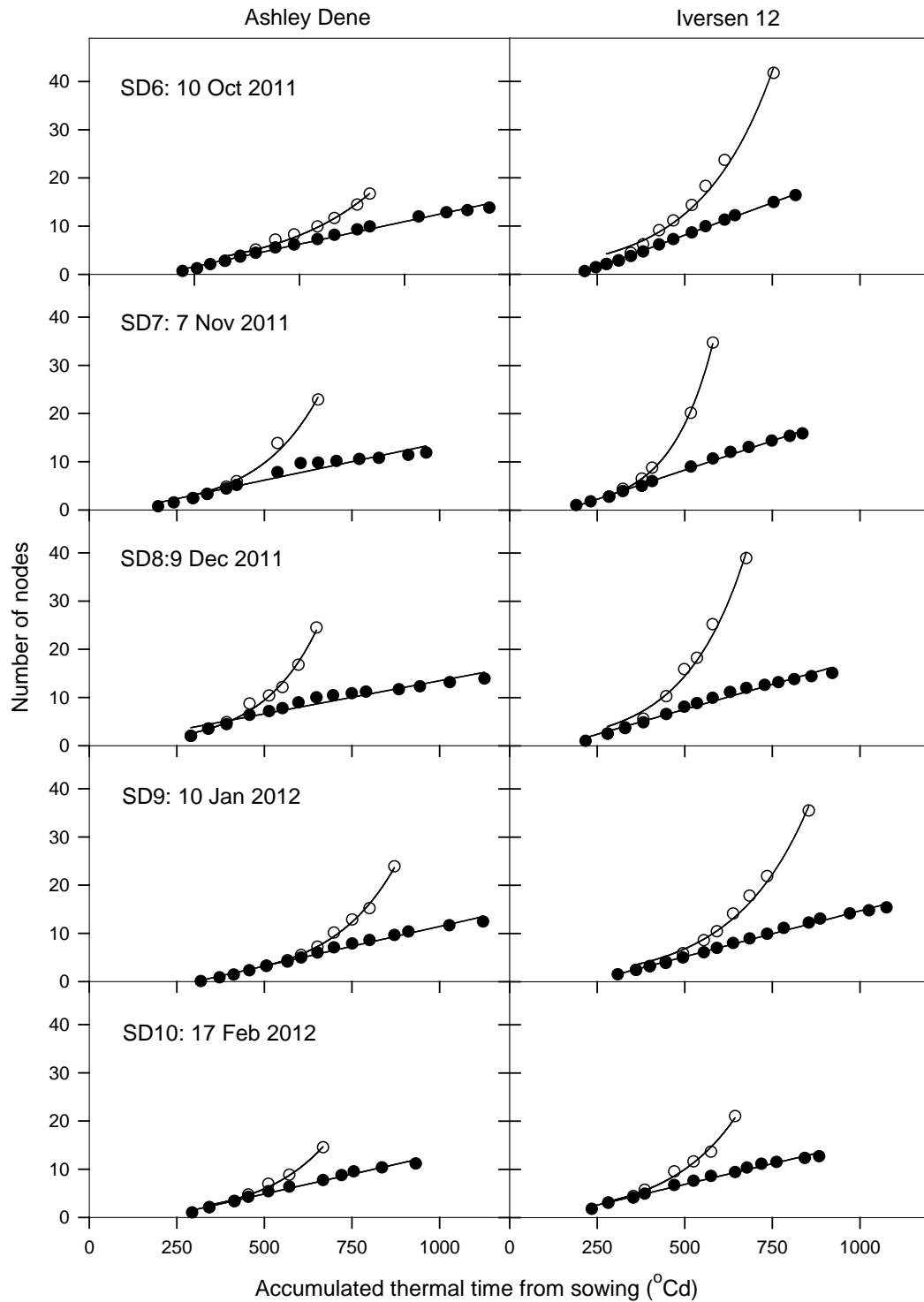


Figure 5.4 The number of mainstem (●) and total (○) nodes for seedling lucerne in relation to thermal time accumulation from sowing to 50% flowering grown at Ashley Dene and Iversen 12 after sowing on five dates from October 2011 to February 2012 at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Equations for regressions presented in Appendix 11.

5.3.1.3 *Regrowth lucerne mainstem node appearance*

Sowing date in the establishment year did not affect ($P>0.25$) mainstem or total node accumulation rates within an individual regrowth cycle in the second year at Ashley Dene or Iversen 12. The mean data are presented in Figure 5.5. Rate of node appearance was constant within each regrowth cycle ($R^2>0.96$), however differed amongst regrowth cycles ($P<0.001$). At Ashley Dene, the phyllochron was constant for the first two cycles (44 °Cd) but increased 75% in the following regrowth period to 71 °Cd and was 58 °Cd for the final two regrowth periods. Phyllochron for crops at Iversen 12 ranged from 31 °Cd in the second cycle to a maximum of 44 °Cd in the final regrowth cycle.

5.3.1.4 *Regrowth lucerne branching*

The total number of nodes per mainstem for lucerne regrowth crops increased linearly in relation to accumulated Tt (Figure 5.5), and was constant within each regrowth cycle ($R^2>0.95$). The total mainstem node appearance rate was fastest ($P<0.001$) in cycle 1 and 2 in crops at Ashley Dene (18 °Cd/total node), but almost doubled to 38 °Cd/total node in cycle 3. Axillary node appearance rate was fastest ($P<0.001$) in regrowth cycles 4 and 5 in crops at Iversen 12 with a new node appearing every 11.5 °Cd, compared with the final cycle when node appearance rate doubled.

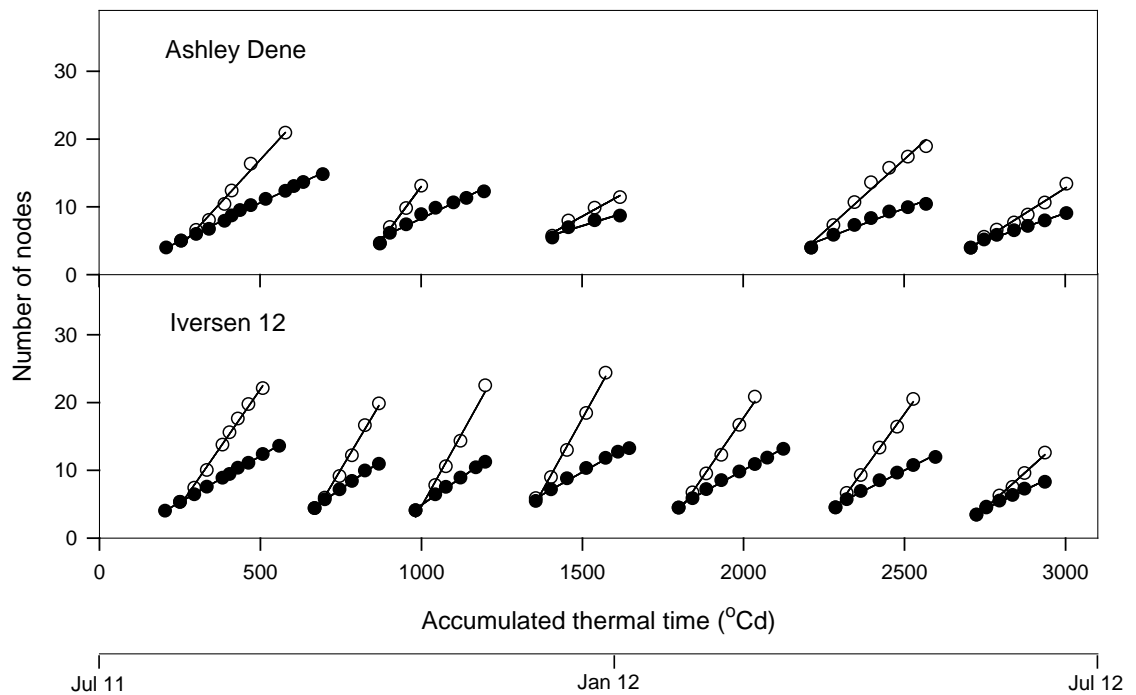


Figure 5.5 The number of mainstem (●) and total (○) nodes for second year lucerne grown at Ashley Dene and Iversen 12 from June 2011 to July 2012 at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Equations for regressions presented in Appendix 11.

The seasonal differences in phyllochron are shown in Figure 5.6. The phyllochron increased at the beginning of each growth season, peaked in mid-summer before decreasing again by winter. To explain the seasonal pattern of phyllochron, the influence of photoperiod (Pp) at the start of the growth period for each cycle was examined.

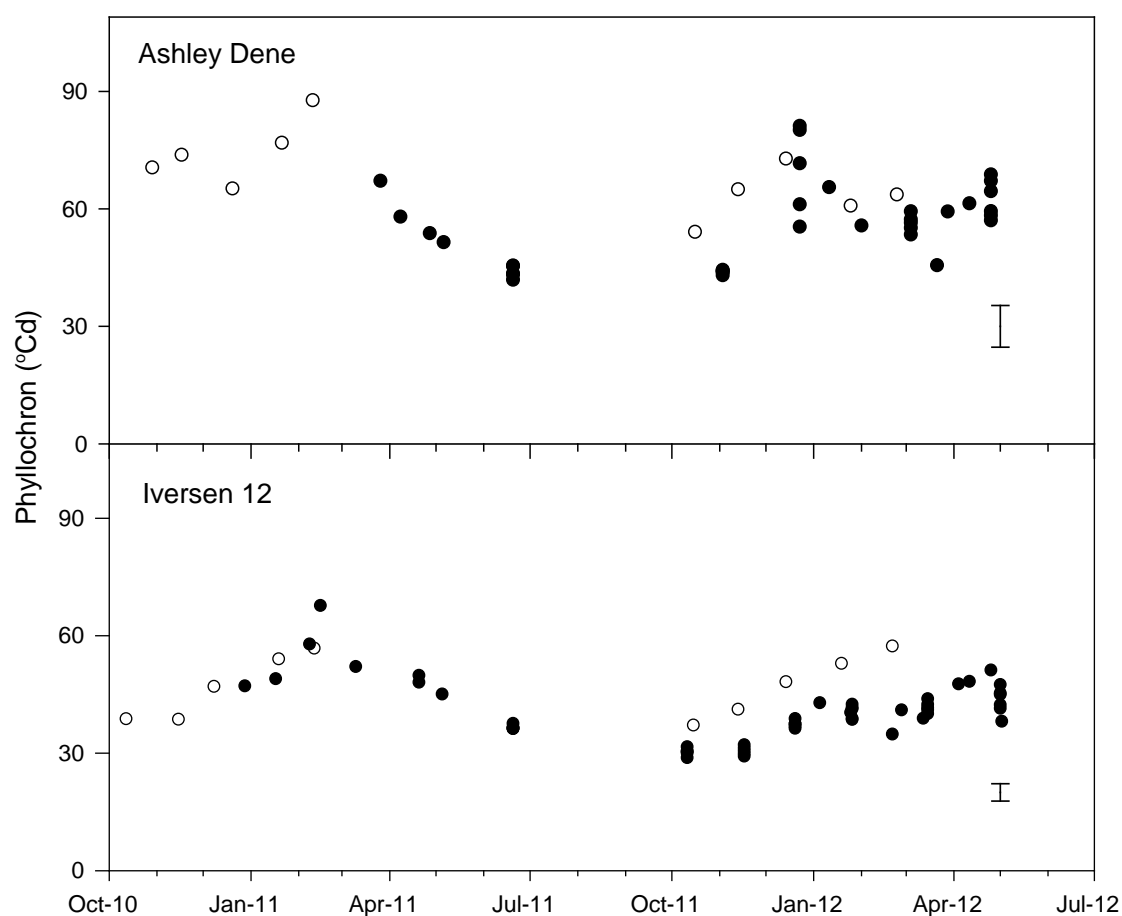


Figure 5.6 Phyllochron of mainstem seedling (○) and regrowth (●) lucerne measured from October 2010 to July 2012 at Ashley Dene and Iversen 12 at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Error bar represents l.s.d ($P = 0.05$).

5.3.1.5 *Phyllochron in relation to photoperiod*

There was no apparent relationship between phyllochron and Pp displayed in seedling or regrowth crops at Ashley Dene, although there was evidence of minimum values of 50 and 40 °Cd, respectively. At Iversen 12, when seedling lucerne emerged into increasing photoperiods, the phyllochron increased from 38 °Cd at 14 h to 50 °Cd at 16.5 h, a 3.7 °Cd increase for each additional daylight hour (Figure 5.7). When seedlings emerged into decreasing photoperiods, the phyllochron increased at a faster

rate ($P < 0.05$) of 4.7 °Cd per hour from 50 °Cd at 16.5 h to 60 °Cd at 14.5 h. This resulted in the phyllochron being about 30% longer at a Pp of 15 hours in a decreasing Pp environment compared with an increasing one. A similar pattern occurred in regrowth lucerne, although the first regrowth cycle which started its growth period near the shortest day (~10 h) displayed a longer phyllochron ($P < 0.001$) of 38 °Cd compared with 30 °Cd in the following two cycles.

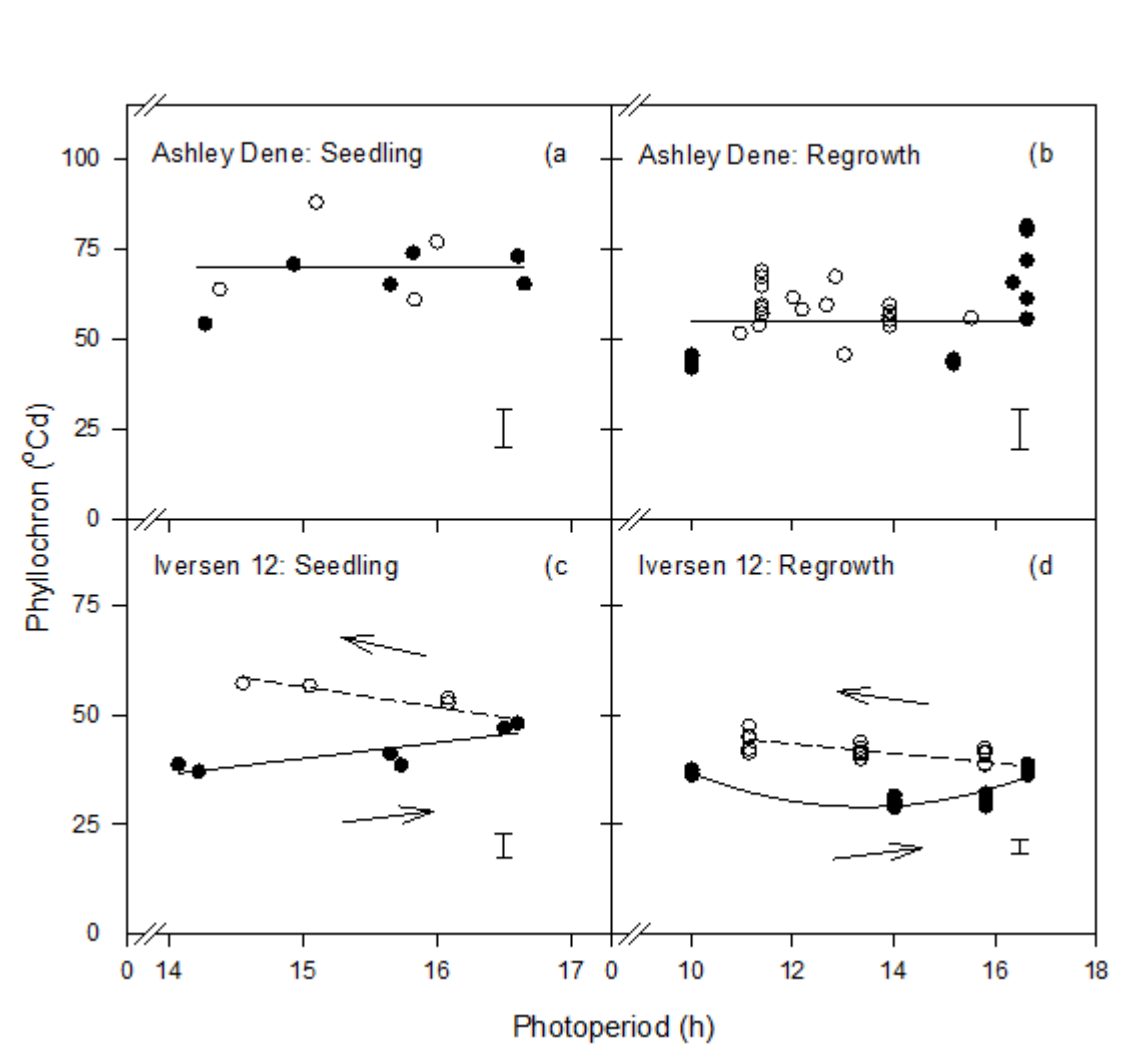


Figure 5.7 Phyllochron of seedling (a,c) and regrowth (b,d) lucerne in response to increasing (●) and decreasing (○) photoperiods at the start of each growth period when grown at Ashley Dene (a,b) and Iversen 12 (c,d), Lincoln University, Canterbury, New Zealand.

Note : Error bar represents l.s.d ($P = 0.05$). Arrows indicate direction of photoperiod change.

a); (—) $y = 69.6$. b); (—) $y = 54.7$.

c); (—) $y = -14.8 + 3.66x$, $R^2 = 0.73$. (-----) $y = 126.9 + -4.69x$, $R^2 = 0.81$.

d); (—) $y = 149.8 - 18.0x + 0.67x^2$, $R^2 = 0.76$. (-----) $y = 56.6 + -1.10x$, $R^2 = 0.65$.

5.3.1.6 *Rate of branching in relation to phyllochron*

The rate of axillary leaf production showed a strong linear increase in relation to phyllochron (Figure 5.8) with an R^2 of 0.92. For every mainstem node, there were ~2.5 axillary leaves. For example, when the phyllochron was 40 °Cd, axillary leaf appearance rate was 16 °Cd.

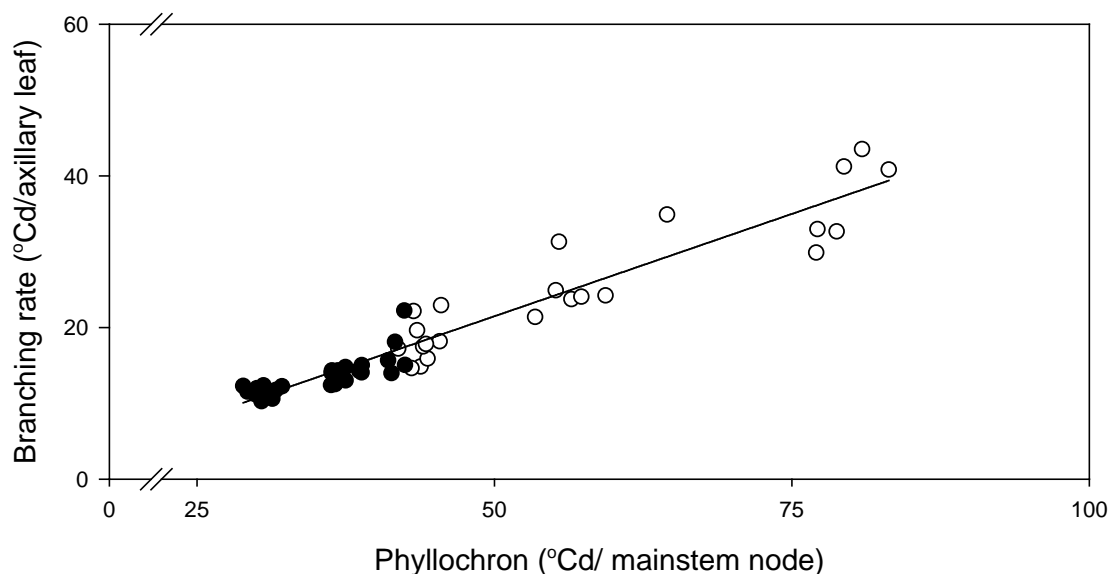


Figure 5.8 The rate of secondary node appearance (branching) in relation to the rate of mainstem node appearance (phyllochron) for dryland lucerne crops grown at Ashley Dene (○) and Iversen 12 (●) in 2011/2012, Lincoln University, Canterbury, New Zealand.

Note: Linear regression (—); $y = 0.54x - 5.51$ $R^2 = 0.92$. Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira et al. (2011).

5.3.1.7 Shoot population

Stem population of seedling lucerne crops averaged 470/m² at Ashley Dene (Table 5.1) and 770/m² at Iversen 12 (Table 5.2). However, sowing date did affect stem population ($P<0.01$) with January sown lucerne having about 35% higher stem population than the seedling means at both sites. The regrowth phase immediately following the seedling phase of each resulted in higher stem populations, by up to 50%. However, when this first regrowth cycle occurred late in the season there was a reduction in population (~20%). Most second year crops displayed a stable population of >800 stems/m². The exception was the third regrowth cycle at Ashley Dene which declined by 25% for the early sown crops compared with the later sown crops which declined 45% to 500 stems/m².

Table 5.1 Shoot population (shoots/m²) of lucerne grown at Ashley Dene at the end of each growth period for two seasons, subjected to different sowing dates at Lincoln University, Canterbury, New Zealand.

Sowing date	Establishment (2010)			Year two (2011)			
	Seedling	R1	R2	R1	R2	R3	R4
October	528 _{bc}	1036 _a	714	881	885	623 _{ab}	876
November	539 _{bc}	868 _a	804	820	839	673 _a	1006
December	650 _{ab}	590 _b	-	801	867	616 _b	885
January	734 _a	640 _b	-	724	898	498 _c	915
February	502 _c	-	-	781	872	482 _c	830
Mean	471	784	759	802	872	579	902
P	<0.05	<0.05	ns	ns	ns	<0.05	ns
SEM	41.5	62.5	23.2	61.5	40.7	52.6	37.2

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$). Establishment; sowing to 30 June 2011, Year two; 1 July 2011 to 30 June 2012.

Table 5.2 Shoot population (shoots/m²) of lucerne grown at Iversen 12 at the end of each growth period for two seasons, subjected to different sowing dates at Lincoln University, Canterbury, New Zealand.

Sowing date	Establishment (2010)				Year two (2011)					
	Seedling	R1	R2	R3	R1	R2	R3	R4	R5	R6
October	490 _c	824	1004	1069	1220 _a	1150	850	944	835	870
November	781 _b	935	906	1054	1120 _{ab}	1089	898	846	856	824
December	607 _{bc}	901	960	-	1076 _{bc}	1048	879	919	849	744
January	1120 _a	869	-	-	963 _{cd}	1025	940	885	920	735
February	836 _b	661	-	-	916 _d	916	849	816	831	811
Mean	767	838	957	1061	859	1046	883	882	858	797
P	<0.001	ns	ns	ns	<0.05	ns	ns	ns	ns	ns
SEM	77.1	91.3	58.6	43.1	43.1	49.7	47.5	39.2	43.2	62.6

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).
Establishment; sowing to 30 June 2011, Year two; 1 July 2011 to 30 June 2012.

5.3.2 Canopy expansion

5.3.2.1 *Seasonal leaf area index*

Canopy expansion for lucerne crops grown at Ashley Dene is displayed in Figure 5.9, and Iversen 12 in Figure 5.10. The fitted logistic curves displayed a high correlation between LAI and accumulated Tt ($R^2 > 0.70$ at Ashley Dene and $R^2 > 0.90$ at Iversen 12), the wide range of coefficients describing the curves demonstrated this was not a constant relationship.

LAI for crops in the establishment year at Ashley Dene displayed canopy expansion rates of $< 0.003 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ and LAI did not exceed 2.5 (m^2/m^2). In comparison, LAI in crops at Iversen 12 displayed a longer duration of linear canopy expansion, at rates of up to $0.011 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$, and all crops LAI exceeded 2.5.

In the second season, LAI in regrowth crops at Ashley Dene did not exceed 3.5, with the summer regrowth cycle displaying a LAI < 1 for about two months. In contrast, crops at Iversen 12 all exceed a final LAI of 3.5 (except for the last cycle) with a maximum LAI of ~ 6 being attained. Sowing date in the establishment year did affect ($P < 0.05$) the LAI reached at the end of each regrowth phase in the second season. October sown crops on average had a $\sim 30\%$ higher final LAI than the February sown crops at Iversen 12.

5.3.2.2 *Leaf area expansion rates*

Linear regressions were fitted to LAI data against Tt for each regrowth cycle to determine if a single value of leaf area expansion rate (LAER) could be found. LAER for seedling crops was highest ($P < 0.05$) when sown in mid-summer with crops at Ashley Dene expanding leaf area at a rate of $0.003 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ (Figure 5.11) compared with Iversen 12 with a LAER of $0.011 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ (Figure 5.12). LAER differed ($P < 0.05$) between regrowth cycles and sowing dates in the second season. These were highest in late spring and autumn at Ashley Dene ($0.007 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$) compared with $0.016 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ for the October sown crop in early spring at Iversen 12.

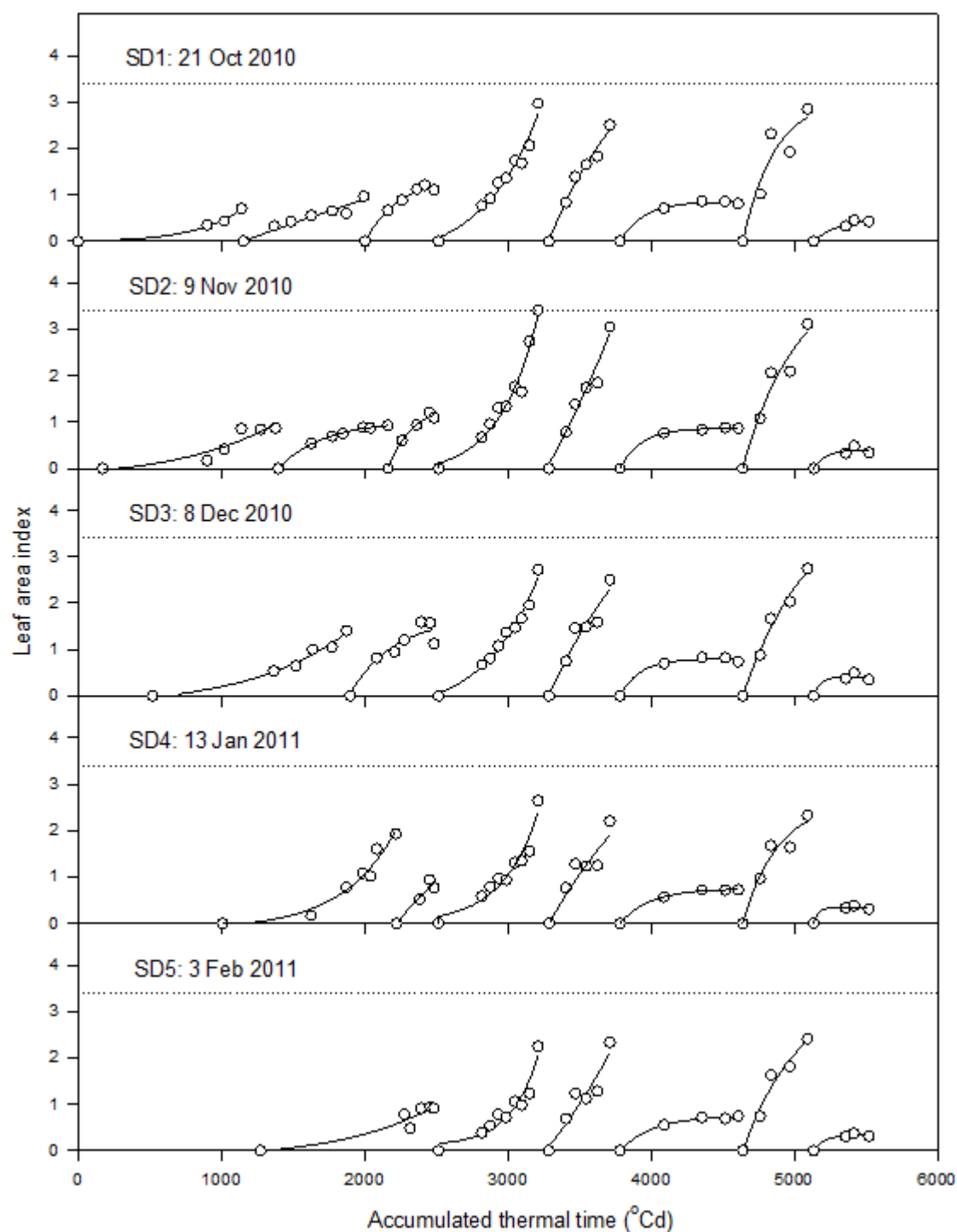


Figure 5.9 Leaf area index of lucerne grown at Ashley Dene from five sowing dates over two seasons from October 2011 to July 2012 at Lincoln University, Canterbury, New Zealand.

Note: Lines are fitted logistic function from Equation 5.1. Thermal time accumulated using air temperature ($T_b = 1\text{ }^{\circ}\text{C}$) as per Teixeira *et al.* (2011). Dotted line represents LAI_{crit} (Figure 5.13).

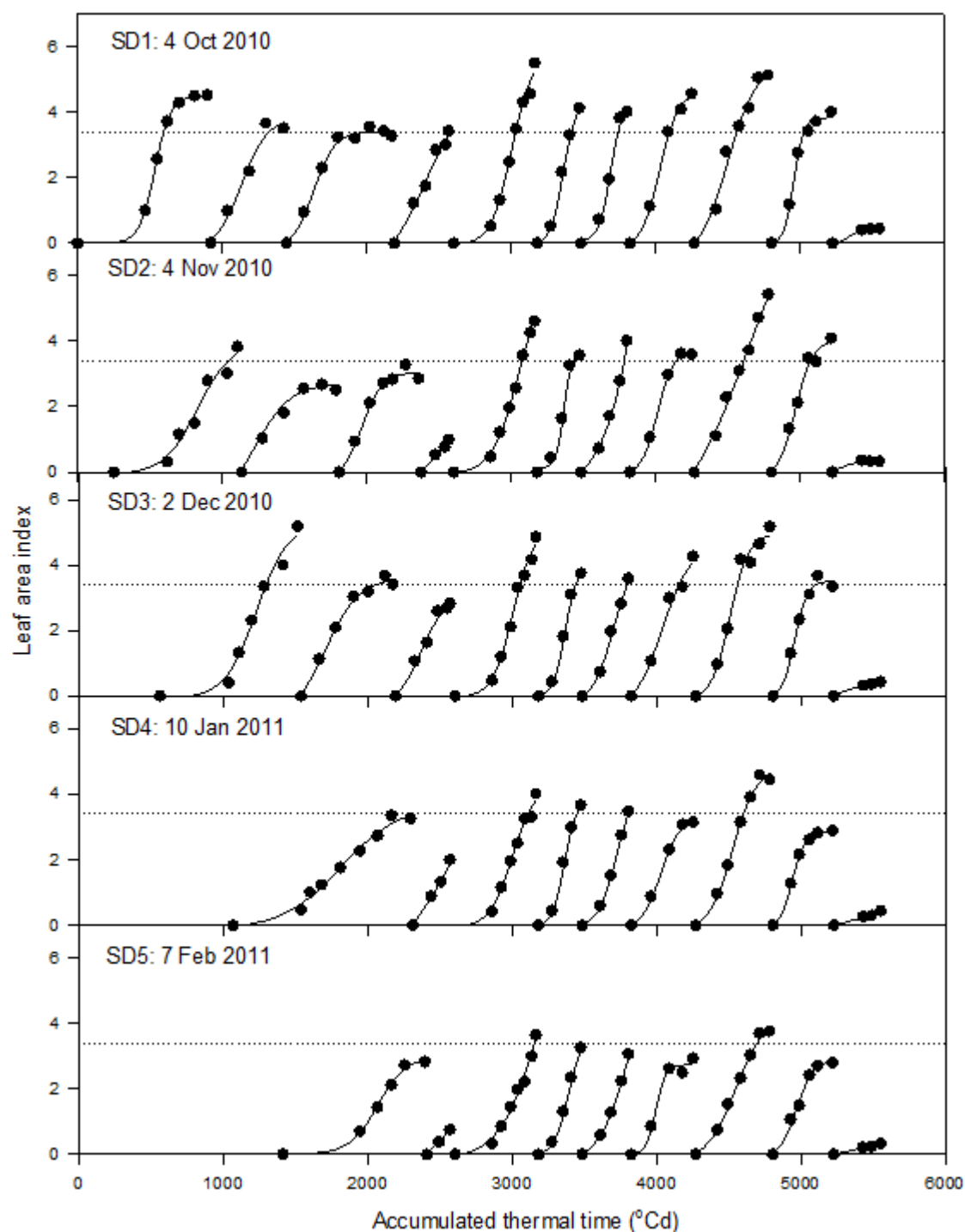


Figure 5.10 Leaf area index of lucerne grown at Iversen 12 from five sowing dates over two seasons from October 2011 to July 2012 at Lincoln University, Canterbury, New Zealand.

Note: Lines are fitted logistic functions from Equation 5.1. Thermal time accumulated using air temperature ($T_b = 1\text{ }^{\circ}\text{C}$) as per Teixeira *et al.* (2011). Dotted line represents LAI_{crit} (Figure 5.13).

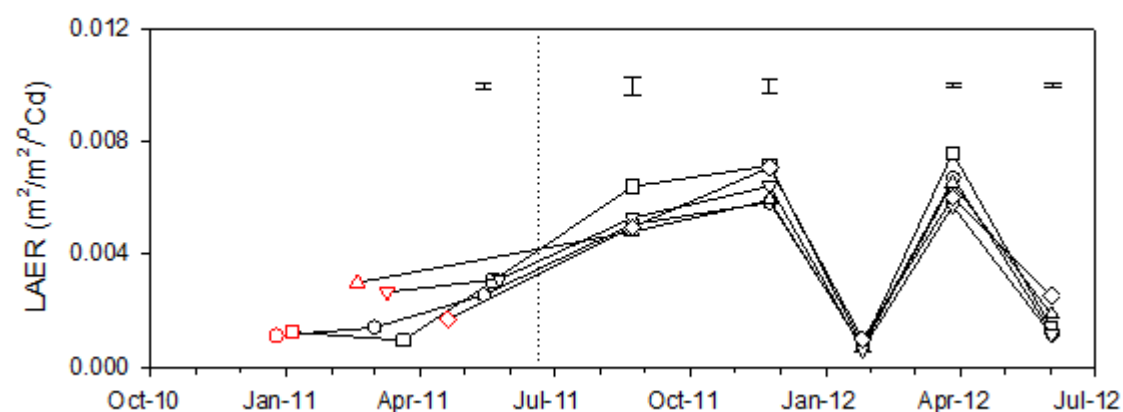


Figure 5.11 Leaf area expansion rate (LAER) of seedling lucerne sown on five dates (present in red); SD1 (October; ○), SD2 (November; □), SD3 (December; △), SD4 (January; ▽) and SD5 (February; ◇) and subsequent regrowth phases from October 2010 to July 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Bar represents pooled l.s.d ($P = 0.05$) of LAER from regressions. Dotted line represents end of establishment season, June 2011.

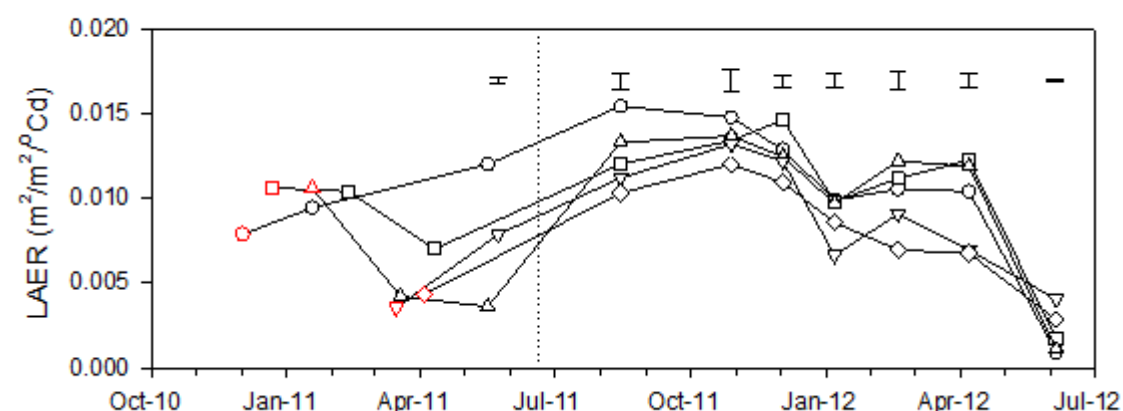


Figure 5.12 Leaf area expansion rate (LAER) of seedling lucerne sown on five dates (present in red); SD1 (October; ○), SD2 (November; □), SD3 (December; △), SD4 (January; ▽) and SD5 (February; ◇) and subsequent regrowth phases from October 2010 to July 2012 at Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Bar represents pooled l.s.d ($P = 0.05$) of LAER from regressions. Dotted line represents end of establishment season, June 2011.

5.3.3 Canopy architecture

The canopy architecture was quantified by the extinction coefficient, k of 0.89 (Section 5.2.3.2). The relationship between LAI, measured independently of the fraction of solar radiation intercepted by the canopy (R/R_o) at a particular LAI showed a similar pattern of light interception between seedling and regrowth crops at both experimental sites (Figure 5.13). The relationship indicated a conservative critical LAI (LAI_{crit}), the point when 95% of solar radiation was intercepted, of 3.4.

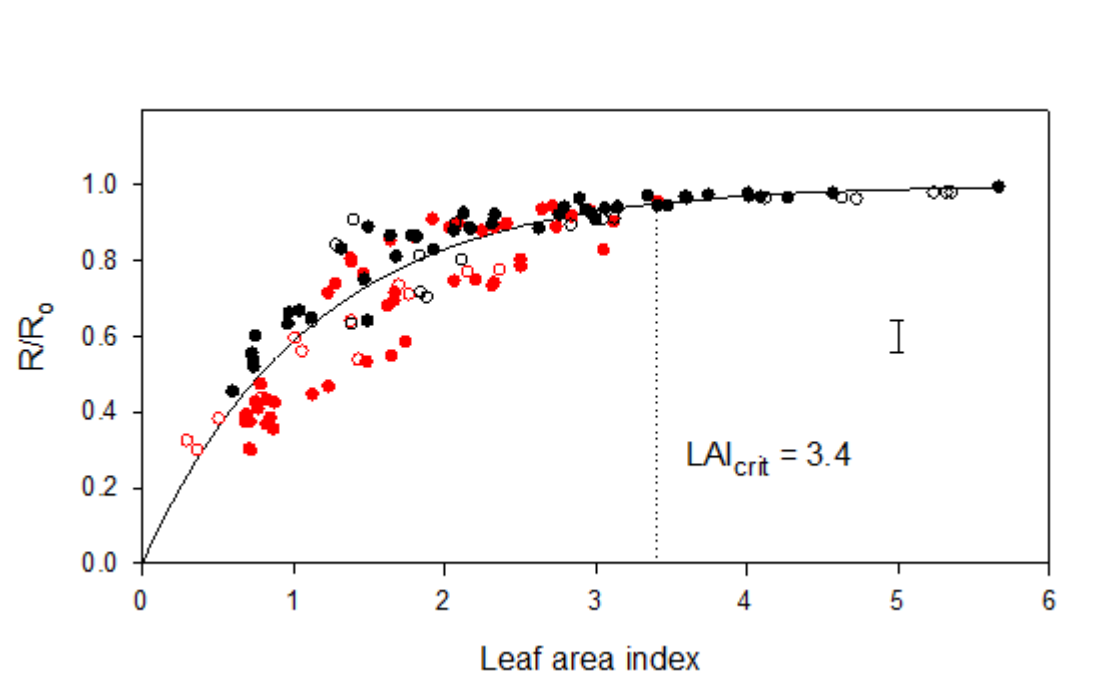


Figure 5.13 The relationship between leaf area index and the fractional solar radiation interception (R/R_o) of seedling (○) and regrowth (●) lucerne, grown at Ashley Dene (red) and Iversen 12 (black) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Leaf area index calculated from destructive DM samples and fractional solar radiation measurements taken with Sunscan canopy analyser. Error bar represents one SEM. Regression (—) $y = 1 - \exp(-0.89x)$, $R^2 = 0.86$.

5.3.4 Towards explaining LAER

The effect of canopy development on LAI was used to determine the importance of these components on LAER, seasonal LAI and therefore radiation interception.

5.3.4.1 LAI in relation to canopy development

The expansion of LAI against mainstem node number showed a variable exponential increase ($R^2 = 0.64$, data not shown). When LAI expansion was regressed against total leaves per mainstem the relationship was linear ($R^2 = 0.70$, Figure 5.14). LAI increased at a rate of 0.17 per total leaf, however seasonal variation was evident. For example, at 10 leaves per stem LAI ranged from 0.5 to 2.0.

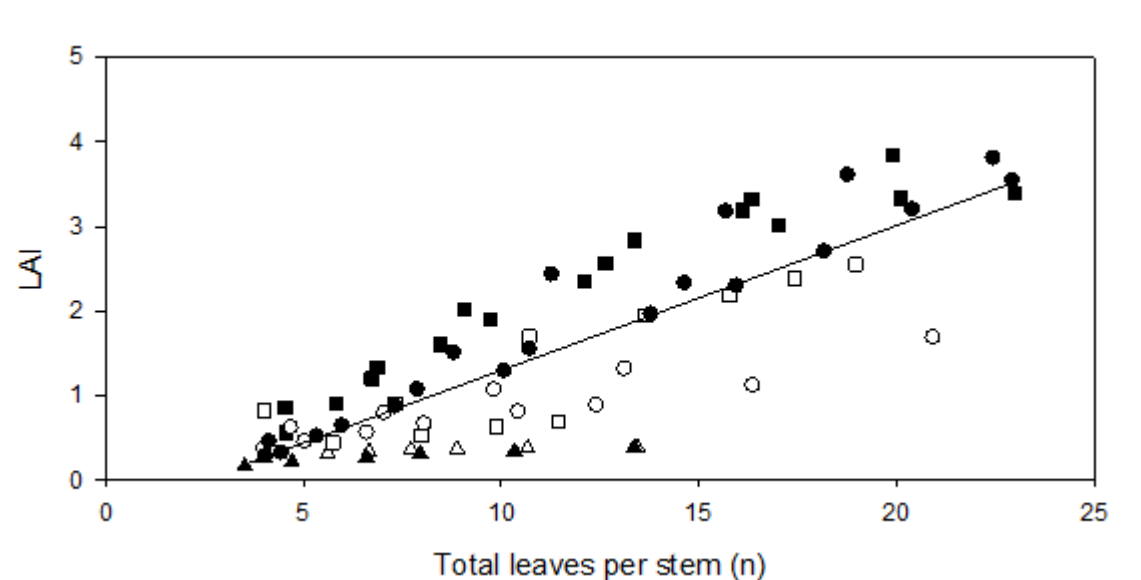


Figure 5.14 Leaf area index (LAI) in relation to total leaves per shoot for dryland lucerne grown at Ashley Dene (○□△) and Iversen 12 (●■▲) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Spring regrowth cycles are marked with circles, summer with squares and autumn with triangles. Linear regression (—): $y = 0.17x - 0.41$, $R^2 = 0.70$.

5.3.4.2 LAI in relation to leaf number

The expansion of LAI showed a strong linear increase in relation to total leaves/m² (Figure 5.15) with $R^2 > 0.85$. But, the response differed between crops at Ashley Dene and Iversen 12, and within each regrowth phase depending on the season. In spring (September – November) crops at both sites had ~20 000 leaves/m², however crops at Ashley Dene reached a LAI of 1.5, 60% less ($P < 0.001$) than crops at Iversen 12. In summer, the regrowth phases for the crops at Iversen 12 were consistent with that of the spring regrowth phase, however the crops at Ashley Dene displayed two different ($P < 0.05$) relationships. At Ashley Dene, the early summer (December- January) regrowth phase reached a LAI of 0.90 with 8000 leaves/m² compared with the late summer regrowth phase (February - March) which reached a LAI of 2.5 with 17 000 leaves/m². The autumn regrowth phases were consistent between sites and a LAI of 0.40 was reached with 10 000 leaves/m².

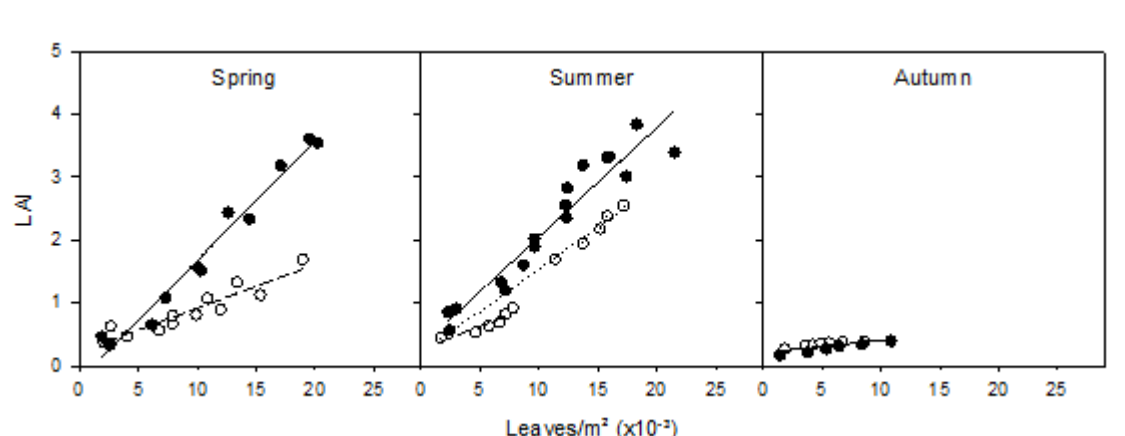


Figure 5.15 Leaf area index (LAI) in relation to total number of leaves per m² for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Linear regressions: Spring; (-----) $y = 0.00007x + 0.23$, $R^2 = 0.86$. (—) $y = 0.00019x - 0.21$, $R^2 = 0.97$. Summer; (-----) $y = 0.00007x + 0.27$, $R^2 = 0.86$. (.....) $y = 0.00010x + 0.20$, $R^2 = 0.99$. (—) $y = 0.00017x + 0.32$, $R^2 = 0.91$. Autumn; (—) $y = 0.00002x + 0.21$, $R^2 = 0.92$.

The slope of the fitted regressions in Figure 5.15 indicates mean individual leaf area, which was plotted against date for individual regrowth phases (Figure 5.16a). For crops at Ashley Dene mean leaf area was $\sim 60 \text{ mm}^2$ for the first three regrowth phases, which increased ($P < 0.001$) to 115 mm^2 in the fourth cycle in late summer. For crops at Iversen 12 mean leaf area was greatest ($P < 0.001$) at 215 mm^2 in the second (spring) and seventh (autumn) regrowth phase. On average, leaves were 60% larger in crops at Iversen 12 compared with those at Ashley Dene. For the final regrowth phase of the season crops at both sites had a leaf size of 25 mm^2 .

Leaf size in relation to mean air temperature demonstrated a bilinear relationship (Figure 5.16b) for crops grown at both sites. This indicated maximum leaf size at both sites was attained when mean temperature was $\sim 12^\circ\text{C}$ of 112 mm^2 and 240 mm^2 at Ashley Dene and Iversen 12, respectively. Increases in temperature beyond this point decreased leaf size by 18 mm^2 per degree for crops at both sites.

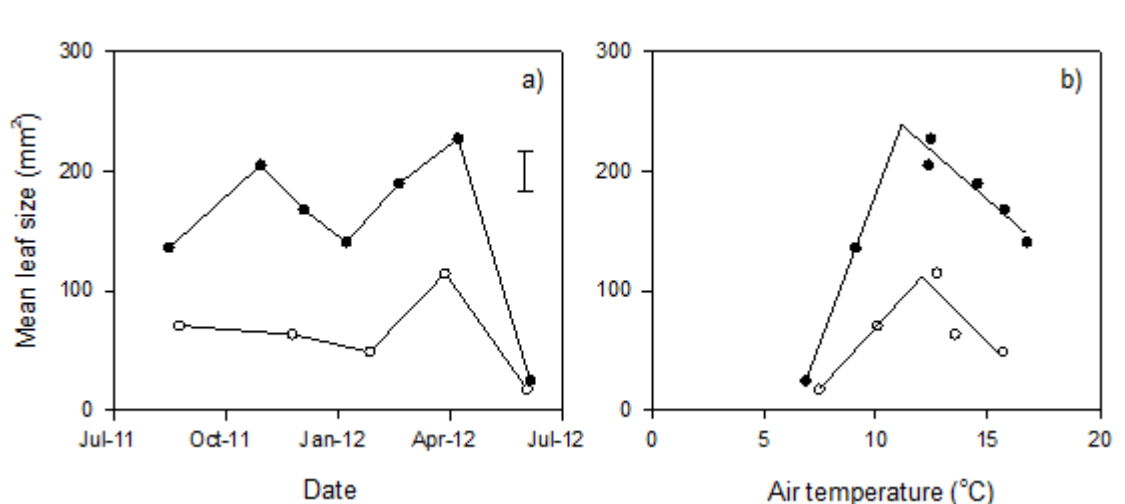


Figure 5.16 Mean leaf size (mm^2) for individual regrowth phases in relation to date (a) and mean air temperature (b) for dryland lucerne grown at Ashley Dene (\circ) and Iversen 12 (\bullet) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Error bar represents pooled l.s.d ($P = 0.05$). Broken stick regressions (—); Ashley Dene; $y = 20.6(x < 12.1)$, $y = -19.1*(x > 12.1)$, $R^2 = 0.45$. Iversen 12; $y = 50.1(x < 11.2)$, $y = -16.7*(x > 11.2)$, $R^2 = 0.97$.

LAER in relation to mean leaf size was described by a broken-stick regression (Figure 5.17) with an R^2 of 0.82. LAER increased 0.00008 per mm^2 when individual leaf size increased from 20 to 150 mm^2 . LAER became constant at 0.012 $\text{m}^2/\text{m}^2/^\circ\text{Cd}$, when leaf size was greater than 150 mm^2 .

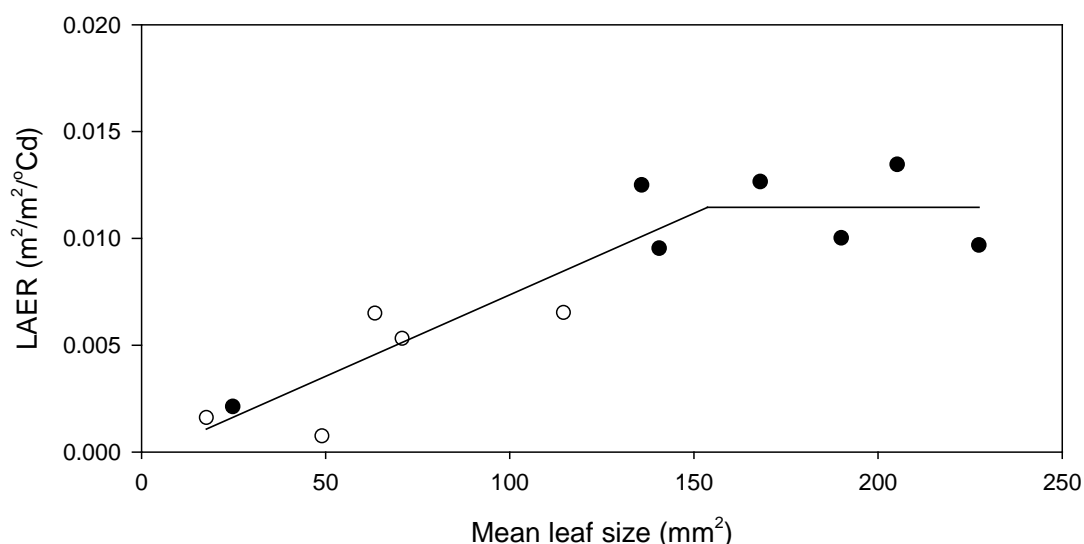


Figure 5.17 Leaf area expansion rate (LAER) in relation to mean leaf size for individual regrowth phases for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Broken stick regression (—); $y = 0.00008(x < 153.7)$, $y = 0.012(x > 153.7)$, $R^2 = 0.82$.

5.3.4.3 LAI in relation to DM and canopy nitrogen

Aboveground crop nitrogen (N) uptake showed a strong linear increase in response to shoot yield with an R^2 of 0.94 (Figure 5.18). N uptake was 35.6 kg N/t DM, which shows a mean canopy N content of 3.6%. The critical crop nitrogen content is defined as the minimum nitrogen uptake necessary to achieve maximum biomass accumulation. Mostly, data points were close to or above the critical N uptake level presented by Lemaire *et al.* (2007). A group of data points were below this level, mainly seedling crops grown at Ashley Dene where shoot yield <1 t DM/ha.

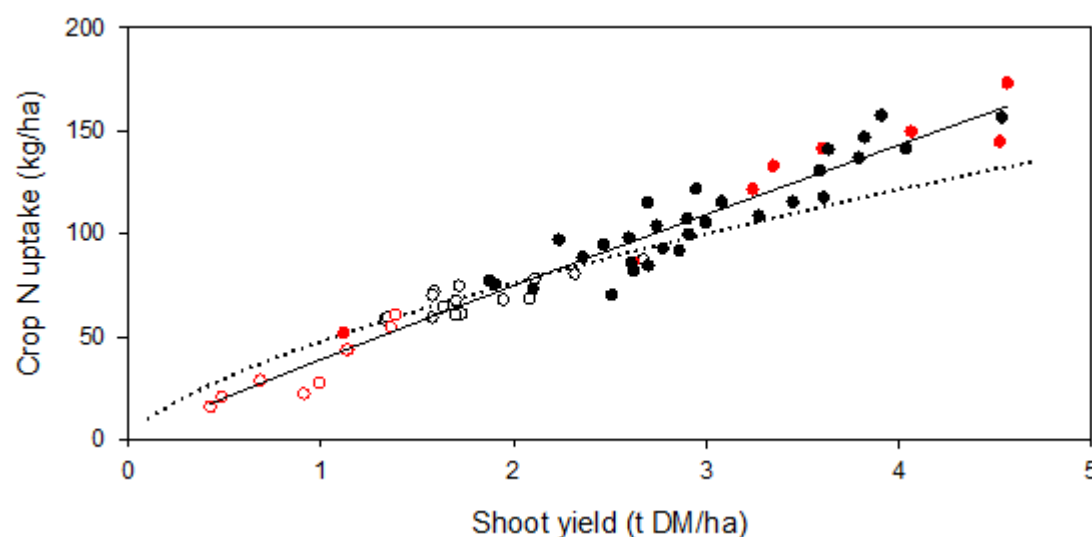


Figure 5.18 Crop nitrogen (N) uptake in relation to shoot yield for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Seedling crops are presented in red. Regressions: (—) $y = 35.6x + 5.47$, $R^2 = 0.94$. Critical N uptake curve (.....); $y = 48x^{0.67}$, for lucerne grown in a temperate environment adapted from Lemaire *et al.* (2007).

Crop N uptake was a linear function of LAI expansion for both seedling and regrowth crops grown at both sites (Figure 5.19). A constant N uptake of 27 kg N per unit of LAI (or 2.7 g m² leaf area) was estimated. This was shown to be consistent with the critical N uptake for LAI expansion presented by Lemaire *et al.* (2007).

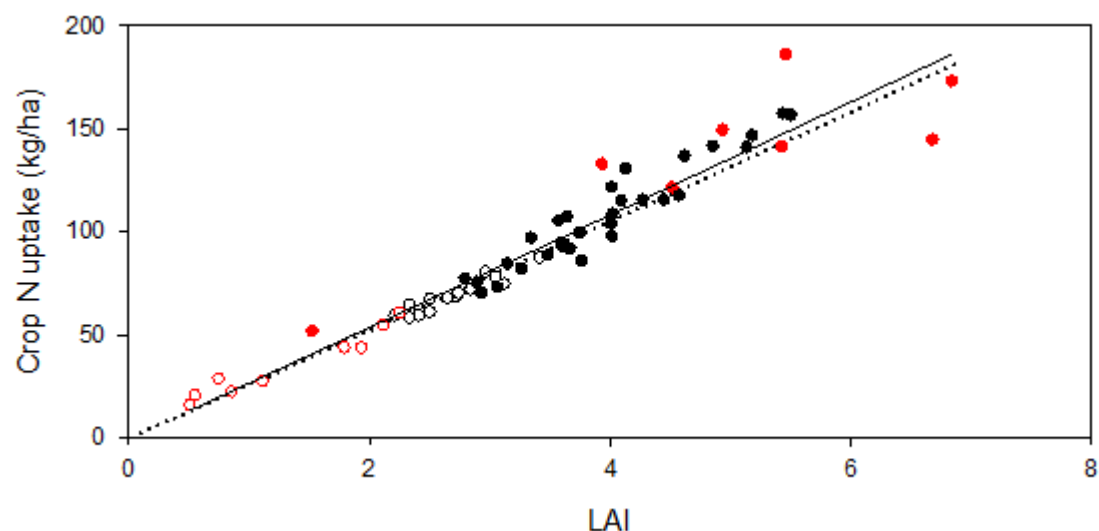


Figure 5.19 Crop nitrogen (N) uptake in relation to leaf area index (LAI) for dryland lucerne grown at Ashley Dene (○) and Iversen 12 (●) from July 2011 to June 2012 at Lincoln University, Canterbury, New Zealand.

Note: Seedling crops are presented in red. Regressions: (—) $y = 27.3x - 0.66$, $R^2 = 0.93$. Critical N uptake curve (.....); $y = 25.4x^{1.03}$, for lucerne grown in a temperate environment adapted from Lemaire *et al.* (2007).

5.3.5 Radiation interception

5.3.5.1 Total accumulated intercepted radiation

Total accumulated intercepted radiation in relation to DM for the entire measurement period (2010 to 2012) is displayed in Figure 5.20. On average, crops grown at Ashley Dene intercepted 3000 MJ/m² of solar radiation 30% less than crops at Iversen 12 which intercepted 4500 MJ/m². Mean RUE_{shoot} for the crops at Ashley Dene was 0.28 g DM/MJ, compared with 0.58 g DM/MJ for crops at Iversen 12.

Cumulative data showed a strong relationship ($R^2 > 0.98$) between intercepted radiation and DM, but at times points were systemically above or below the regression line suggesting RUE_{shoot} was not constant. This relationship was tested for lucerne crops for each season, and then for each regrowth cycle.

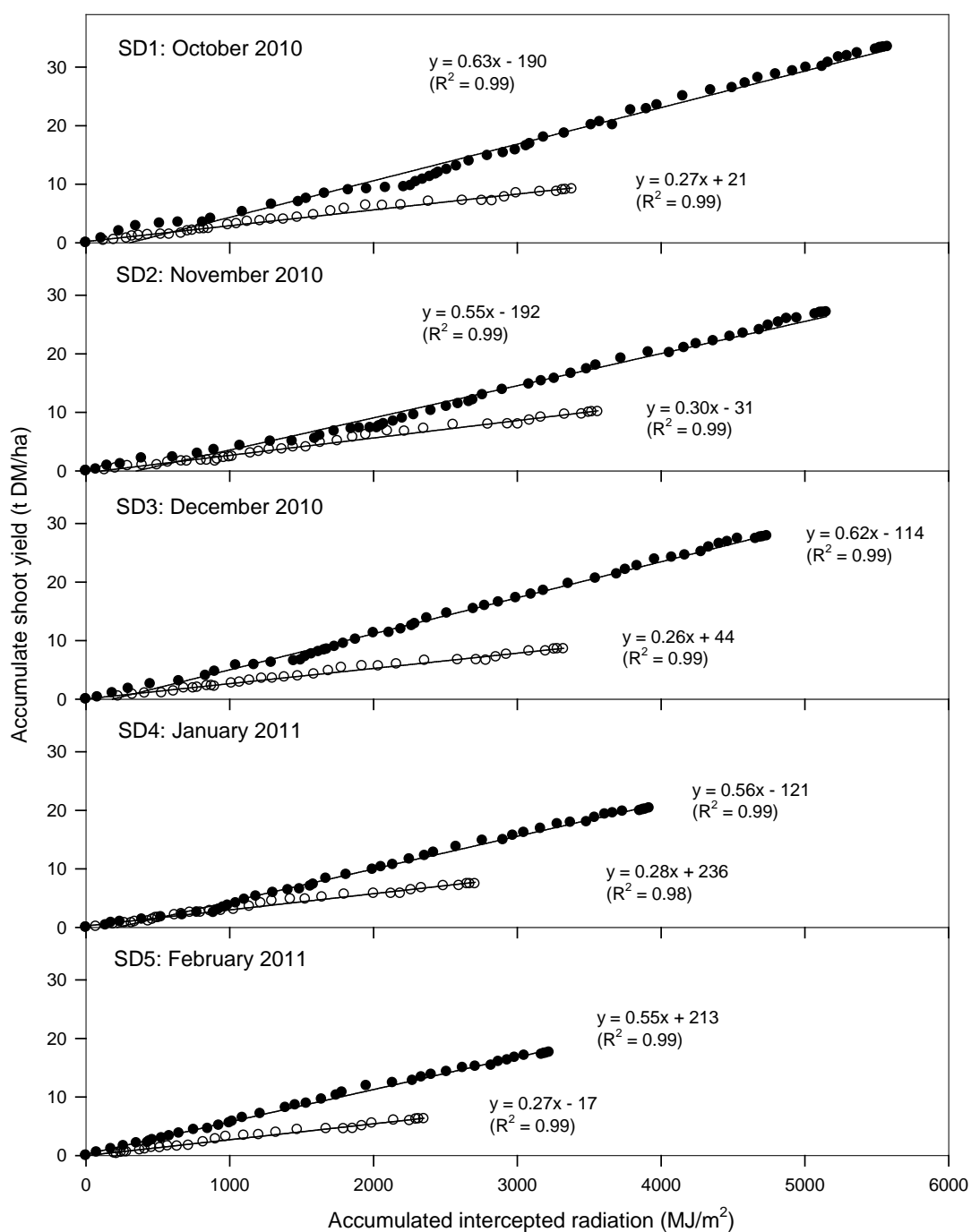


Figure 5.20 Relationship between accumulated shoot yield and accumulated intercepted total solar radiation by lucerne crops sown on five dates at Ashley Dene (○) and Iversen 12 (●) for both the establishment (2010/11) and the subsequent growth season (2011/12) at Lincoln University, Canterbury, New Zealand.

5.3.5.2 *Annual accumulated intercepted radiation*

In the establishment season, at Ashley Dene intercepted radiation was highest in crops sown from October to December (940 MJ/m²), which decreased by ~70% to 290 MJ/m² (Table 5.3) when sowing was delayed until February. A similar pattern occurred in the following regrowth season. Crops that had been sown up to the previous December intercepted a maximum of 2500 MJ/m² compared with 2150 MJ/m², or a reduction of 15%, for those sown after this. RUE_{shoot} was constant between sowing dates and seasons at 0.27 g DM/MJ, consistent with the long-term RUE_{shoot} result.

Table 5.3 Seasonal accumulated intercepted radiation (R_i; MJ/m²) and shoot radiation use efficiency (RUE_{shoot}; g DM/MJ) for lucerne sown on five dates in the establishment (sowing to June 2011) and year two (June 2011 to July 2012) at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Sowing date	Establishment		Year two	
	R _i	RUE _{shoot}	R _i	RUE _{shoot}
October	859 _a	0.28	2519 _a	0.28
November	1007 _a	0.23	2535 _a	0.31
December	947 _a	0.24	2453 _a	0.27
January	498 _b	0.30	2233 _b	0.27
February	290 _c	0.24	2072 _b	0.28
P	<0.001	ns	<0.001	ns
SEM	52.0	0.023	61.3	0.019

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

At Iversen 12 early sown crops had the highest ($P<0.001$) intercepted radiation in the establishment year. October and December sown lucerne intercepted 2260 MJ/m² of radiation (Table 5.4). Delayed sowing from January to February reduced interception by 50%. Mean RUE_{shoot} was 0.41 g DM/MJ for first year crops and 0.63 g DM/MJ for crops growing in the second season. Sowing date affected RUE_{shoot} ($P<0.01$) with crops in the second season which had been sown by December having a 15% higher RUE_{shoot} than those that were sown later.

Table 5.4 Seasonal accumulated intercepted radiation (R_i ; MJ/m²) and shoot radiation use efficiency (RUE_{shoot}; g DM/MJ) for lucerne sown on five dates in the establishment (sowing to June 2011) and year two (June 2011 to July 2012) at Iversen 12, Lincoln University, Canterbury, New Zealand.

Sowing date	Establishment		Year two	
	R_i	RUE _{shoot}	R_i	RUE _{shoot}
October	2457 _a	0.47 _a	3115 _a	0.71 _a
November	2046 _a	0.38 _b	3057 _{ab}	0.63 _b
December	1672 _b	0.49 _a	3021 _b	0.66 _{ab}
January	978 _c	0.34 _b	2912 _c	0.59 _{bc}
February	470 _d	0.35 _b	2808 _c	0.55 _c
P	<.001	<.001	<.001	0.01
SEM	39.6	0.027	28.7	0.033

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

5.3.5.3 Radiation use efficiency

Analysis of individual regrowth cycles showed RUE_{shoot} differed ($P < 0.001$) among sowing dates and regrowth phases. However, the relationship explained less of the yield differences at Ashley Dene ($R^2 = 0.55$ to 0.99) compared with Iversen 12 ($R^2 > 0.90$). Seedling lucerne had a RUE_{shoot} of 0.23 g DM/MJ, which was consistent at both sites. RUE_{shoot} remained at this level for the establishment season, although there was evidence of RUE_{shoot} increasing up to 0.41 g DM/MJ towards the end of the first season for regrowth cycles in October and November sown crops. At Ashley Dene RUE_{shoot} for regrowth lucerne in the second season was constant at 0.27 g DM/MJ for three out of 4 cycles, except in summer when RUE_{shoot} decreased to 0.10 g DM/MJ. In Iversen 12, sowing in the establishment season affected RUE_{shoot} ($P < 0.001$) with earlier sown crops consistently having a 25% higher RUE_{shoot} .

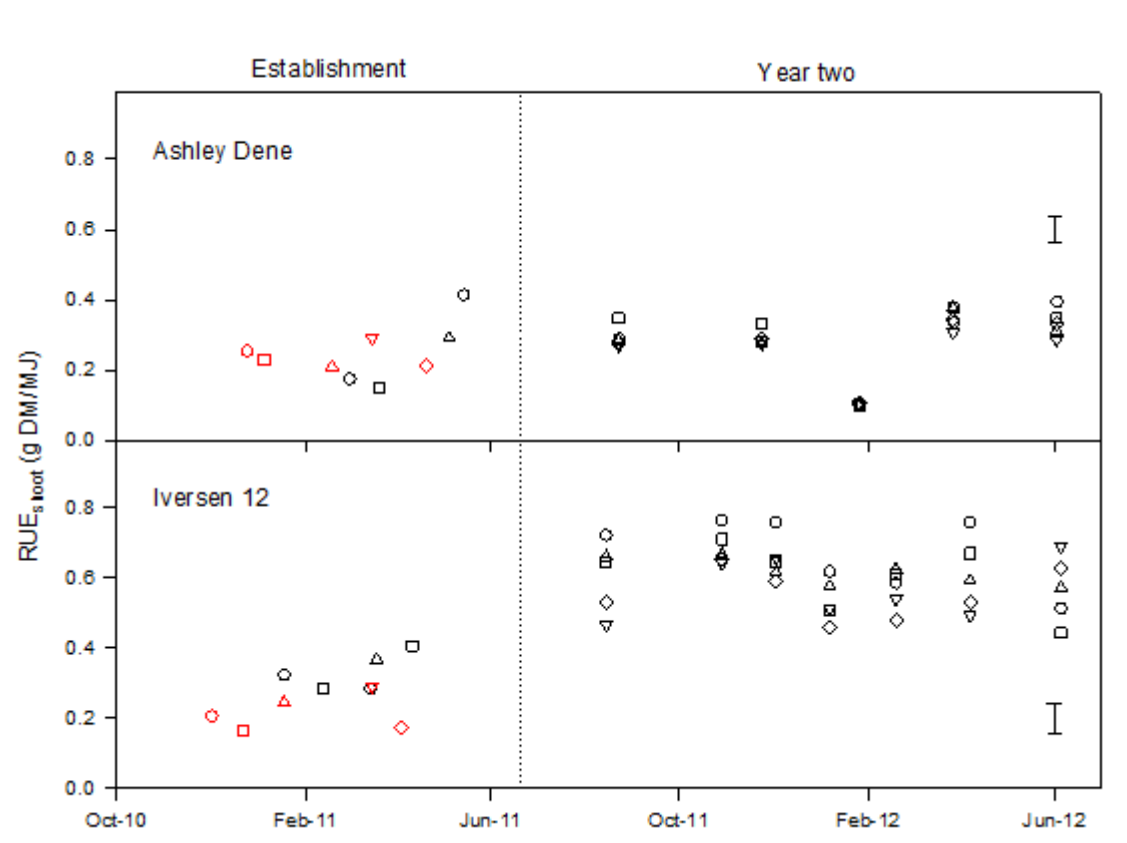


Figure 5.21 Shoot radiation use efficiency (RUE_{shoot}) of lucerne sown on five dates; October (○), November (□), December (△), January (▽) and February (◇) at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Seedling crops are presented in red. Error bar represents pooled l.s.d ($P = 0.05$) of RUE_{shoot} from regressions.

5.3.5.4 *Total radiation use efficiency*

The RUE_{total} for the crops sown in the second season from which below ground biomass (crown and 300 mm of taproot) had been sampled was calculated. RUE_{total} was then compared with RUE_{shoot} to give an indication of seasonal partitioning of DM (Table 5.5). Mean RUE_{total} was 0.50 g DM/MJ for crops grown at Ashley Dene compared with 0.82 g DM/MJ for Iversen 12. Crops at Ashley Dene displayed RUE_{total} twice that of RUE_{shoot} . At Iversen 12, crops sown from November to January displayed the highest RUE_{total} of 0.92 g DM/MJ and a RUE_{shoot} of 0.56 g DM/ha, which was consistently 60% of RUE_{total} .

Table 5.5 Shoot (RUE_{shoot}) and total (RUE_{total}) radiation use efficiency (RUE; g DM/MJ) for lucerne sown on five dates in the establishment (sowing to June 2012) season at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Sowing date	Ashley Dene		Iversen12	
	RUE_{shoot}	RUE_{total}	RUE_{shoot}	RUE_{total}
October	0.27 _{ab}	0.47 _c	0.53 _a	0.77 _b
November	0.22 _{bc}	0.42 _c	0.57 _a	0.89 _a
December	0.29 _a	0.57 _{ab}	0.53 _a	0.89 _{ab}
January	0.32 _a	0.64 _a	0.60 _a	0.98 _a
February	0.18 _c	0.40 _c	0.35 _b	0.59 _c
P	<0.005	<0.05	<0.001	<0.001
SEM	0.021	0.066	0.084	0.051

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$).

5.4 Discussion

Development and growth differed between seedling and regrowth crops. Seedling crops experienced a longer phyllochron and slower branching rate which resulted in lower leaf area expansion rates than regrowth crops. Crops at Ashley Dene had a longer phyllochron relative to crops in Iversen 12. However, differences in LAI expansion rates were mainly associated with smaller individual leaf area. Therefore, the yield differences presented in Chapter 4 will be explained by the patterns of intercepted radiation and radiation use efficiency.

5.4.1 Intercepted radiation and DM yield

Accumulated intercepted radiation explained ~98% of the differences in DM yields among crops (Figure 5.20). The proportion of intercepted radiation increased exponentially with LAI, to a maximum when LAI was 3.4 (Figure 5.13). Therefore, a reduction in canopy expansion limited the amount of energy the crops were able to capture for photosynthesis (Equation 2.1). The cause of the differences in LAI among crops will be examined in relation to canopy development, expansion and canopy architecture.

5.4.2 Canopy development

5.4.2.1 *Mainstem node appearance*

Expression of phyllochron is most likely related to assimilate supply which is described in relation to Pp to show the seasonal pattern (Section 2.3.1.1). Assimilate supply is influenced by DM partitioning, which differs between seedling and regrowth crops, seasonally and also in response to water stress (Section 4.3.3). Mainstem node appearance was constant in thermal time (Figure 5.4 and 5.5) for each growth phase, but was dynamic throughout the season (Figure 5.6). For crops at Iversen 12 seasonal phyllochron variation was described in relation to photoperiod at the start of the growth period (Figure 5.7) and the hysteresis displayed is consistent with the literature of lucerne grown in a similar environment (Brown and Moot, 2004; Brown *et al.*, 2005b; Teixeira *et al.*, 2011). The phyllochron was 37 °Cd in spring but increased to 50 °Cd in

autumn for regrowth and 60 °Cd for seedling crops. Brown *et al.* (2005b) suggested phyllochron remained constant, but the expression of it was limited as available assimilate was preferentially partitioned below ground as photoperiod increased. Leaf appearance rates are determined by the rate of cell division and expansion at the stem apex (Hay and Walker, 1989) which is driven by assimilate supply. Hunt and Thomas (1985) found that in perennial ryegrass, at light saturation temperature had little effect on phyllochron, however as temperature increased, the irradiance required to attain the maximum potential phyllochron also increased. This suggested the supply of assimilate, which is regulated by irradiance (Hay and Walker, 1989) can influence the leaf appearance rate. These authors also found that by limiting assimilate supply through low irradiance (24% light transmission) coupled with high temperature conditions the leaf appearance rate was reduced and phyllochron was increased, but root production was consistent with that grown under light saturation. This suggests the root fraction is a stronger assimilate sink and the shoot yield is compromised to maintain partitioning below ground. The results from the current research showed assimilate partitioned below ground was ~30% in spring which increased to ~50% by autumn (Figure 4.10). This is consistent for established lucerne (Teixeira *et al.*, 2008) which further supports the suggestion by Brown *et al.* (2005b) that higher assimilate demand for root storage may limit the expression of the maximum potential leaf appearance rate in lucerne. Phyllochron for crops grown at Ashley Dene did not show hysteresis. The crops displayed a minimum phyllochron of 50 °Cd, increasing up to 90 °Cd, which could not be explained solely in relation to photoperiod (Figure 5.7). These crops experienced high levels of partitioning below ground throughout the entire establishment season of >50%.

There was no apparent relationship between the fractional partitioning of DM below ground and phyllochron for lucerne in the establishment season (Appendix 12; Figure 0.7a). Crops at Ashley Dene were observed to experience water stress which would compound the possible relationship of this data. In response to water stress crops reduce LAI as a mechanism to decrease transpiration and limit future water stress (Jamieson, 1999), which was shown in lucerne by Brown *et al.* (2009). The authors reported phyllochron increased ~60% when water stressed (Figure 2.8a). The effect of water stress on canopy development will be examined in more detail in the next chapter.

The initial hypothesis was seedling crops would not be inflicted to severe water stress because of the lower water demand of seedling crops relative to regrowth. Seedling biomass assessments during the early establishment period showed plants at Ashley Dene were half the size of those at Iversen 12 (Table 4.3). The difference was associated with individual leaf area, which were on average 60% smaller for regrowth crops grown at Ashley Dene (Figure 5.16), probably due to limited assimilate supply due to water stress. This may have been compounded by the higher partitioning of assimilate below ground of 25%, relative to Iversen 12 crops. This reduction in assimilate supply for crops grown at Ashley Dene possibly resulted in a decrease in leaf appearance rate, for example spring sown seedling crops at Ashley Dene had a phyllochron of 55 °Cd compared with 38 °Cd at Iversen 12 (Figure 5.6).

5.4.2.2 *Branching*

Total node accumulation was exponential for seedling crops (Figure 5.4) compared with regrowth crops which displayed a linear increase in relation to thermal time (Figure 5.5). Stem number was up to 50% lower in seedling crops compared with regrowth crops (Tables 5.1 and 5.2), which suggests the lower competition for light in seedling crops, reduced shading in the lower layers of the canopy and nodes continued to produce leaves. The canopy influences the red to far-red light (R:FR) ratio. A decrease in the R:FR can modify the canopy through increased stem elongation and restricted branching or tillering (Section 2.1.4). Therefore the lower stem population in seedling crops would be expected to stimulate branching due to higher R:FR.

Rate of branching was conservative, and showed less plasticity compared with the other components of LAI (Section 2.3.1). Mainstem node appearance explained 92% of the variation in observed axillary leaf production (Figure 5.8). Axillary leaves were produced at a rate of ~2.5 per mainstem node which is consistent with that reported for irrigated lucerne in summer by Brown *et al.* (2005b). This result may have been due to the relatively consistent stem populations of the crops within sites, which were likely maintained by differences in shoot number per plant as populations were all above the minimum threshold to maximise yield. Axillary leaf production was recorded up to leaf senescence. Brown *et al.* (2005b) showed a leaf senescence rate of ~0.3 leaves per

mainstem leaf in irrigated lucerne which increased when the crop experienced canopy closure, due to mutual shading. Therefore, it is suggested that the rate of branching may be consistent between crops, however net leaf appearance differs due to senescence which can be influenced through components of LAI e.g. stem number. This means when determining LAI, leaf senescence is an important component to consider, however in the present study total leaf number gave a moderate ($R^2 = 0.70$) description of canopy expansion (Figure 5.14), which was largely driven by individual leaf area (Figure 5.17).

5.4.2.3 *Extinction coefficient*

The consistent extinction coefficient (k) found in the present results among crops allowed the prediction of intercepted radiation from crop LAI using a single value throughout the season. The k , which describes canopy architecture, was 0.89 and consistent between seedling and regrowth crops (Figure 5.3). Crops had a critical leaf area index of 3.4 (Figure 5.13), which was consistent with that reported by Teixeira *et al.* (2011) who showed a constant k for both seedling and regrowth crops of 0.93. This differs from Robertson *et al.* (2002) who reported a seedling k value of 0.57 which suggests leaves became more erect to allow light to penetrate further into the canopy to utilise the limited leaf area of an incomplete canopy more efficiently. However, Mattera *et al.* (2013) reported a stable k of 0.72 in lucerne canopies which varied in LAI from 4.1 to 2.9 due to row spacing treatments, which supports Varella (2002) who reported k in regrowth lucerne crops was insensitive to different light environments. The exponential relationship between k and intercepted radiation (Equation 2.3) means an error associated with LAI measurement will have a greater impact on the proportion of intercepted radiation at low (<2.0) LAI (Hay and Walker, 1989), which occurred regularly for the crops at Ashley Dene (Figure 5.9). Moran *et al.* (1989) reported lucerne responded to water stress by arranging leaves more vertically (25% decrease in leaf angle) to reduce the interception solar radiation and limit water loss through transpiration. If this response to water stress occurred, albeit undetected, in the present study an overestimation of intercepted radiation could occur. For example, a 25% decrease in k when soil moisture content dropped below 50% of PAWC for regrowth crops at Ashley Dene would have resulted in a reduction in annual intercepted radiation of 8%.

5.4.3 Canopy expansion

Canopy expansion was driven mostly by individual leaf area. Maximum potential LAER was $0.016 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ shown for the Iversen 12 crops in the spring regrowth cycles (Figure 5.12). LAER below this optimum were most likely limited by water stress, particularly for all crops at Ashley Dene and by available assimilate for establishing crops, which was preferentially partitioned below ground. Maximum potential LAER for seedling and regrowth crops were 0.011 and $0.016 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$ for those sown in Iversen 12 (Figure 5.12). These values are consistent with that for fully irrigated lucerne grown in the same environment (Teixeira *et al.*, 2011). Seedling crops which had slower development rates and less shoots per area relative to regrowth crops experienced reduced canopy expansion rates. The consequence of lower LAER for seedling crops resulted in a maximum LAI of 4.0 being reached compared with 6.0 for the regrowth crops (Figure 5.10). As a consequence of slower development seedling crops are more susceptible to weed invasion. Weed invasion was more prevalent in the spring sown crops following seedbed preparation with the emergence of annual ryegrass and broad leaf weeds (Section 3.3.4). Agronomic management needs to account for this to maintain stand persistence.

Maximum LAER at Ashley Dene was a third of those at Iversen 12. The consequence of slow expansion rates prevented canopy closure in all crops which reduced radiation intercepted for photosynthesis on average by 30% compared with crops at Iversen 12. Crops at Ashley Dene had fewer leaves available to capture radiation due to their longer phyllochron and lower stem population. However, individual leaf area appears to have the largest effect on LAER, with leaves on average 60% smaller than those in Iversen 12 (Figure 5.16a). The maximum leaf area is genetically determined, however expression depends on environmental factors such as; temperature, radiation, water and nitrogen (Hay and Walker, 1989). It appears individual leaf area expansion may also be responding to other components of LAI index, most likely number of leaves. This was shown in Figure 5.17 where LAER increased linearly up to a mean leaf size of 150 mm^2 . Increases in leaf size beyond this did not increase LAER. Leaf size possibly interacts with leaf appearance, for example in late summer when the phyllochron decreased, crops compensated for this by an increase in individual leaf area. Maximum leaf area was attained when mean air temperature was $\sim 12^\circ\text{C}$ (Figure 5.16b). This is

less than half the proposed optimum temperature for growth and development (Figure 2.2). Pearson and Hunt (1972) suggested the optimum temperature for leaf expansion was ~20 °C compared to 30 °C for leaf appearance when they noted lucerne subjected to day time temperatures of 15 to 20 °C had a smaller number of leaves with almost twice the rate on expansion than when grown at 30 °C. Observation of crops at Ashley Dene showed small leaves, leaf folding and wilting from loss of turgor. Plant cells require water pressure for expansion and are sensitive to water stress (Section 2.5.3). Brown *et al.* (2009) showed LAI of a dryland crop was only 10% of a fully irrigated crop under severe stress (Figure 2.8a). A likely explanation for a reduction in leaf size area with an increase in temperature is water stress, which is thought to have occurred during the summer regrowth phases at both sites. Canopy expansion in relation to crop water status will be examined in detail in Chapter 6.

Nitrogen (N) uptake does not appear to have restricted LAER. For example, in the second season the crop which yielded the highest (21.5 t DM/ha) had an uptake of ~530 kg N/ha. At sowing, soil N was adequate to establish seedling crops (~100 kg N/ha; Appendix 3 and 4) and crops at both Ashley Dene and Iversen 12 were shown to be inoculated with the N-fixing bacteria, *Ensifer meliloti* (Wigley, 2011; Khumalo, 2012). LAER is influenced by nitrogen nutrition, as shown in lucerne by Lemaire *et al.* (2007) who reported a linear accumulation of nitrogen at 30 kg N per unit of LAI, which was consistent with the present study (Figure 5.19). Under N deficiency, leaf area is manipulated to maintain a leaf N concentration above the minimum threshold of ~2 g N/m² leaf required to achieve maximum biomass accumulation which contains about 3.5% N, consistent with that of the present study (Figure 5.18). However, the partitioning of DM may have reduced carbon and nitrogen supply available to expand the canopy. Teixeira *et al.* (2007c) showed in mature lucerne, spring LAER was positively associated with N reserves in perennial DM. Crops in the present study did not display a clear relationship between the level of partitioning of total DM below ground and LAER (Appendix 12, Figure 0.7b). A 'frontier curve' may suggest potential LAER of 0.016 m²/m²/°Cd is expressed when the fractional partitioning of DM to the roots (P_{root}) is > 35% which decreases to close to zero when P_{root} increases to 60%. However it is unclear how environmental factors such as temperature and photoperiod influence this relationship and more data are required.

On average, crops grown at Ashley Dene intercepted 3000 MJ/m² of solar radiation 30% less than crops at Iversen 12 which intercepted 4500 MJ/m². But, after two years mean annual yield was 3 fold greater for the crops at Iversen 12 (Table 4.4). Therefore the dominant mechanism which reduced yield was RUE, which will be discussed.

5.4.4 Radiation use efficiency and DM yield

Differences in RUE was the dominant mechanism which reduced DM yield among crops. This was because, although the pattern of leaf area differed between sites, regrowth crops generally maintained LAI of 2 to 3 at Ashley Dene. Due to the exponential relationship between R/R_0 and LAI this meant crops were often intercepting up to 80% of incoming radiation by the end a regrowth phase. For seedling crops sown in Iversen 12, mean RUE_{shoot} was 35% lower than in the following regrowth year (Table 5.4). This result is consistent with Teixeira *et al.* (2011) who showed seedling lucerne had a RUE_{shoot} of 0.60 g DM/MJ compared with regrowth lucerne of 0.80 g DM/MJ. Crop photosynthetic capacity is closely linked to leaf N content as 50% of the soluble protein in C₃ leaves can be made up of Rubisco (Sinclair and Horie, 1989), the principle enzyme responsible for CO₂ fixation (Hay and Walker, 1989).

Crop biomass contained 3.5% N (Figure 5.19), which showed LAI was manipulated to maintain N% above the critical limit where leaf photosynthetic capacity is compromised (Lemaire *et al.*, 2007). The decrease in RUE_{shoot} is associated with DM partitioning when the root fraction had a greater demand for limited assimilate. Avice *et al.* (1997) showed in regrowth lucerne a decrease in RUE_{shoot} from 0.94 to 0.73 g DM/MJ in crops with reduced nitrogen reverses in perennial DM. To account for the partitioning dynamics, RUE_{total} was calculated for crops where root DM was sampled (Table 5.5). RUE_{total} was about twice that of RUE_{shoot} at both sites which accounts for root partitioning in these crops at similar levels. Maximum RUE_{total} of ~0.95 g DM/MJ was attained from lucerne sown in mid-summer at Iversen 12, which is within the range found by Thiebeau *et al.* (2011) of 0.92 to 1.42 g DM/MJ regrowth lucerne. A decrease in RUE_{total} in the early and late sown crops suggests these crops were limited by temperature. Brown *et al.* (2006b) showed a strong linear increase in RUE with temperature from 0.8 g DM/MJ at 9 °C to 1.6 g DM/MJ at 17 °C (Figure 2.6). RUE_{shoot}

for regrowth crops grown at Iversen 12 were normalised for mean air temperature (RUE_a) (Figure 5.22). This showed the measured RUE_{shoot} was lower than that of the RUE_a from August to November which indicates a possible temperature limitation to photosynthesis. Brown (2004) showed the potential DM production at optimum temperature was 1.6 g DM/MJ, which is 24% higher than that shown in Figure 5.22 during spring of 1.21 g DM/MJ.

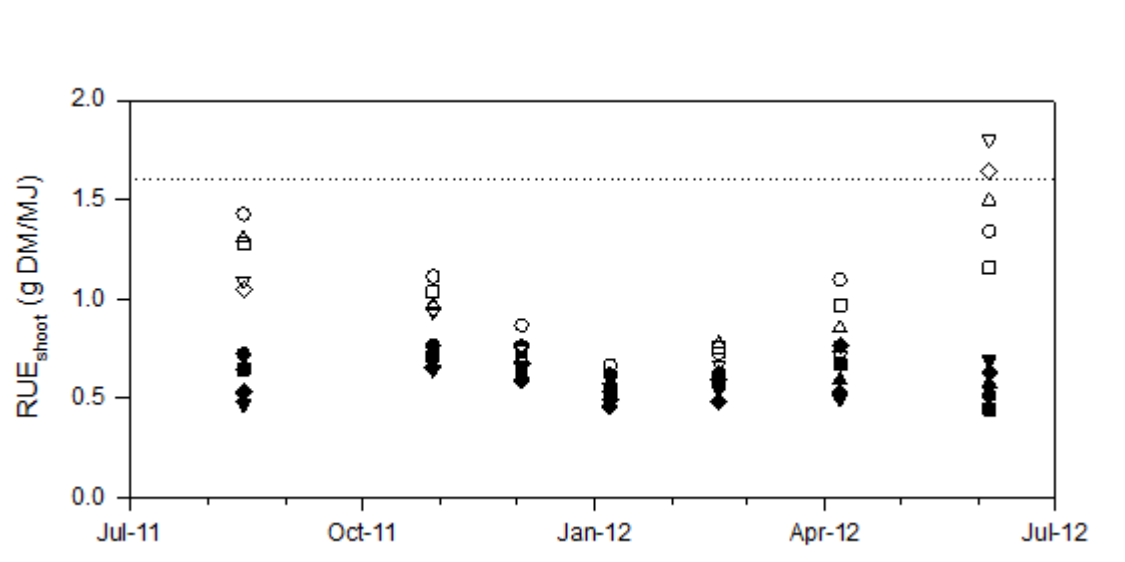


Figure 5.22 Measured (●) and temperature adjusted (○) shoot radiation use efficiency (RUE_{shoot}) for second year dryland lucerne sown on five dates in the previous season; October (○), November (□), December (△), January (▽) and February (◇) at Iversen 12 from July 2011 to July 2012, Lincoln University, Canterbury, New Zealand.

Note: RUE_{shoot} adjusted for Temperature as per Brown *et al.* (2006b); RUE_{shoot} increases linearly from nil at 0 °C to maximum of 1.6 g DM/MJ when temperatures >18 °C. Dotted line denotes maximum potential RUE_{total} (Brown *et al.*, 2006b).

In the current study RUE_{total} does not include DM lost due to root respiration which was reported by Teixeira *et al.* (2009) to be ~0.035 g/g root DM/day. Root mass ranged at the start of the season from ~5.3 t DM/ha for crops sown in the previous spring to 1.1 t DM/ha for the autumn sown crop (Section 4.3.3). This implies a larger root respiration for the spring sown crops and a possible lower RUE_{shoot} compared with the autumn sown crops. The opposite occurred (Figure 5.22), with a RUE_a for spring sown crops of 1.41 g DM/MJ compared to 1.07 g DM/MJ. Assuming RUE_{total} was consistent among these crops, this suggests the late sown lucerne preferentially partitioned more DM

below ground, and a single partitioning factor is unsuitable when determining shoot yield using RUE_{total} .

Crops grown at Ashley Dene did not show the same seasonal variation in RUE_{shoot} , which was limited to 0.3 g DM/MJ (Table 5.5). These crops displayed high levels of DM partitioning to roots throughout the season of ~50% (Section 4.3.3). This resulted in RUE_{total} twice that of RUE_{shoot} . It seems that root partitioning at Ashley Dene was only partially responsible for the low field RUE_{shoot} reported. RUE_{shoot} decreased to 0.10 g DM/MJ for the summer rotation where severe water stress was observed with a maximum LAI of 0.8 and a final DM yield of 0.7 t/ha for the two month growth period. RUE is sensitive to water stress and was shown in lucerne by Brown *et al.* (2009) who reported RUE_{shoot} decreased linearly from the potential maximum to zero under severe water stress (Figure 2.8).

The efficiency at which intercepted radiation was converted to biomass was the dominant mechanism which explained differences in yields among crops. This was due to the DM partitioning dynamics of these crops, and also, mostly likely water stress. The remainder, was attributed to the amount of intercepted radiation by the crops, which was driven by the pattern of LAI mainly through expansion of individual leaves. These components of yield will now be quantified in relation to water stress. This will determine if the relationships responsible for the decrease in radiation capture and use efficiency are consistent among crops, and whether water supply was the dominant environmental variable which determined yield.

5.5 Conclusions

These results show both seasonal LAI and RUE contributed to yield differences. Slower developing crop canopies had reduced LAER rates which resulted in less radiation being intercepted. RUE_{shoot} differences was the dominant mechanism which contributed to reduced seasonal DM yield which was partly explained by the partitioning of DM between shoot and root fractions. Specific conclusions are:

- Accumulated intercepted radiation explained most ($R^2 = 0.98$) of the differences in DM yield among crops. On average, crops at Ashely Dene intercepted 30% less radiation than those at Iversen 12.
- Canopy development and expansion determined LAI, and therefore intercepted radiation. Differences in LAI were mainly due to the expansion of individual leaves. Maximum potential LAER was 0.011 and 0.016 m²/m²/°Cd for seedling and regrowth crops, respectively. LAER increased 0.00008 per mm² up to an individual leaf area of 150 mm².
- Total leaf number was mainly determined by phyllochron, which explained most ($R^2 = 0.92$) of the differences in branching rate. Spring sown seedling lucerne at Iversen 12 displayed the shortest phyllochron of 37 °Cd, which increased to 57 °Cd when sown in late summer. Phyllochron was >50 °Cd for all crops at Ashley Dene.
- RUE_{shoot} was the dominant mechanism which reduced DM yield among crops. On average RUE_{shoot} for crops at Ashley Dene was half of that compared with those at Iversen 12. At Iversen 12 RUE_{shoot} displayed a seasonal pattern, 0.68 g DM/MJ in spring and early summer when decreased to 0.45 g DM/MJ in late summer. RUE_{shoot} was consistently 0.27 g DM/MJ at Ashley Dene.

The yield forming processes will now be quantified in relation to water. The ratio between water demand and supply will be determined to identify when water stress occurred. Water stress will be related to the yield forming components of lucerne to determine if the mechanisms which reduce yield in relation to water stress were consistent among crops.

6 Soil water extraction and how water limitation affects growth of lucerne

6.1 Introduction

The previous chapter described canopy development and expansion of crops which differed in yield. The crop canopy sets the potential for radiation interception, which drives yield (Section 2.2). But, temperature only accounted for part of the differences in seasonal patterns of LAI, and water stress was apparent. Furthermore, there were differences in RUE, which is another important component for determining yield which was not fully explained. The aim of this chapter is to explain how water supply differed with site and sowing date and how water shortage influenced the formation of yield.

Water use (WU) is often calculated as the minimum of the actual crop transpiration (E_T) and the potential transpiration which represents the demand for water from the canopy (EP_T) (Ritchie, 1972; Monteith, 1986) (Equation 6.1);

Equation 6.1
$$WU = \min(E_T, EP_T)$$

E_T is the result of both soil (McLaren and Cameron, 1990) and root (Jamieson and Ewert, 1999) characteristics (Section 2.5.1). The first objective is to quantify the water available for extraction and how site and sowing date influenced this. Crop demand (EP_T) is normally measured when supply is non-limiting, but can be predicted based on atmospheric data, through Penman evapotranspiration adjusted for crop canopy (French and Legg, 1979; Brown *et al.*, 2012). When demand for water exceeds supply crops experience water stress and yield often declines (Section 2.5.3). Therefore, the second objective was to quantify crop physiology responses to water stress to understand the mechanisms responsible for the observed differences in crop yield.

6.2 Materials and methods

6.2.1 Soil water

6.2.1.1 *Neutron probe access tube installation*

Neutron probe access tubes were installed to a depth of 2.3 m in each plot being measured. Due to the stony soil profile at Ashley Dene (Section 3.1.2) it was impossible for the conventional installation method to auger through the compacted gravels which occurred throughout the soil profile. To overcome this, it was necessary to spike access holes using a 50 mm steel spike and a vibrating head attachment on a 20 tonne excavator. Aluminium tubes (47 mm OD) were then installed. To maintain consistency this method was used at both experimental sites. Previous experience in a similar soil type using this installation method showed no effect on actual soil moisture (Mills, 2007). Access tubes were installed 5-7 days following each sowing date, to allow mechanical sowing of the entire plot but prevent damage to seedling lucerne.

6.2.1.2 *Measurements*

Volumetric soil water content (VWC) was measured in 22 layers of the soil profile to a depth of 2.3 m at 10 to 14 d intervals. The top layer (0-0.2 m) was measured with a time domain reflectometer (TDR; Trace system, Soil Moisture Equipment, Santa Barbara, California, USA) with 0.2 m long stainless steel rods within 0.2 m of the neutron probe access tube. The remaining 21 layers were measured at their mid-point with a neutron probe (Troxler Electronic Industries Inc, Research Triangle Park, North Carolina, USA). The neutron probe was calibrated for a Templeton silt loam which has the same parent material as the Wakanui silt loam series, and only differs in the depth to gravels (Cox, 1978). This intensity of measurement (0.1 m intervals) is required on these highly variable, alluvial outwash soils.

6.2.1.3 *Water use and soil water deficit*

The amount of water in the soil, soil water content (SWC) was calculated to a depth of 2.3 m using Equation 6.2.

Equation 6.2
$$SWC = \sum_{bot}^{top} \theta * d$$

Where θ is the volumetric water content (VWC) of individual layers as measured in Section 6.2.1.2, d is the depth of the layer, *top* is the 0 to 0.2 m layer and *bot* is the 2.2 to 2.3 m layer.

The water use (WU, mm per period) was calculated for each measurement period using Equation 6.3;

Equation 6.3
$$WU = P_R - (SWC_E - SWC_S)$$

Where P_R is the sum of rainfall for the same period, SWC_S and SWC_E represent the actual soil water content of the profile as measured (Section 6.2.1.2) for the start and end of the period, respectively. This equation assumes no rainfall is lost as drainage or runoff.

Daily water use (WU_{daily}) was then calculated (Equation 6.4) based on the WU compared with accumulated Penman potential evapotranspiration (EP) for the same period. WU_{daily} was then calculated based on EP for each day (P_{daily}).

Equation 6.4
$$WU_{daily} = (WU/EP) * EP_{daily}$$

6.2.1.4 Soil water deficit

The soil water deficit (SWD) was calculated from the difference between the drained upper limit (Section 6.2.1.5) and SWC. Daily SWC was calculated from the actual SWC measurements made every 10-14 days and WU_{daily} as described above. Daily SWD was calculated by adding WU_{daily} and subtracting rainfall (R) from the previous days SWD (SWD_i) (Equation 6.5);

Equation 6.5
$$SWD = SWD_i + WU_{daily} - R$$

6.2.1.5 Drained upper limit

Drained upper limit (DUL) was defined as the maximum stable volumetric water content which was measured 5 days after complete soil recharge, to allow for drainage (Section 6.2.1.6). Complete recharge was known to occur in the plots which were sown in the second season as they were chemically fallowed for the previous season, incurring ~600 mm of rainfall and no plant water extraction. Mean DUL for the soil profile to 2.3 m depth for Ashley Dene was 305 mm and 760 mm for Iversen Field (Figure 6.1). The plant available water capacity (PAWC) of the soil is the difference the DUL and the lower limit (LL) of water extraction by a mature crop which has fully explored all soil moisture (McLaren and Cameron, 1990). This was determined for the crops in the second season when the SWD was maximised. The PAWC to 2.3 m was 130 mm and 360 mm for Ashley Dene and Iversen 12 respectively (Figure 6.1). Distribution of water down the soil profile differed between sites with 50% of total extractable water in the top 0.5 m at Ashley Dene compared with 25% at Iversen 12. DUL for individual plots varied up to 20% of mean values reinforcing the need for the intensive soil water measurements due to the variability of these soils over short distances. This research intends to compare seedling and mature lucerne water extraction in the same year.

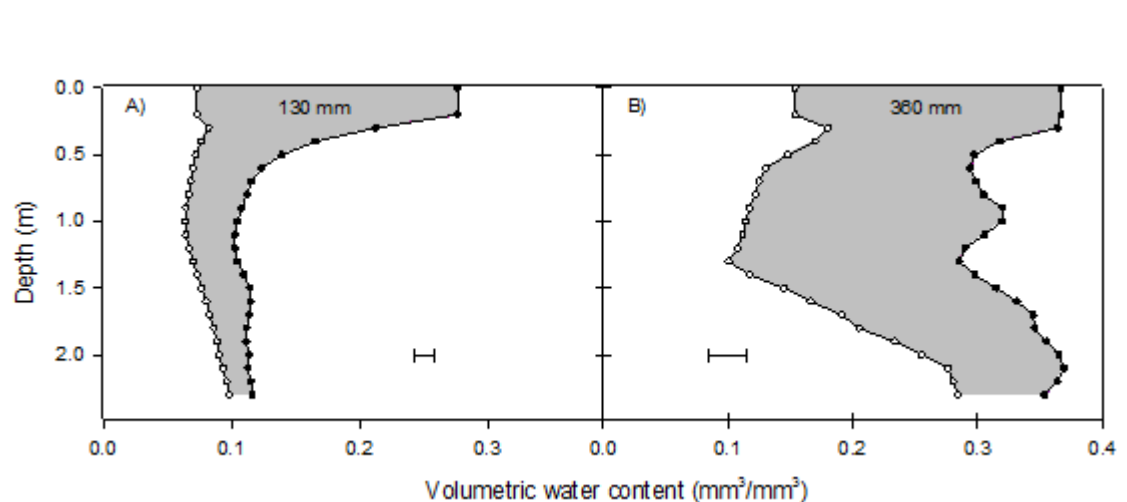


Figure 6.1 Upper (●) and lower (○) limits of mature lucerne water extraction to 2.3 metres at Ashley Dene (A) and Iversen Field (B) at Lincoln University, Canterbury, New Zealand. Shaded areas and numbers represent plant available water content.

6.2.1.6 Drainage

Accounting for drainage was considered an important factor in the water balance because of the free-draining soils with low DUL relative to annual rainfall, particularly at Ashley Dene. Maximum daily SWC was set at DUL and water in excess of this was considered drainage.

6.2.2 Crop water use

Water use was partitioned into transpiration by the canopy (E_T) and soil evaporation (E_s) (Ritchie, 1972). Brown (2004) showed the importance of accounting for E_s with up to 30% of annual rainfall being lost as E_s from dryland lucerne in this environment. The loss would be expected to increase with slow developing crop canopies such as those for seedling lucerne and crops grown on the low PAWC soils at Ashley Dene in the present study.

6.2.2.1 Soil evaporation (E_s) model

Brown (2004) evaluated four methods of calculating soil evaporation for lucerne grown at Iversen Field and showed the Ritchie calculation modified to account for soil drying by crop roots gave the most accurate description of E_s (Brown *et al.*, 2004).

This Ritchie method calculates E_s in two stages; Stage 1 (E_{s1}) is energy limited and is driven by EP which is adjusted for ground cover (Equation 6.6);

Equation 6.6
$$E_{s1} = EP * (1-R/R_o) \quad \text{when } \sum E_s \leq U$$

Ground cover ($1-R/R_o$) was calculated from LAI data (Beer's Law; Equation 2.3) and extrapolated to daily values from fitted logistic curves to LAI measurements for each growth period. E_s is summed daily and E_{s1} is shifted to Stage 2 (E_{s2}) when $\sum E_s$ exceeds U and E_s is assumed to be diffusion limited (Equation 6.7);

Equation 6.7
$$E_{s2} = \alpha * t^{1/2} \quad \text{when } \sum E_s > U$$

Where t is time (days) and U and α are soil texture properties of 9 mm and 4.4 mm/day^{-1/2} reported for a silt loam soil (Jamieson *et al.*, 1995a), similar to that of Iversen Field. The literature did not provide values for a soil containing a high (30%) stone content such as that at Ashley Dene, but it was assumed that the soil fraction, which holds the soil water, has a similar texture and therefore the reported values are appropriate for both soil types. Rainfall is subtracted from $\sum E_s$ and t declines to account for the subsequent increase in E_s (Equation 6.8);

Equation 6.8
$$t = [(\sum E_s - U)/\alpha]^2$$

A limitation of the Ritchie Method is that it does not account for crop water use in the topsoil. Crops use water preferentially from the uppermost soil layer, and only extract water from the deeper layers when water demand exceeds that supplied (Sheaffer *et al.*, 1988; Brown *et al.*, 2009). This results in an overestimation of E_s , because when the crop extracts water in the top layer and the lower limit is reached, E_s ceases. To account for this, a water balance for the top layer (0-0.2 m) was run parallel to the E_s calculation. E_s occurred when the SWC content of the top layer was greater than the lower limit. The lower limit was found by the minimum SWC measured.

6.2.2.2 Validating the soil evaporation model

The E_s calculation was validated using measured SWC from the top layer (0-0.2 m) in fallow plots within each experiment. Measurements were made at Ashley Dene in the second season, from 15 October 2011 to 22 June 2012 and at Iversen 12 in the first season, 3 January 2011 to 9 December 2011. Measurements were made using TDR every 7 to 14 days (Section 6.2.1.2). Fallow plots received regular herbicide applications to prevent weed growth and consequent plant water extraction.

Observed data showed the SWC of the 0.2 m layer at Ashley Dene ranged from 27 mm (field capacity) to 14 mm and at Iversen 12, 35 mm at field capacity to 28 mm (Figure 6.2a and b). The E_s model had a RMSD (Section 6.2.6) of 4.2 mm (21% of the mean) and 4.7 mm (16% of the mean) when used to predict SWC at Ashley Dene and Iversen 12, respectively. The E_s model accounted for 84% of the variation of observed SWC

within the two sites (Figure 6.2c). Therefore, it appears to be sufficient in its current form to estimate soil evaporation within both experimental sites.

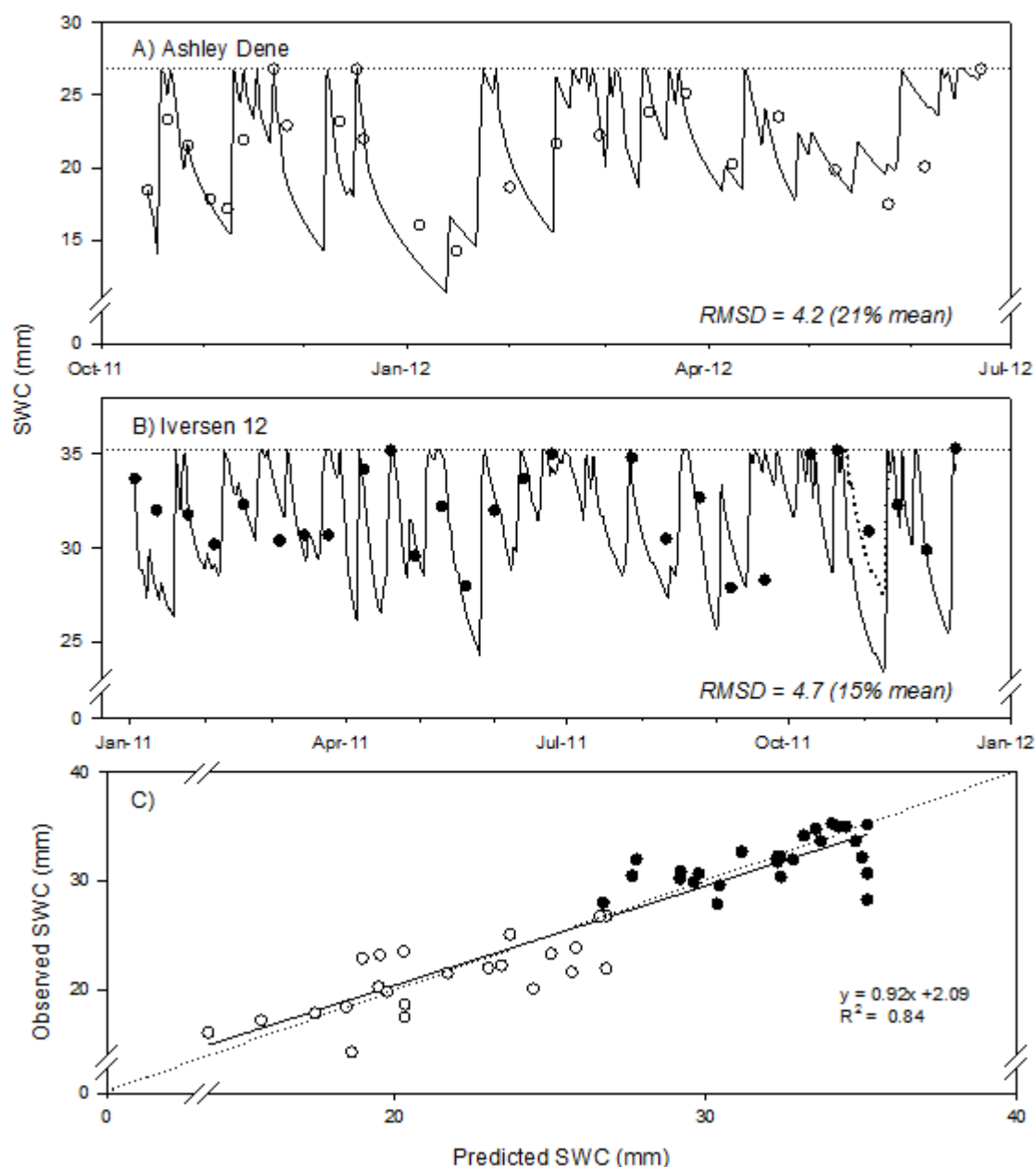


Figure 6.2 Comparison of measured (○●) and predicted (—) soil water content (SWC) for the 0-0.2 m soil layer of fallow treatments at Ashley Dene (A, ○) and Iversen 12 (B, ●), Lincoln University, Canterbury, New Zealand.

Note: Measured values from time domain reflectometry (TDR; 0-0.2 m). Predicted values calculated using Ritchie Method (Section 6.2.2.1). In Figure 6.2A and B (····) denotes drained upper limit. RMSD is root mean squared deviation. In Figure 6.2B VWC was modified (---) to account for four days of observed water ponding following a ~60 mm rainfall event when soil was already at DUL.

6.2.3 Patterns of water extraction

6.2.3.1 *Plant available water capacity*

Plant available water capacity (PAWC) was determined for each individual soil layer for each plot. PAWC was determined by the difference between DUL (Section 6.2.1.5) and the lower limit (LL) of water extraction PAWC. The LL to water extraction was identified as the lowest measured VWC.

6.2.3.2 *The model for water extraction*

The ‘Monteith framework’ (Monteith, 1986) was used to describe the pattern of water extraction for individual layers. Brown *et al.* (2009) validated this model for dryland lucerne for both seedling and regrowth lucerne in a deep silt loam soil consistent with that of Iversen 12. The present study compares the effects of soil type on seedling and regrowth lucerne water extraction patterns in the same season. To describe the SWC over time (SWC_t) a broken-stick model (Equation 6.9), which consisted of a switch function (S_c) from a linear phase, where SWC was constant prior to the start of extraction (t_c), followed by an exponential decrease in SWC_t to the lower limit (LL). The rate of extraction is described by the extraction decay constant ($-kl$). The model was fitted to 23 individual layers per plot.

Equation 6.9 $SWC_t = LL + PAWC \exp(-kl(t-t_c)S_c)$ $S_c = 0 \text{ if } t \leq t_c$

$$S_c = 1 \text{ if } t > t_c$$

Patterns of water extraction were analysed in the 2011/12 season which allowed the comparison of seedling and regrowth crops. For seedling crops models were fitted from sowing (10 October 2011) to maximum SWD which occurred on 24 May 2012. Water extraction was observed to start in early August 2011 for regrowth crops, however a large rainfall event returned SWC to DUL on 21 October 2011. Models were fitted from this point to maximum SWD which occurred on 16 January 2012 and 25 May 2012 at Ashley Dene and Iversen 12, respectively.

6.2.3.3 *Extraction front velocity*

Crops display a consistent pattern of water extraction from the uppermost soil layer, which moves progressively down the profile, indicated by t_c (Equation 6.9) as the soil dries (Monteith, 1986). The rate at which water is extracted down the soil profile is defined as the extraction front velocity (EFV; mm/day) and is the slope of the linear regression of t_c for individual soil layers over time. The effect of PAWC on seedling and regrowth lucerne EFV in the same season will be examined.

6.2.4 **Water use efficiency**

Water use efficiency (WUE; kg DM/ha/mm) was calculated from the slope of the linear regression of accumulated shoot DM and crop water use over the same period. The regressions were fitted to annual and individual regrowth cycle DM yields. Seasonal WUE results are presented for the mid-point of each regrowth period. In the second season, 2011/12 the extraction front reached the maximum measurement depth (2.3 m) in the third regrowth phase at Ashley Dene and the fourth at Iversen 12. The consequence of this was crop WU was underestimated because any water extracted below this depth could not be accounted for, which would therefore increase apparent WUE. Extra crop WU was added for these periods, up to maximum SWD to maintain the WU/EP ratio of the individual regrowth phase (WUE was assumed constant for individual regrowth cycles). The amount of water added differed with treatment. On average it was assumed lucerne extracted a further 10-15 mm and 40-50 mm of water beyond 2.3 m at Ashley Dene and Iversen 12, respectively. The maximum depth of extraction was calculated by the assumption the DUL and LL of the layers below were consistent with the 2.3 m soil layer and the rate of crop water extraction, EFV (Figure 6.8) and $-k_l$ (Figure 6.9) were consistent for each crop. Maximum depth of water extraction were ~2.5 m and ~2.7 m at Ashley Dene and Iversen 12, respectively.

6.2.5 Quantifying the effect of water stress

Water stress was quantified as the ratio between water supply and demand (E_T/EP_T) (Jamieson *et al.*, 1998; Robertson *et al.*, 2002; Brown *et al.*, 2009). Water supply was quantified as crop transpiration (E_T), calculated from the soil water balance, accounting for WU losses not associated with transpiration (soil evaporation and drainage). Crop water demand (EP_T) was calculated by multiplying daily Penman evapotranspiration by crop cover (French and Legg, 1979). An E_T/EP_T value of 1.0 ($E_T = EP_T$) shows no water limitations to the crop, as water stress increases, transpiration decreases in relation to water supply, reducing E_T/EP_T . Mean E_T/EP_T was calculated for each regrowth phase and then compared in relation with yield forming processes to determine the effect of water stress on crop canopy development and growth. This framework was applied to second year crops only. Extractable water for crops in the establishment season depends on root growth down the soil profile which would influence water supply and therefore potential stress.

To allow the comparison of the effect of water stress on the components which determine yield the effect of water stress needed to be isolated from other environmental influences such as temperature and photoperiod.

6.2.5.1 Water stress in relation to canopy development

To account for differences in mainstem leaf appearance rate throughout the season in response to photoperiod (Figure 5.7) the phyllochron for individual regrowth periods was quantified in relation to the predicted phyllochron. The predicted phyllochron was attained from fully irrigated 'Kaituna' lucerne grown in the same environment as the present study as displayed in Figure 2.5. The photoperiod at the start of each regrowth period was used to predict the non-water limited phyllochron.

The maximum rate of branching throughout the season has not been quantified in the literature. Brown *et al.* (2005b) showed irrigated 'Kaituna' lucerne displayed a maximum branching rate of 2.5 axillary leaves per mainstem node in mid-summer, but was also possibly a function of stem population which has been shown in annual crops (Hay and Walker, 1989). Therefore, branching is presented as axillary leaves per

mainstem node, which accounts for seasonal temperature and photoperiodic influences on mainstem node appearance, which was shown to affect branching rate (Figure 5.8). There may be further influences, such as stem population which are not accounted for.

6.2.5.2 *Water stress in relation to LAER*

LAER data were presented as a function of predicted maximum LAER which was reported by Teixeira *et al.* (2009) for irrigated ‘Kaituna’ lucerne in the same environment as the present research and is displayed in Figure 2.4. Maximum LAER is $0.016 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$, but is regulated by daylength when Pp is $<12.5 \text{ h}$. Predicted LAER is determined by the Pp at the start of each individual regrowth phase.

6.2.5.3 *Water stress in relation to RUE_{shoot}*

Seasonal maximum RUE_{shoot} was determined by the assumption RUE_{total} is 1.6 g DM/MJ which is regulated by air temperature below 18°C (Figure 2.6). The fraction of RUE_{shoot} was then determined by accounting for the partitioning of DM below ground which is described in relation to Pp (Figure 2.7a). The partitioning coefficient was determined for irrigated ‘Kaituna’ lucerne grown in the same environment as the present study, defoliated every 42 days. The limited dataset of root DM collected in the present study agrees with the proposed relationship for crops grown at Iversen 12, however for crops at Ashley Dene the partitioning fraction was set at 0.50 based on Figure 4.12.

6.2.6 **Statistics**

The soil evaporation model Section 6.2.2.2 was validated by comparing the predicted and observed data using the root mean squared deviation (RMSD) as in Equation 6.10 (Kobayashi and Salam, 2000);

Equation 6.10

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (m_i - s_i)^2}$$

Where n is the number of measurements, m_i is the measured value for observation i and s_i is the simulated value for observation i .

Models of water extraction described in Equation 6.9 were fitted by non-linear regression. Models were accepted as having accurately predicted SWC when $R^2 > 0.75$. When models failed and a systematic change in SWC was observed, which indicated extraction by plant roots, both the LL and PAWC parameters were set from calculated values (Section 6.3.1.2) and the model rerun. All regressions were fitted (Draper and Smith, 1998) with GENSTAT (version 14.1) (Lawes Agricultural Trust, IACR, Rothamsted, U.K.).

6.3 Results

6.3.1 Soil water deficit and plant available water capacity

6.3.1.1 *Soil water deficit*

During the establishment season (2010/11) all crops had an initial soil water deficit (SWD) of ~50 mm at sowing, except for the February sown crop at Iversen 12 when SWD increased to ~100 mm (Figure 6.3). Following sowing, WU exceeded rainfall until the maximum SWD was reached for the establishment season on 25 March 2011 for both Ashley Dene and Iversen 12. The maximum SWD differed ($P < 0.001$) among sowing dates, with the maximum SWD at Ashley Dene of ~100 mm occurring in October to December sown crops, compared with 320 mm in the October sown crop at Iversen 12 (Table 6.1). The SWD was reduced to zero (field capacity) during the winter period; late July at Ashley Dene and a month later at Iversen 12. Field capacity was reached again at both sites on the 21 October following a 60 mm rainfall event (Figure 3.2). The October sown crop at Iversen 12, which had the largest SWD during the establishment year, was the only treatment not to return to field capacity with a minimum SWD of 45 mm (Figure 6.1).

In the second year, SWD steadily declined until the maximum deficit was reached at Ashley Dene on 16 January compared with 24 May 2012 at Iversen 12. Sowing date did not affect ($P > 0.12$) maximum SWD with mean values of 130 mm at Ashley Dene and 336 mm at Iversen 12 (Figure 6.3).

Table 6.1 Maximum soil water deficit (mm) of dryland lucerne measured in the establishment (2010/11) and second (2011/12) growth season at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Sowing date	<u>Ashley Dene</u>		<u>Iversen 12</u>	
	Establishment	Year two	Establishment	Year two
October	108 _a	128	320 _a	361
November	99 _a	129	269 _b	331
December	99 _a	138	221 _c	324
January	84 _b	131	143 _d	322
February	59 _c	125	151 _d	343
Mean	90	130	221	336
P	<0.001	ns	<0.001	ns
SEM	4.15	5.65	8.46	10.7

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$). SEM = standard error of the mean, ns = not significant.

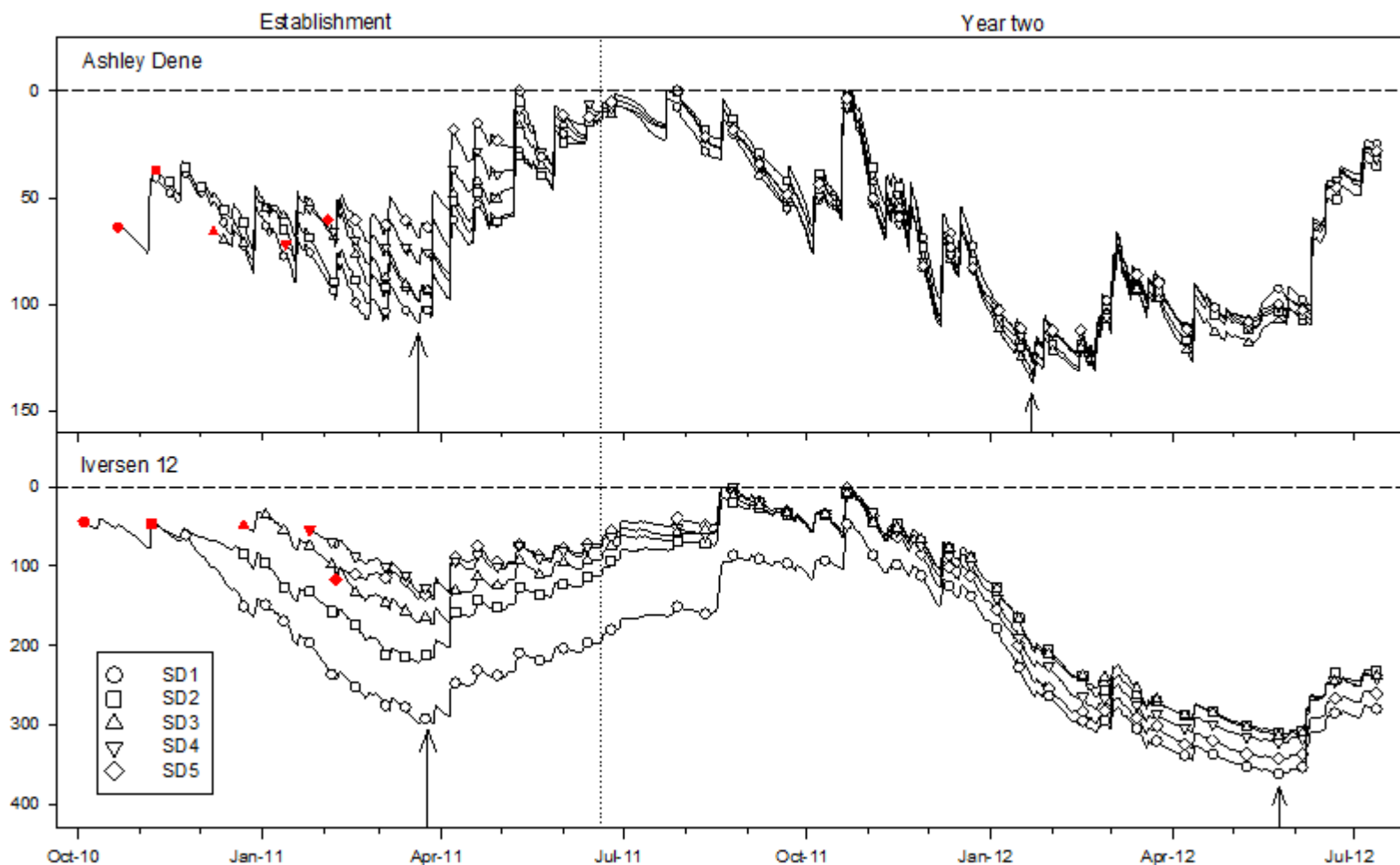


Figure 6.3 Soil water deficit to 2.3 m from October 2010 to July 2012 for dryland lucerne sown on five dates at Ashley Dene and Iversen 12 Lincoln, University, Canterbury, New Zealand.

Note: Red points show sowing date for each treatment. Arrows indicate date of maximum soil water deficit in the establishment and second year.

6.3.1.2 *Plant available water capacity and extracted water*

The plant available water capacity (PAWC) and extraction pattern of soil water at maximum SWD for the seedling phase (sowing to 50% flowering), establishment and second season of growth are displayed in Figure 6.4 for crops grown at Ashley Dene, and Figure 6.5 for Iversen 12 crops. The extractable water during the seedling phase differed ($P<0.05$) with sowing date at Ashley Dene. October to January sown crops had the highest extractable water of 86 ± 4.3 mm, compared with 59 mm, 30% less for the February sown crop. Sowing date did not affect ($P<0.32$) the extractable water for crops grown in Iversen 12 with a mean of 149 ± 7.6 mm being extracted. Crops at both sites extracted water to ~1.5 m in the seedling phase. Further water extraction in the establishment season following the seedling phase occurred for the first three sowing dates at both sites. The October sown crops at Iversen 12 extracted a further 160 ± 8.5 mm compared with 33 mm for the same sowing date at Ashley Dene, both to a depth of ~1.6 m.

In the second season sowing date did not affect ($P>0.22$) PAWC, with lucerne extracting 130 mm at Ashley Dene and 336 mm at Iversen 12. The pattern of soil water extraction was influenced by site with 50% of the total PAW being extracted in the top 0.5 m at Ashley Dene compared with only 25% of total PAW at Iversen 12 to the same depth. Below 1.5 m lucerne extracted ~30 mm/m at Ashley Dene compared with ~130 mm/m at Iversen 12. DUL was greater than LL at the maximum depth of measurement therefore it is assumed crops at both sites extracted water to an estimated depth of 2.4 m and 2.7 m at Ashley Dene and Iversen 12, respectively (Section 6.2.4).

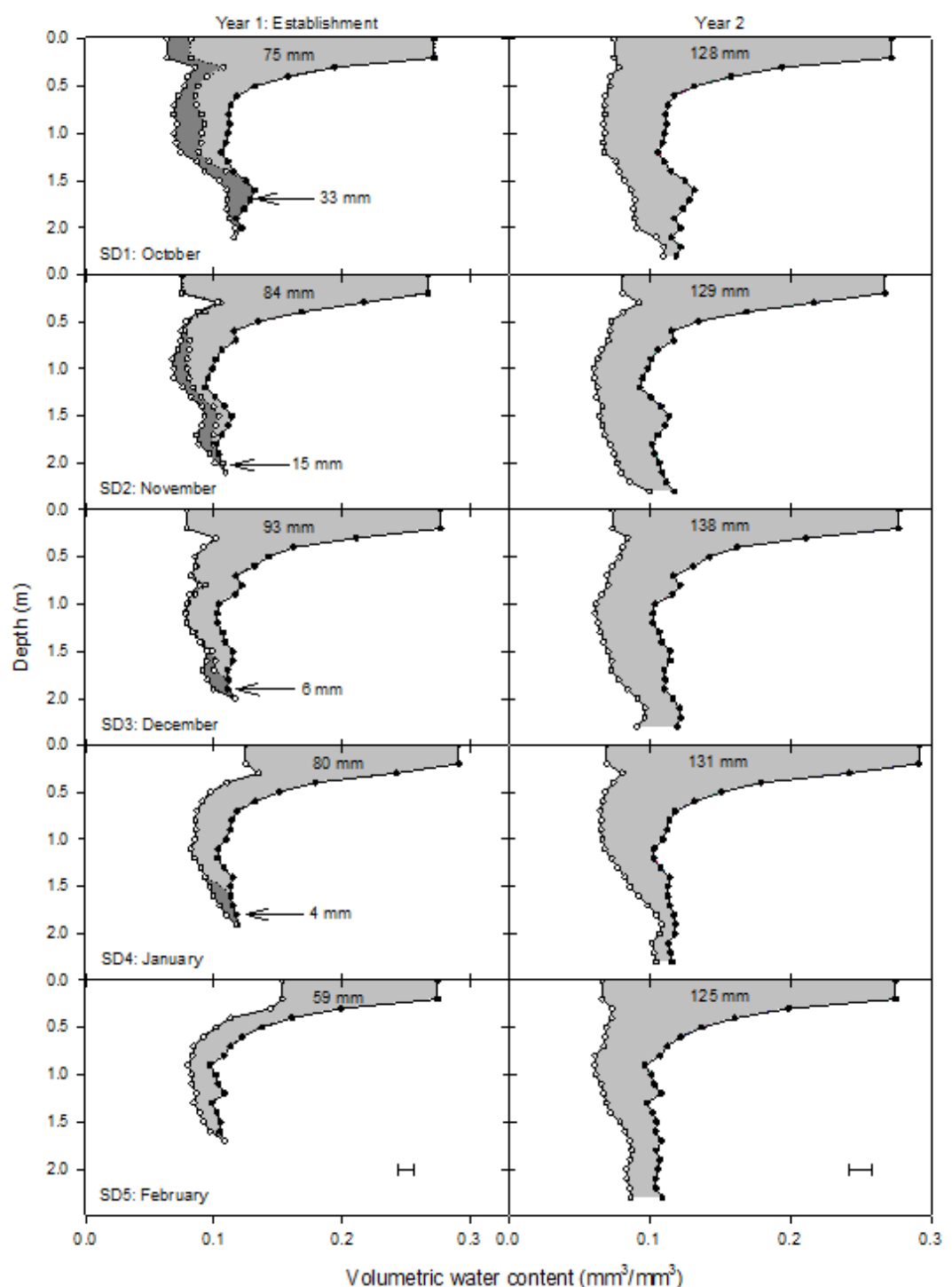


Figure 6.4 Upper (●) and lower (○) limits of lucerne water extraction measured in the establishment (2010/11) and subsequent (2011/12) year sown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Shaded area and numbers represent the plant available water capacity. In the establishment year, ■ represents extraction for the initial seedling crop and ■ is further extraction in the subsequent regrowth phases in the establishment season (total water extraction for the establishment year is ■ + ■).

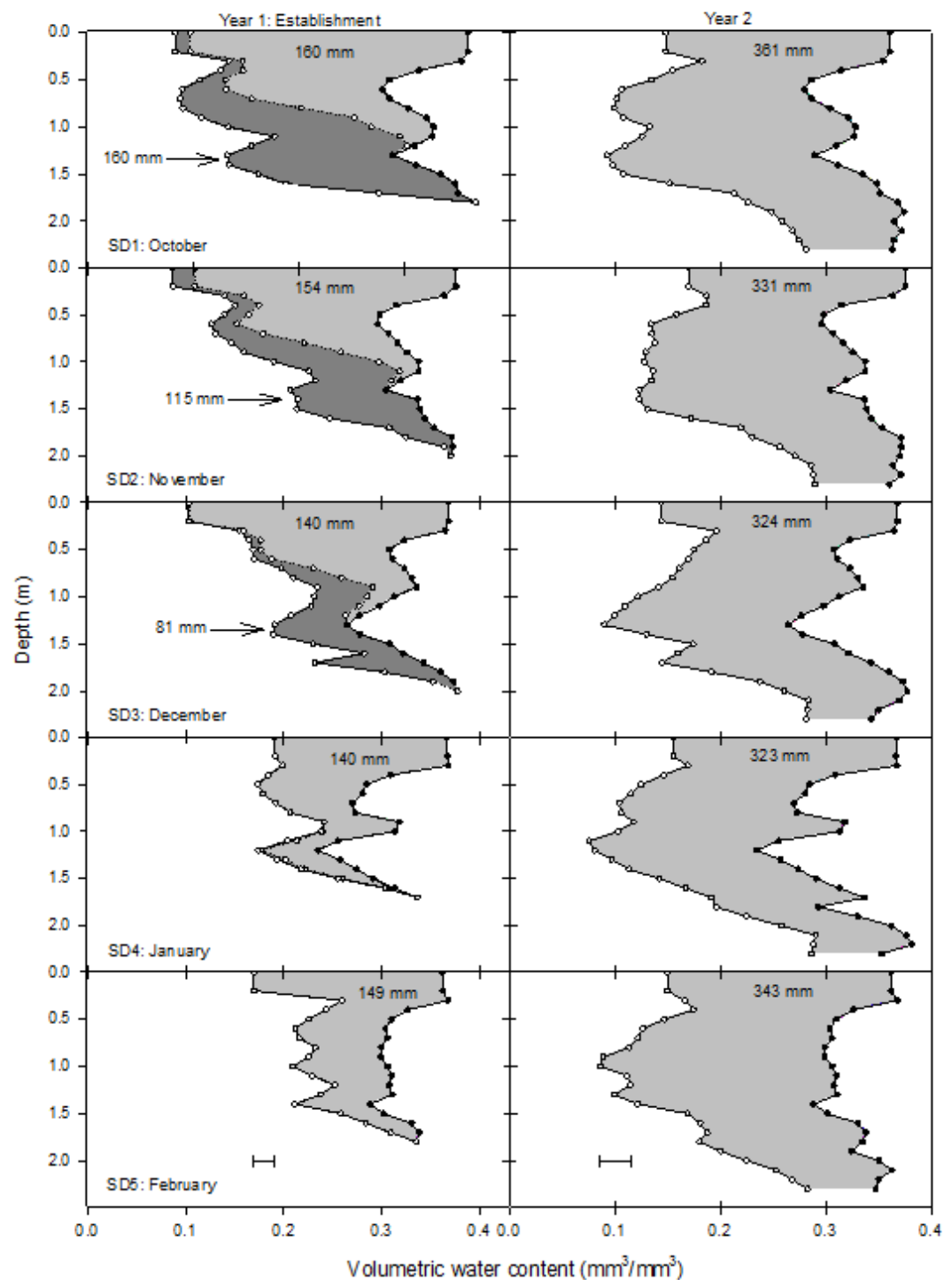


Figure 6.5 Upper (●) and lower (○) limits of lucerne water extraction measured in the establishment (2010/11) and subsequent (2011/12) year sown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Shaded area and numbers represent the plant available water capacity. In the establishment year, ■ represents extraction for the initial seedling crop and ■ is further extraction in the subsequent regrowth phases in the establishment season (total water extraction for the establishment year is ■ + ■).

6.3.1.3 *Seasonal extraction pattern*

The pattern of water extraction for six representative individual soil layers is shown in Figures 6.6 and 6.7 for second year lucerne at Ashley Dene and Iversen 12, respectively. The model (Equation 6.9) gave an accurate description of the change in SWC with a mean R^2 of 0.88 (range 0.65 to 0.99) at Ashley Dene and 0.95 (range 0.75 to 0.99) at Iversen 12, for 144 curves fitted at both sites. Extraction began in the 0.25 m soil layer on the 25 October 2011 at both sites. Extraction was initiated in the lowest measured layer (2.25 m) on 23 December 2011 at Ashley Dene, 80 days earlier ($P < 0.001$) than at Iversen 12.

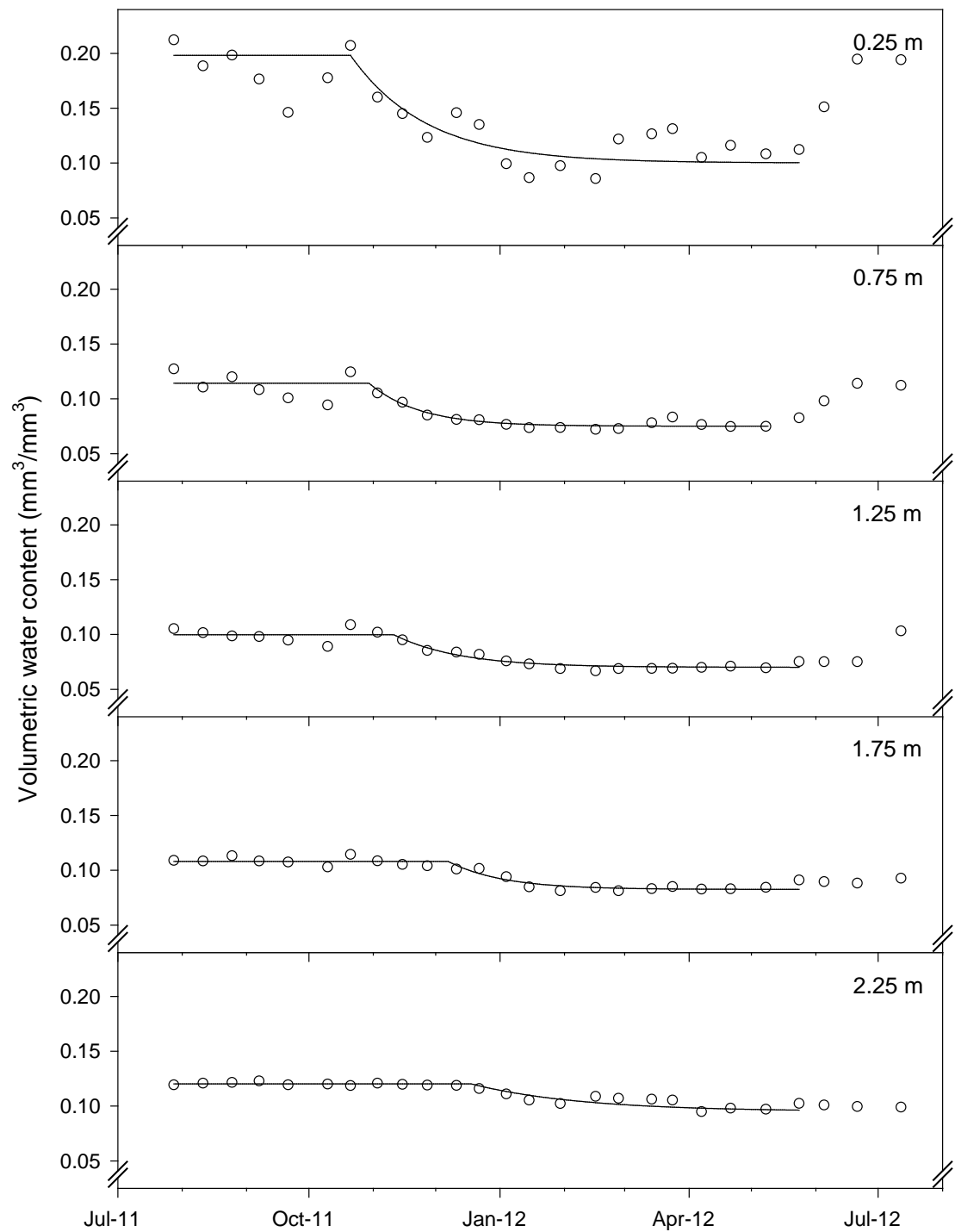


Figure 6.6 Water extraction patterns at five 0.1 m soil layers for a dryland lucerne crop in the second season from August 2011 to July 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

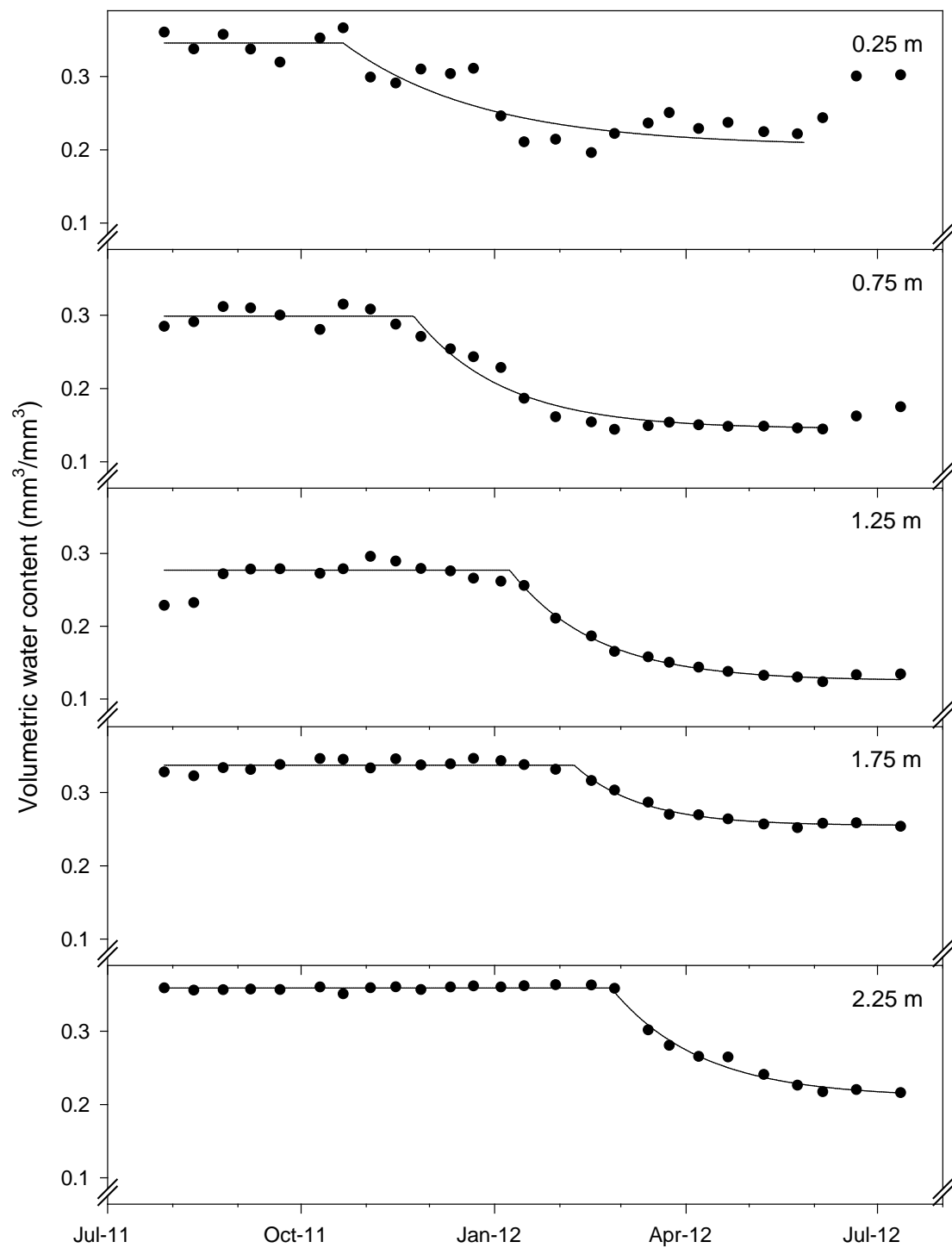


Figure 6.7 Water extraction patterns at five 0.1 m soil layers for a dryland lucerne crop in the second season from August 2011 to July 2012 at Iversen 12, Lincoln University, Canterbury, New Zealand.

6.3.1.4 *Extraction front velocity*

The extraction front velocities (EFV) for lucerne establishment and regrowth were compared in the 2011/2012 season. To do this, the extraction patterns were compared between sowing date 6 (sown 10 October 2011) and sowing date one, which had been sown October 2010 and was in its second year of growth. The EFV for lucerne establishment and regrowth differed ($P < 0.05$) between sites. EFV for crops in the establishment phase was 15.1 mm/day at Ashley Dene (Figure 6.8a) compared with 12.9 mm/day at Iversen 12 (Figure 6.8b). The EFV of establishing crops at Ashley Dene displayed a weaker ($R^2 = 0.68$) linear decline over time compared with those at Iversen 12 ($R^2 = 0.95$). Logistic regression improved the relationship of extraction depth over time ($R^2 = 0.74$; data not shown) at Ashley Dene as there was evidence of a lag period from sowing to early December (0.4 mm/day), followed by rapid extraction down the soil profile (~50 mm/day) and then a similar lag period. Crops at both Ashley Dene and Iversen reached maximum extraction depth in late February 2012.

The EFV in the second season was 32.6 mm/day ($R^2 = 0.97$) at Ashley Dene (Figure 6.8c) compared with 14.2 mm/day at Iversen 12 ($R^2 = 0.97$) (Figure 6.8d). The EFV reached the maximum depth of measurement (2.25 m) on 23 December 2011 at Ashley Dene and 11 March 2012 at Iversen 12.

The extraction rate constant, $-k_l$ varied over the depth of the profile and differed ($P < 0.001$) between sites. The mean $-k_l$ was 0.043/day at Ashley Dene or double that of Iversen 12 (Figure 6.9). The $-k_l$ at Iversen 12 ranged from 0.012 to 0.042/day compared with that of Ashley Dene which ranged from 0.023 to 0.065/day.

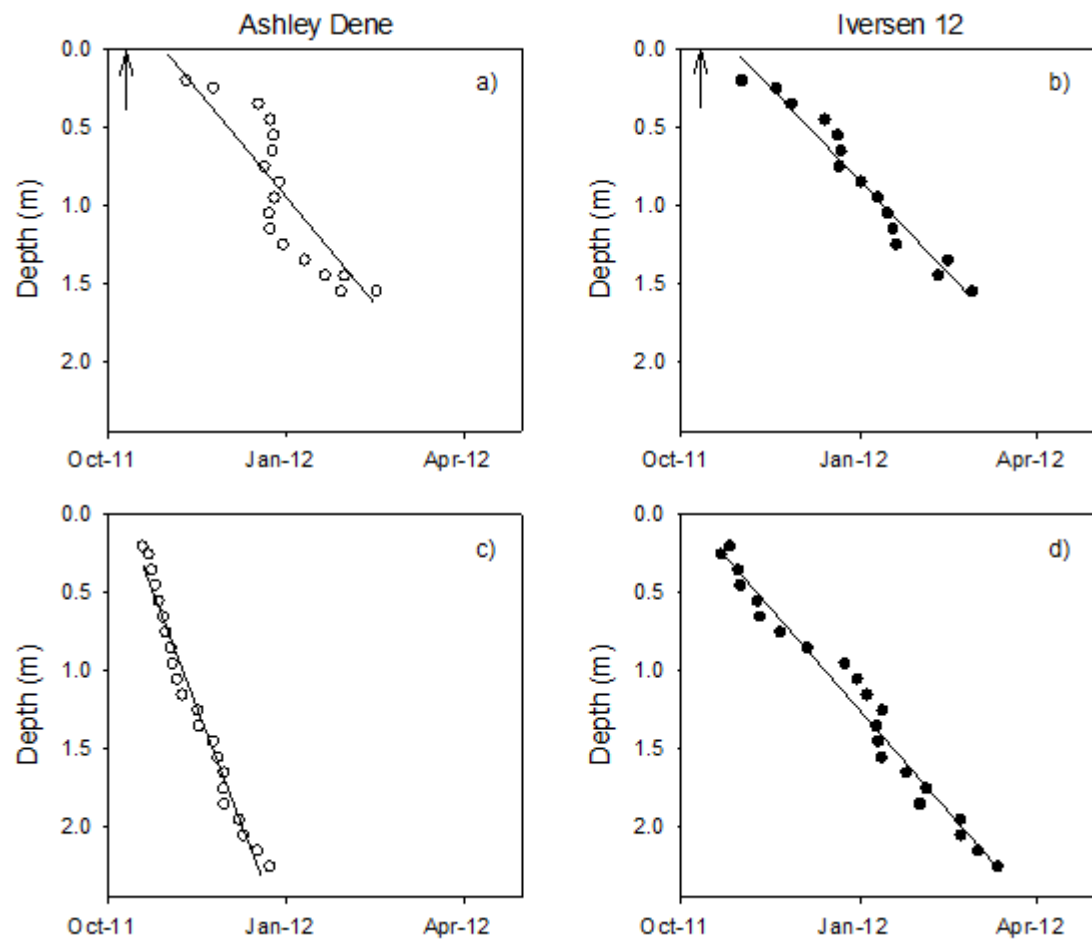


Figure 6.8 Time of water extraction (t_c) for each individual soil layer for seedling (a,b) and regrowth (c,d) dryland lucerne at Ashley Dene (○) and Iversen 12 (●) for the 2011/12 season at Lincoln University, Canterbury, New Zealand.

Note: Start times were 10 October and 21 October 2011 for seedling and regrowth crops, respectively.

Slopes: a) -15.1 mm/d , $R^2 = 0.68$. b) -32.6 mm/d , $R^2 = 0.97$. c) -12.9 mm/d , $R^2 = 0.95$. d) -14.2 mm/d , $R^2 = 0.97$. Arrows mark the sowing date.

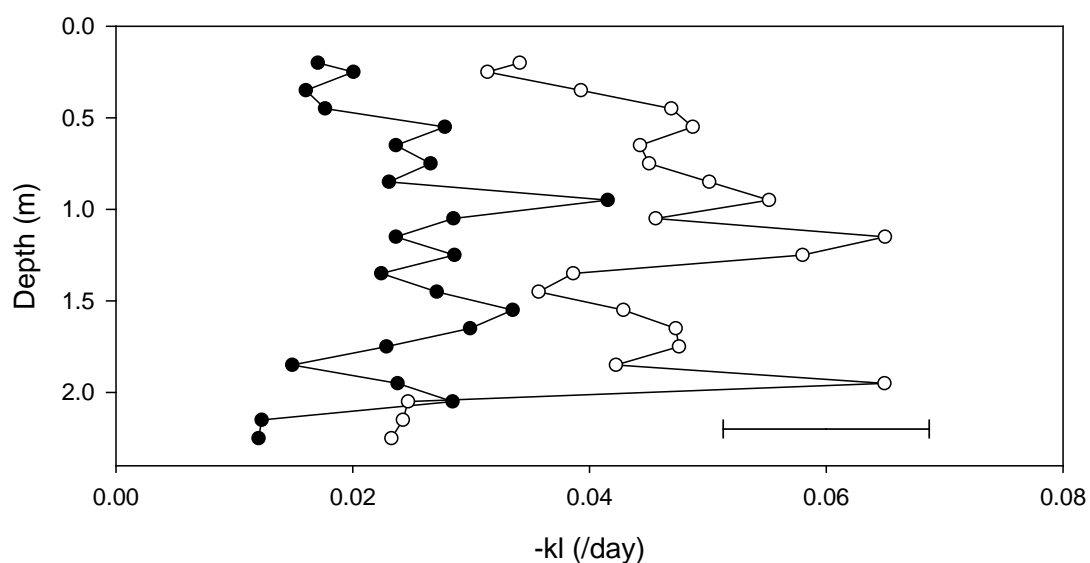


Figure 6.9 Extraction decay constant ($-kl$) of second year dryland lucerne over a 2.25 m soil profile at Ashley Dene (○) and Iversen (●) in the 2011/12 season at Lincoln University, Canterbury, New Zealand. Error bar represent l.s.d ($P = 0.05$).

6.3.2 Water use and yield

6.3.2.1 Water use efficiency

Total accumulated WU in relation to DM for the entire 22 month measurement period (October 2010 to July 2012) is displayed in Figure 6.10. On average, crops grown at Ashley Dene used 365 mm, or 60% less than those at Iversen 12. Sowing date affected ($P < 0.001$) WU with the October sown crop at Ashley Dene using 402 mm of water, 24% more than the February sown crop. At Iversen 12, the October sown crop used 1106 mm, 33% more than the February sown crop. The efficiency of DM production in relation to WU, water use efficiency (WUE: kg DM/ha/mm) was constant ($P > 0.57$) among sowing dates at Ashley Dene with a mean WUE of 22.0 kg DM/ha/mm. WUE differed with sowing date ($P < 0.001$) at Iversen 12 with October to December sown crops producing 31.7 kg DM/ha/mm compared with the two later sowing dates at 25.1 kg DM/ha/mm, or 21% less. The cumulative data showed a strong relationship ($R^2 > 0.98$) between WU and DM. However, at times points systemically fell above or below the regression line, which suggests WUE was not constant. This relationship was tested for lucerne crops for each season, and then for each individual regrowth phase.

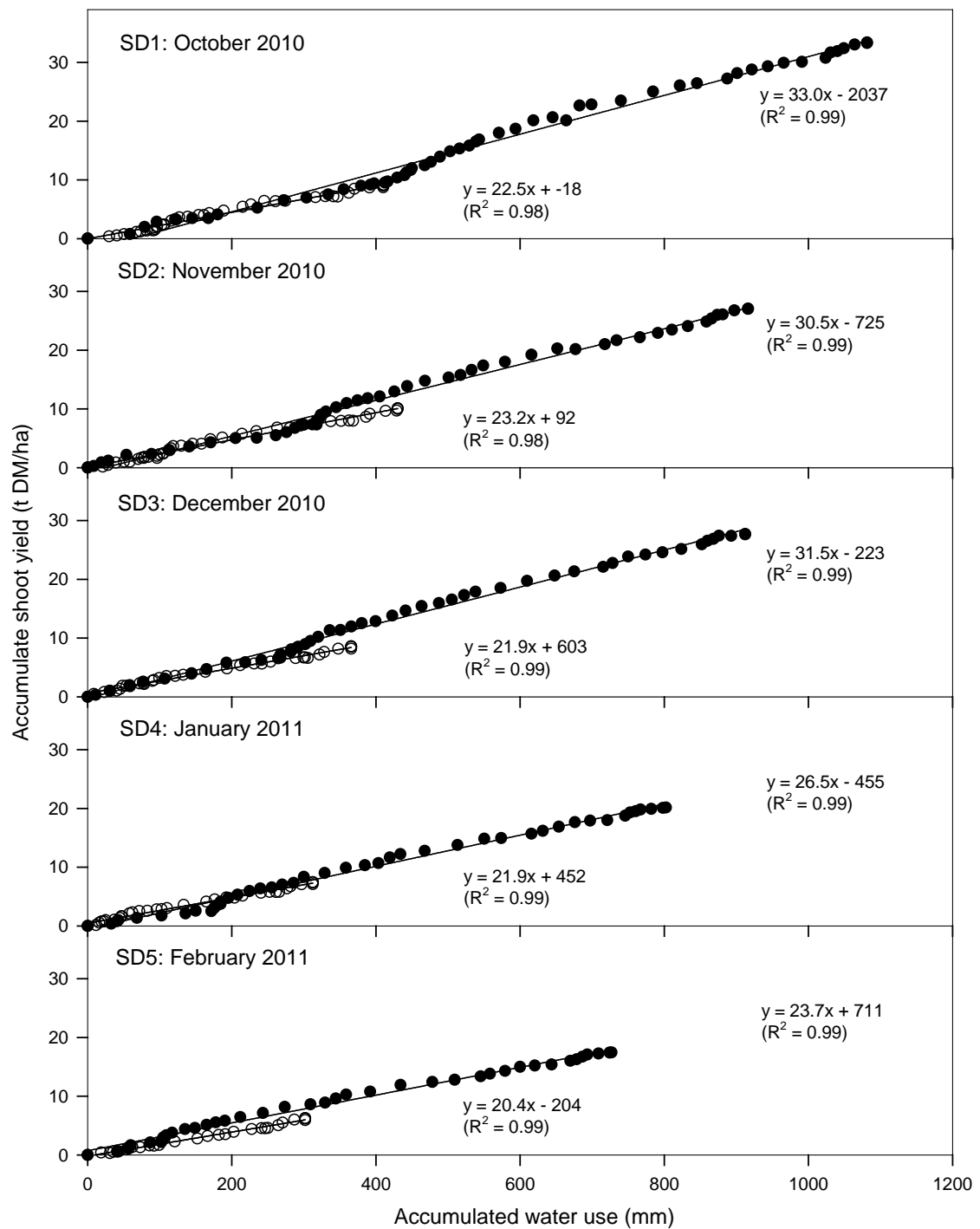


Figure 6.10 Accumulated shoot yield in relation to accumulated water use for lucerne crops sown on five dates at Ashley Dene (○) and Iversen 12 (●) for both the establishment (2010/11) and subsequent growth season (2011/12) at Lincoln University, Canterbury, New Zealand.

In the establishment season, crop WU was the highest ($P<0.001$) at Ashley Dene in the crops sown in October and November (101 mm), which decreased by ~50% when sowing was delayed until February (Table 6.2). This later sown crop also had the lowest WUE of 12.4 kg DM/ha/mm compared with a mean of 24.0 kg DM/ha/mm. In the following season, crops that had been sown up to the previous December had a WU of ~300 mm, compared with 270 mm when sowing had been delayed. Mean WUE in the second season was 20.1 kg DM/ha/mm, consistent with the long-term result above.

Table 6.2 Seasonal accumulated water use (WU; mm) and water use efficiency (WUE; kg DM/ha/mm) for lucerne sown on five dates in the establishment (sowing to June 2011) and second year (June 2011 to July 2012) at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Sowing date	Establishment		Year two	
	WU	WUE	WU	WUE
October	98 _{ab}	26.5 _{ab}	304 _a	20.1
November	104 _a	23.5 _b	311 _a	20.4
December	87 _b	25.9 _{ab}	287 _{ab}	18.9
January	54 _c	28.5 _a	268 _b	21.4
February	47 _c	15.4 _c	262 _b	19.6
Mean	78	24.0	286	20.1
P	<0.001	<0.05	<0.05	ns
SEM	5.0	2.43	10.1	1.11

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$). SEM = standard error of the mean, ns = not significant.

At Iversen 12, delayed sowing from October to February during the establishment year reduced WU from 463 mm to 118 mm (Table 6.3). WUE was conservative except for the January sown crop which had the lowest value of 19.9 kg DM/ha/mm. Sowing date

did not affect WU in the second year (623 mm), although WUE differed ($P<0.001$). Crops which had been sown up to the previous December displayed a WUE of ~29.8 kg DM/ha/mm, compared with 23.6 kg DM/ha/mm, 20%, less when sowing later than this.

Table 6.3 Seasonal accumulated water use (WU; mm) and water use efficiency (WUE; kg DM/ha/mm) for lucerne sown on five dates in the establishment (sowing to June 2011) and second year (June 2011 to July 2012) at Iversen 12, Lincoln University, Canterbury, New Zealand.

Sowing date	Establishment		Year two	
	WU	WUE	WU	WUE
October	463 _a	24.5 _a	643	31.3 _a
November	320 _b	22.4 _a	605	28.9 _a
December	299 _b	25.9 _a	619	29.3 _a
January	191 _c	19.9 _b	620	25.1 _b
February	118 _d	24.1 _a	628	22.0 _b
Mean	278	23.4	623	27.3
P	<0.001	<0.05	ns	<0.001
SEM	15.0	1.68	15.2	1.63

Note: Means within a column with different letters are significantly different (l.s.d $\alpha=0.05$). SEM = standard error of the mean, ns = not significant.

Analysis of individual regrowth phases showed WUE differed ($P<0.001$) seasonally among sowing dates. Seedling lucerne had a WUE of 13 to 32 kg DM/ha/mm (Figure 6.11). At Ashley Dene WUE in the second season was constant for the first two regrowth cycles at 22 kg DM/ha/mm but, decreased to 13 kg DM/ha/mm for the third regrowth cycle which occurred during mid-summer. WUE then increased two fold for

the fourth cycle. At Iversen 12 maximum WUE occurred during the first regrowth cycle (44 kg DM/ha/mm) which then decreased linearly by half by the fifth cycle, which occurred during mid-summer. WUE then increased to 40 kg DM/ha/mm in April before decreasing again for the last cycle. Sowing date in the establishment season affected WUE ($P < 0.001$) in the subsequent season with crops sown before the previous December consistently having a 25% higher WUE than later sown crops. This was apparent throughout year two at Iversen 12, however was only evident at Ashley Dene in the first regrowth cycle of year.

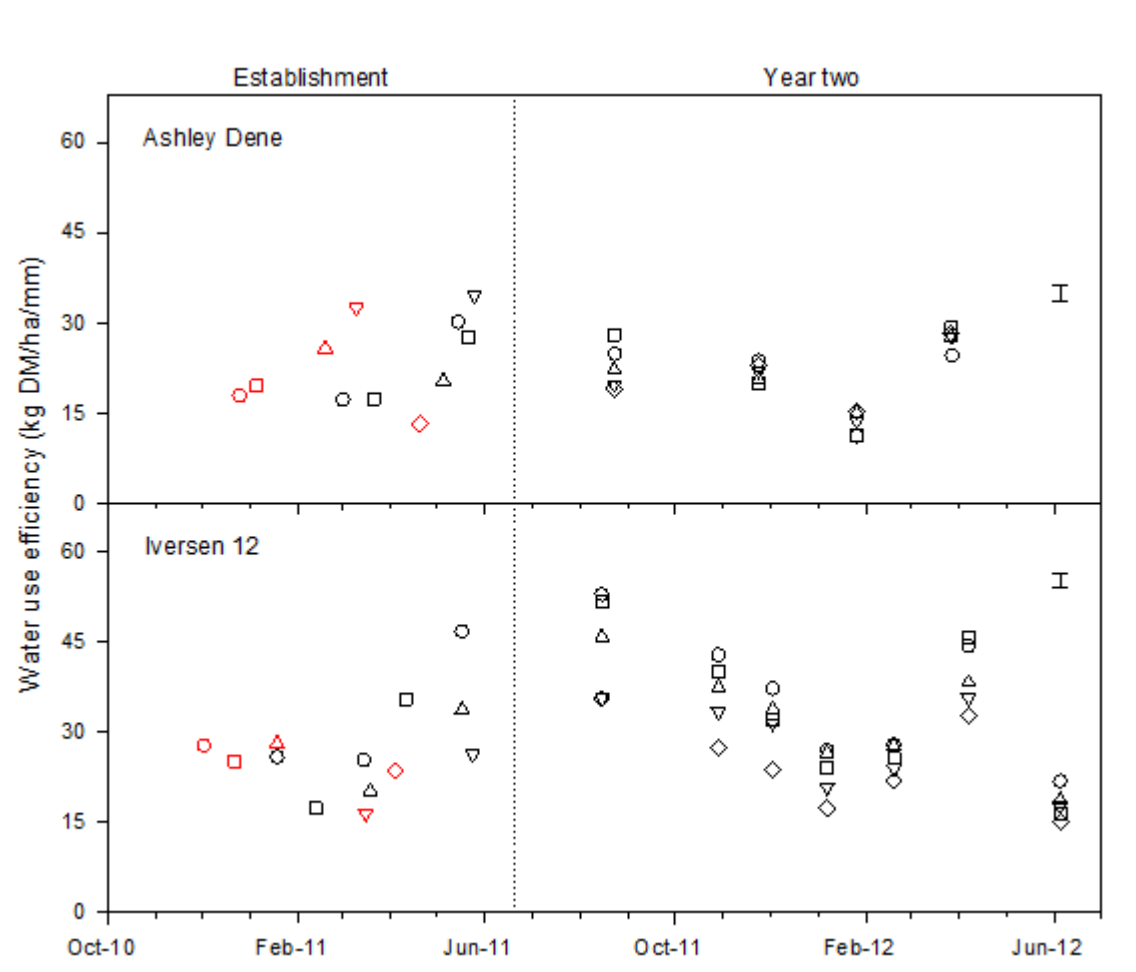


Figure 6.11 Water use efficiency of lucerne sown on five dates; October (○), November (□), December (△), January (▽) and February (◇) at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: Seedling crops are presented in red. Bar represents pooled l.s.d ($P = 0.05$) of WUE.

6.3.3 Water limitations and yield

6.3.3.1 *Quantifying water stress*

Water stress was quantified as transpiration (E_T) from measured SWC in relation to transpiration demand (EP_T), which was daily EP_T multiplied by canopy cover. For crops at Ashley Dene E_T/EP_T was always less than 1.0, which indicates crops were water stressed for all regrowth phases (Figure 6.12a). E_T/EP_T ranged from 0.70 in the first two regrowth phases to 0.17 in the fifth regrowth phase. E_T/EP_T for crops at Iversen 12 varied from 1.10 in the fourth regrowth phase to 0.66 in the final two phases (Figure 6.12b). Water stress was evident in the third regrowth phase when crop E_T was 75% of demand, but the following two regrowth cycles $E_T > 1.0$ which indicates no water stress. EP_T for these regrowth phases may have been underestimated due to water stress in the previous phase causing a reduction in canopy size, and therefore lower EP_T . This will need to be investigated when LAER is related to water stress (Section 6.3.3.4).

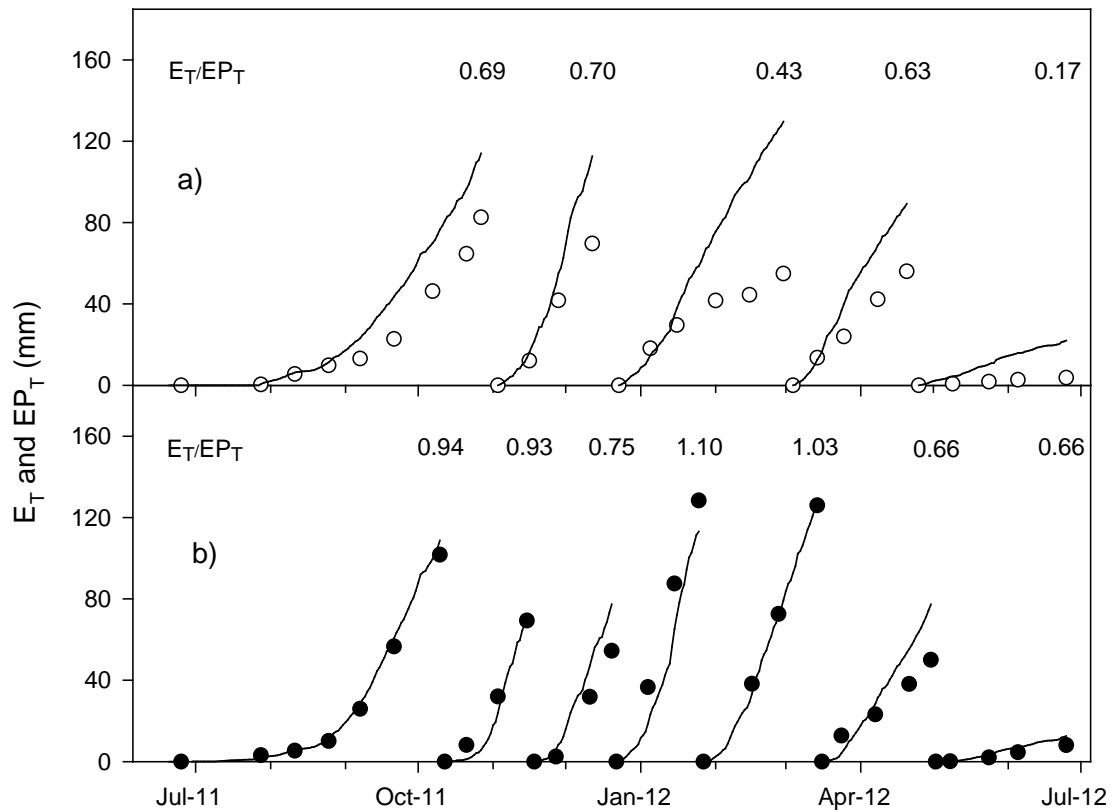


Figure 6.12 Transpiration (E_T) from dryland lucerne grown at Ashley Dene (a; \circ) and Iversen 12 (b; \bullet) compared with transpiration demand (EP_T ; —) from June 2011 to July 2012, Lincoln University, Canterbury, New Zealand. Values above each regrowth period quantify transpiration relative to transpiration demand (E_T/EP_T).

6.3.3.2 Critical limiting deficit

The occurrence and timing of water stress was examined for regrowth lucerne by the relationship between E_T/EP_T and SWD to determine the critical limiting deficit (D_L), the SWD when water stress occurred (Figure 6.13). Data from Ashley Dene showed the theory of critical deficit was unsuitable for this soil type. E_T/EP_T did not reach 1.0, with a maximum of 71% of crop water demand supplied by the soil when the SWD was $< 81 \text{ mm} \pm 18 \text{ mm}$. E_T/EP_T decreased to 0.2 when the SWD increased up to 120 mm. Analysis of data from Iversen 12 suggests the critical deficit could be determined and water stress occurred when $E_T/EP_T < 1.0$. The D_L was $243 \pm 42 \text{ mm}$, beyond this level the E_T/EP_T was reduced by 0.005 per mm of SWD.

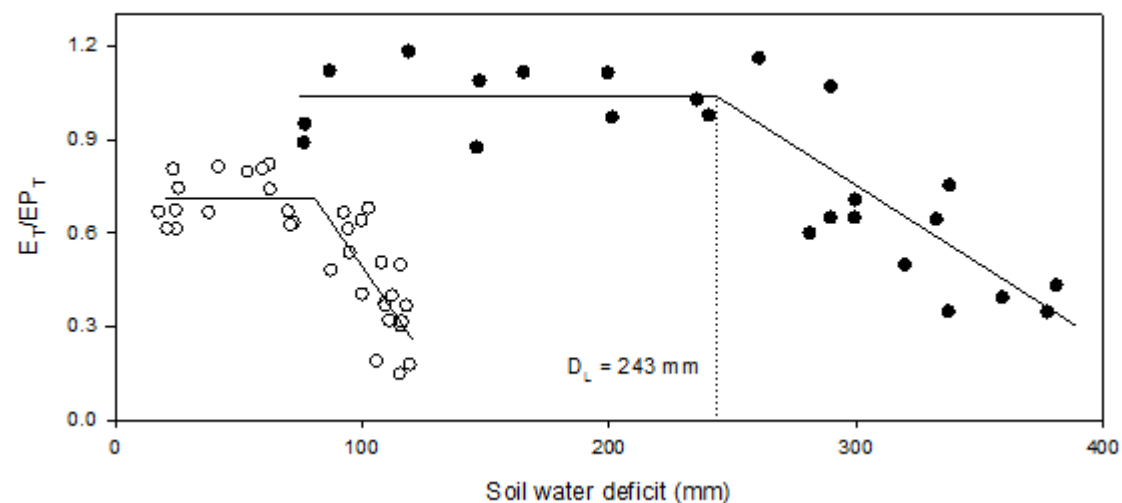


Figure 6.13 The mean soil water deficit in relation to the water stress (E_T/EP_T) for individual regrowth cycles of dryland lucerne at Ashley Dene (○) and Iversen 12 (●) Lincoln University, Canterbury, New Zealand.

Note: Crops were sown in 2010/11, data presented are from the subsequent season, 2011/12. Broken stick regressions (—); Ashley Dene; $y = 0.71(x < 81.0)$, $y = -0.0114*(x > 81.0)$, $R^2 = 0.71$. Iversen 12; $y = 1.0(x < 243)$, $y = -0.0051*(x > 243)$, $R^2 = 0.71$. D_L = critical limiting deficit.

6.3.3.3 Water stress effects on canopy development

The influence of water stress on canopy development; mainstem node appearance rate and branching rate is presented in Figures 6.14 and 6.15. Phyllochron was sensitive to water stress when $E_T/EP_T < 0.70$. Phyllochron increased two fold ($f_{obs/pred} = 2$) when E_T/EP_T decreased from 0.70 to 0.50, and then remained constant. Maximum rate of branching (axillary leaves per mainstem node) was 2.5 per mainstem node when $E_T/EP_T > 0.75$ (Figure 6.15). Rate of branching was reduced by 20% when E_T/EP_T decreased from 0.70 to 0.55 and then remained constant.

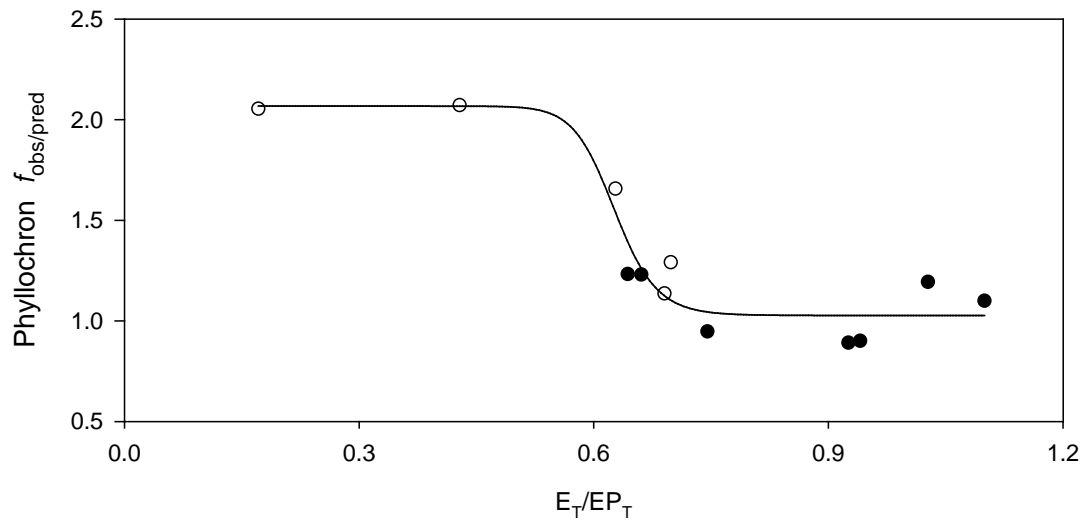


Figure 6.14 Observed phyllochron of dryland lucerne relative to a predicted irrigated crop ($f_{obs/pred}$) in relation to water stress (E_T/EP_T) of crops grown at Ashley Dene (○) and Iversen 12 (●) 2011/2012, Lincoln University, Canterbury, New Zealand.

Note: Logistic regression (—); $y = 1.03 + 1.04 / (1 + \text{Exp}(-34.8 * (x - 0.63)))$ $R^2 = 0.88$.

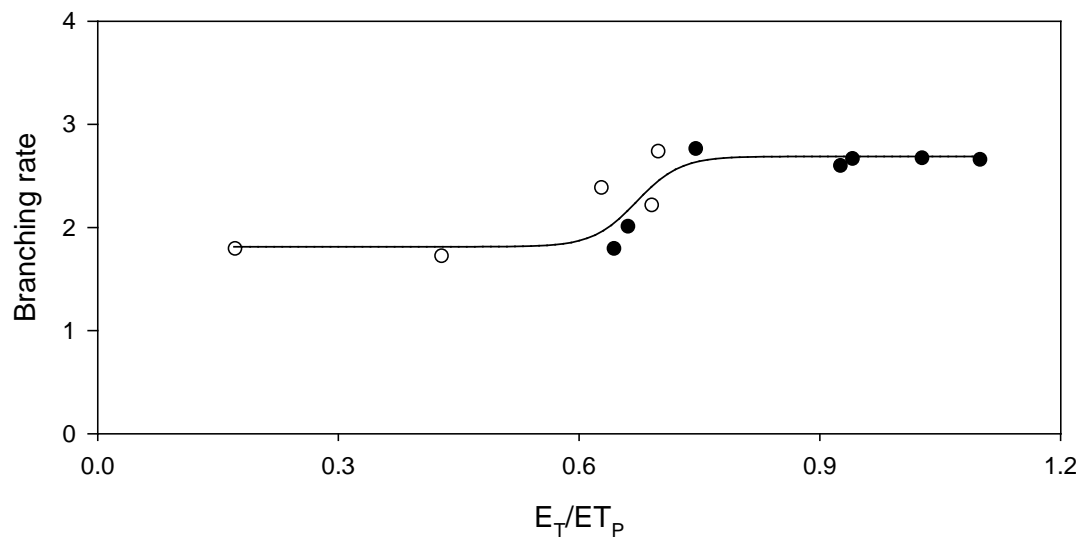


Figure 6.15 Rate of branching (axillary leaves per mainstem node) for dryland lucerne in relation to water stress (E_T/EP_T) of crops grown at Ashley Dene (○) and Iversen 12 (●) 2011/2012, Lincoln University, Canterbury, New Zealand.

Note: Logistic regression (—); $y = 1.81 + 0.88 / (1 + \text{Exp}(-36.87 * (x - 0.67)))$ $R^2 = 0.69$.

6.3.3.4 *Water stress effects on canopy expansion and RUE*

The influence of water stress on canopy expansion and RUE_{shoot} is presented in Figure 6.16a and b. LAER showed increased sensitivity to water stress compared with RUE_{shoot} . LAER was optimum ($f_{obs/pred} \geq 1.0$) when $(E_T/EP_T) > 0.90$. LAER rate decreased to 0.10 of the optimum rate when E_T/EP_T declined from 0.90 to 0.50. Circled points in Figure 6.16 were from the January and February regrowth cycles and were omitted from analysis as water stress was assumed to be underestimated. Water stress was evident in the December regrowth cycle when $E_T/EP_T = 0.75$. The SWD was 150 mm in December which increased to 250 mm in late February which suggests water stress would have occurred during this time, as shown in Figure 6.3. RUE_{shoot} displayed a gradual decrease from $f_{obs/pred}$ of 0.9 to 0.75 in response to a decrease in E_T/EP_T from ≥ 1.0 to 0.80. The $f_{obs/pred}$ then decreased 0.15 when E_T/EP_T declined to 0.40 and remained constant.

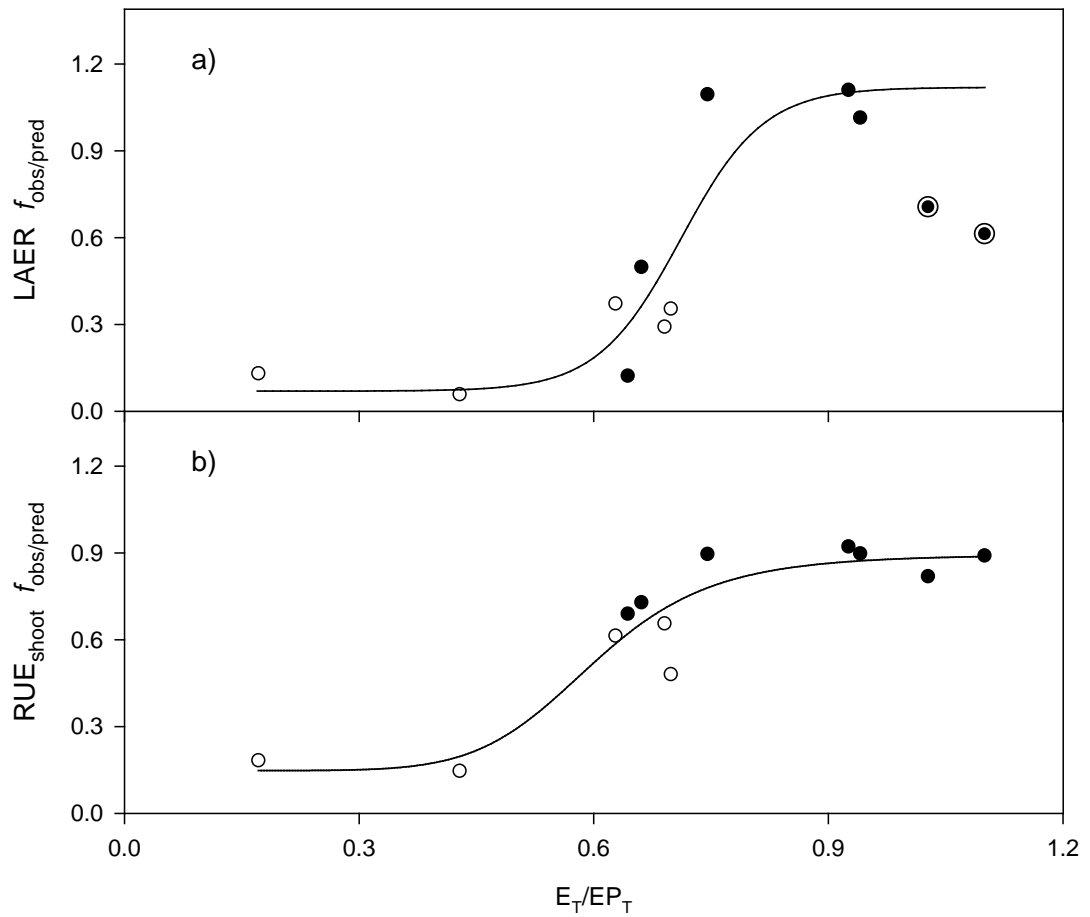


Figure 6.16 Observed LAER (a) and RUE_{shoot} (b) of dryland lucerne relative to a predicted irrigated crop ($f_{obs/pred}$) in relation to water stress (E_T/EP_T) of crops grown at Ashley Dene (○) and Iversen 12 (●) 2011/2012, Lincoln University, Canterbury, New Zealand.

Note: Logistic regression (—); a) $y = 0.14 + 0.75 / (1 + \exp(-13.1 \cdot (x - 0.60)))$ $R^2 = 0.82$. b) $y = 0.07 + 1.05 / (1 + \exp(-18.9 \cdot (x - 0.71)))$ $R^2 = 0.75$. Circled points in Figure 6.16a were omitted from regression analysis E_T/EP_T was most likely underestimated.

6.4 Discussion

The aim of this chapter was to explain the differences in yield forming components of DM production of dryland lucerne (Chapter 4) in relation to water use. Firstly, water extraction by the crops and how efficiently this water was used for growth was compared. The effect of water stress on the yield forming processes which were identified in Chapter 5 was examined.

6.4.1 Plant available water and water extraction

6.4.1.1 *Soil water deficit and critical limiting deficit*

Lucerne crops grown at Ashley Dene had three times less maximum SWD compared with crops grown at Iversen 12 in both the establishment and subsequent season (Table 6.1). Rainfall was comparable between sites (Table 3.2), which implies lucerne at Iversen 12 had greater water extraction which resulted in greater crop water use (Tables 6.2 and 6.3). The method of using SWD to quantify water stress and identify a critical limiting deficit (D_L), the point where yield reductions occur (Penman, 1971) did not give a clear value for the crop at Ashley Dene. E_T/EP_T did not reach 1.0 (Figure 6.13) which means the soil could not meet crop demand at any time. The limitation of this data are the majority of the SWD points below 50 mm occurred during early spring (September) when crop growth may have been limited by temperature. The D_L for the crop at Iversen 12 did show $E_T/EP_T \geq 1$ and water stress occurred beyond a SWD of 243 mm (Figure 6.13). This showed water stress occurred when ~60% of plant available water had been extracted. This is consistent with Sheaffer *et al.* (1988) who reported a decrease in crop transpiration with between 40 to 65% depletion of PAWC. This is higher than the 'rule of thumb' which suggests D_L is half of the PAWC for a given soil (Minchin *et al.*, 2011) as demonstrated by Mills (2007) in soil similar to that of Ashley Dene with a cocksfoot pasture extracting 53% of the 140 mm available water before the onset of water stress. A limitation to the current research is water stress was quantified in relation to crop demand which was the product of canopy cover and EP (French and Legg, 1979). Water stress reduces canopy expansion and therefore crop demand, which would maintain the E_T/EP_T , although water stress was present. This was thought to have occurred in the mid-summer regrowth phases at Iversen 12 when $E_T/EP_T \sim 1.0$,

however LAER was 60% of the predicted maximum (Figure 6.16a). An alternative method is to relate E_T in relation to the water use of a fully irrigated crop which was not possible in the present study. The low PAWC soil at Ashley Dene could not supply water to meet crop demand at any time. Observations in Chapter 5 identified water stress in seedling crops at Ashley Dene and suggested crop water use was limited by supply from the roots. This was also evident in regrowth crops with a maximum E_T/EP_T of 0.7 when SWD was close to zero (Figure 6.13), which further suggests the soil could not supply water at the rate of demand by the lucerne crops. The efficiency of root systems to extract water within a soil layer depends on their spread, density and permeability (Kramer and Boyer, 1995). Dardanelli *et al.* (1997) described the lucerne root system as uniform relative to annual crops and showed water extraction rates (kl) of 0.03 and 0.09/day for lucerne and maize, respectively, when grown on a deep soil under drought conditions. This supports Sheaffer *et al.* (1988) who stated that the strategy of lucerne under moisture limiting conditions is to become semi-dormant using water at low rates and persist by extracting water from deep soil layers. The high stone content at Ashley Dene could also compound the problem of root exploration. In a stone free soil, roots will spread out less uniformly so there will always be an absorbing root close to the site of soil water extraction. In a stony soil, roots would be deflected by stones, to move around them and then down. Less lateral root extension would be expected due to the physical barriers of stones, which reduces the volume of soil available for water extraction.

The SWD in relation to the D_L in the present research suggests that water stress in second year crops at Ashley Dene occurred from the onset of spring growth and in mid-summer for crops at Iversen 12 (Figure 6.3). The extraction patterns of these crops will be examined.

6.4.1.2 *Water extraction patterns*

The PAWC of the two soils interacted with sowing date to successfully create lucerne crops with different patterns of extractable water. This meant water stress conditions were imposed in the same environment without using irrigation. This allowed the extraction pattern of these crops to be studied (Section 2.5.2.3). Lucerne preferentially

extracts water via the shortest path, therefore water extraction from the complete soil profile is not possible when irrigation is applied. Seedling crops at Ashley Dene extracted 50% less water to a similar depth of 1.5 m compared with crops at Iversen 12 (Figures 6.4 and 6.5). Likewise, second year crops at Iversen 12 extracted 340 mm, 60% more than those at Ashley Dene. Water supply is determined by the AWC of the soil and the uptake coefficient (k_l) which is influenced by soil diffusion properties and crop root length density (Jamieson and Ewert, 1999). The two soil types had vastly different soil water profiles (Figure 6.1). The Wakanui silt loam at Iversen 12 had a DUL of $\sim 0.30 \text{ mm}^3/\text{mm}^3$ which was consistent throughout the profile. The Lismore stony silt loam at Ashley Dene which had a DUL of $\sim 0.25 \text{ mm}^3/\text{mm}^3$ in the 0.25 m layer but this decreased to $0.10 \text{ mm}^3/\text{mm}^3$ in the layers below 0.5 m. The Lismore soil is comparable to a soil profile which consists mostly of sand (Dolling *et al.*, 2005). The LL of lucerne water extraction differed between the sites, with crops at Ashley Dene extracting water to a SWC of $0.05 \text{ mm}^3/\text{mm}^3$ (Figure 6.6) compared with $0.15 \text{ mm}^3/\text{mm}^3$ at Iversen 12 (Figure 6.7). The result was mean PAWC to 2.3 m was 58 mm/m at Ashley Dene compared with 160 mm/m at Iversen 12. This is consistent with values reported in the literature (Section 3.1.2). Moot *et al.* (2008) reported the same PAWC for dryland lucerne on similar soil types which resulted in 50% difference in yield.

The Monteith framework (Monteith, 1986) accurately described the extraction patterns of seedling and regrowth lucerne crops. However, a single EFV and $-k_l$ was inappropriate when predicting water extraction rate among crops. Extraction in the establishing crops started ~ 1 month after sowing on the 10 November 2011, soon after the first trifoliate leaf appeared (Section 4.2.2) and LAI started to expand. The EFV was 12.9 mm/day at Iversen 12 which is consistent with Brown (2004) who reported establishing dryland lucerne had an EFV of 12.5 mm/day under similar environmental conditions. The extraction front progression down the profile at Ashley Dene showed a weaker linear relationship ($R^2 = 0.68$) which suggested EFV was not constant over time. A dynamic EFV was reported for lucerne by Dolling *et al.* (2005) who reported the EFV changed four fold as the extraction front progressed down the soil profile to 4 m and suggested soil physical and chemical properties may have affected root growth. There are no known soil chemical properties that would impede root extension at

Ashley Dene, although the sub soil layers which consist of high stone content may provide a physical restriction to root growth (Passioura, 1991; Watt *et al.*, 2006).

It appears that the EFV did not represent root growth during the establishment phase at Ashley Dene. During the lag phase LAI was 0.45, and crop water demand was one third of EP. The rapid increase in EFV coincided with a 60 mm rainfall event (Figure 4.3) when the LAER increased to $0.015 \text{ m}^2/\text{m}^2/^\circ\text{Cd}$, near maximum rate, which suggests roots were already present in these layers, and extraction of water was driven by crop demand from the expanding canopy. The EFV then decreased following defoliation in January and crop demand was close to zero. It is suggested the EFV lagged behind root extension and was dynamic in response to crop water demand. In annual and establishing crops the downward progression of the EFV can be explained by primary root growth where crop water demand exceeds supply (Robertson *et al.*, 1993a). However, Singh *et al.* (1998) stated that the EFV was decreased when rewetting of upper layers was sufficient to meet crop water demand, which was shown in lucerne by Brown *et al.* (2009). Conversely, where crop demand is less than the potential supply of the soil layers by the advancing root, the EFV lags behind root growth.

Results presented in Chapter 4 showed crops at Ashley Dene maintained high (50%) partitioning of DM below ground. Taproot biomass is associated with reserves rather than water extraction which occurs in the fine root hairs, however there may be a link between the two. It appears these crops may have prioritised DM to maintain potential root growth under severe water stress. Robertson *et al.* (1993b) showed with intensive SWC measurements (4 to 5 days) extraction patterns could be modelled using a sigmoidal relationship, and it was possible to differentiate between time of roots entering a soil layer and water extraction for crop growth. Further research using this method may confirm a lag between root extension and water extraction, especially when ontogeny is prioritising root growth over canopy expansion.

A single EFV was inappropriate when describing water extraction of regrowth crops. EFV differed in regrowth crops between sites. Crops at Ashley Dene had an EFV of 32.6 mm/day, twice that of crops at Iversen 12 (Figure 6.8b and d). The EFV for the

Iversen 12 crop of 14.2 mm/day was consistent with that shown by Brown (2004) of 15.6 mm/day for regrowth lucerne in the same environment. Dolling *et al.* (2005), who examined lucerne extraction patterns on a range of soil types, reported soil texture had a major effect on EFV and the soil which had the lowest PAWC had the highest EFV. This result suggests the lucerne at Ashley Dene compensated for the low PAWC by extracting water down the profile at twice the rate of that at Iversen 12 from within each soil layer (Figure 6.9). The extraction rate, $-kl$ is a function of root length density and crop demand. This suggests the crops at Ashley Dene may have invested more DM in the root system to extract the lower PAW, or the low PAWC soil meant demand exceeded supply and $-kl$ increased to compensate this. A further possibility is $-kl$ would have been inherently higher at Ashley Dene because the volume of soil available for water extraction is lower due to the high stone content of the profile. This result shows extraction rate is influenced by crop water demand, although the EFV increased two fold at Ashley Dene, demand still exceeded supply and water stress occurred. The effect of water stress on yield forming components will now be discussed.

6.4.2 DM yield in relation to water stress

6.4.2.1 Water use efficiency

Crop DM productivity in a water scarce environment should not be solely measured on WUE. WUE differed among crops mainly due to reduction in photosynthetic capacity due to water stress, but also because of the dynamics of DM partitioning. Cumulative data from two seasons showed strong ($R^2 > 0.97$) relationships between crop WU and DM yield (Figure 6.10), although analysis of individual growth cycles showed seasonal WUE varied three fold (Figure 6.11). Mean WUE was 22 and 29 kg DM/ha/mm for crops at Ashley Dene and Iversen 12, respectively. This result is consistent with dryland lucerne grown in a similar environment (Brown *et al.*, 2005a; Moot *et al.*, 2008; Tonmukayakul *et al.*, 2009). Crops at Ashley Dene experienced higher levels of water stress, which is normally associated with increases in WUE (Condon *et al.*, 2002; Passioura, 2006), however displayed a ~25% decrease in WUE, which suggest water stress reduced photosynthetic capacity. When water demand exceeds supply, stomata close and there is a reduction in gaseous water loss, which is greater than the associated

decrease in photosynthesis, which in turn increases WUE. WUE is intrinsically linked with RUE (Hay and Walker, 1989) which was shown to be affected by water stress in the present study (Figure 6.16b). WUE displayed a similar pattern to that of RUE_{shoot} (Figure 5.21), which was shown to be affected by the partitioning of DM between shoot and root fractions. This result was clear in regrowth crops which displayed a decrease in WUE in mid-summer to that of establishing crops (Figure 6.11) when it was shown partitioning was split evenly between above and below ground fractions.

6.4.2.2 *Water stress and canopy development and expansion*

Temperature only partly explained the canopy forming processes associated with radiation capture in these crops, which were affected by water stress. Canopy development was less sensitive to water stress than expansion, which resulted in crops at Ashley Dene, on average intercepting 30% less radiation than those at Iversen 12 (Figure 5.20). LAER showed increased sensitivity to water stress compared with RUE_{shoot} (Figure 6.16), which was mostly explained by differences in individual leaf area. Crops at Ashley Dene had on average leaves which were 60% smaller leaves than those at Iversen 12 (Figure 5.16). Differences in LAER in relation to water stress were also partly explained by slower rates of canopy development. Phyllochron increased two fold when E_T/EP_T decreased from 0.70 to 0.50 which was most evident in crops at Ashley Dene which experienced prolonged, severe water stress (Figure 6.14). Rate of branching was less sensitive to water stress (Figure 6.15), as mainstem node number was shown to be strongly ($R^2 = 0.91$) related to axillary leaf production (Figure 5.8). This was consistent with Hay and Walker (1989) who suggested development processes are less sensitive to water stress than canopy expansion. This was also shown for lucerne by Brown *et al.* (2009) who suggested individual leaf expansion probably had the largest influence on LAI development.

6.4.2.3 *Water stress and radiation use efficiency*

The RUE_{shoot} was less sensitive to water stress compared with LAER, however had a greater effect on yield. This is because regrowth crops generally still reached a LAI of 2 to 3 at Ashley Dene (Figure 5.9), and >3 at Iversen 12 (Figure 5.10), although canopy

expansion rates were reduced due to water stress. Because of the exponential relationship between R/R_o and LAI (Figure 5.13), this meant crops were generally intercepting 80 to 90% of incoming radiation, and therefore a decrease in RUE would have a greater effect on yield. For example, the E_T/EP_T was 0.70 for the second regrowth cycle for the crop at Ashley Dene (Figure 6.12). LAER rate and RUE_{shoot} were reduced to ~65% of the maximum potential rate. However, LAI was 2.5 and therefore ~80% of incoming radiation was being intercepted. The 65% decrease in RUE_{shoot} therefore had a greater effect on yield. RUE_{shoot} showed a linear decrease as E_T/EP_T decreased from 1.0 to 0.3 (Figure 6.16b). Water and CO_2 share a similar pathway during photosynthesis, when stomata close to reduce water loss through transpiration, CO_2 assimilation declines (Jamieson *et al.*, 1995a; Jamieson, 1999). The influence of water stress on RUE_{shoot} of lucerne was shown by Brown *et al.* (2009) who reported a 1:1 decrease in RUE relative to declining E_T/EP_T which was due to stomatal closure reducing transpiration and the canopy becoming less responsive to incoming radiation (Brown *et al.*, 2012).

The mechanisms responsible for yield loss did not change between seasons and sites, rather the level of stress incurred. This means the relationships formed among components of yield and water stress can be applied to explain yield in lucerne crops outside of the present study. This was demonstrated when data from the present study of LAER and RUE in relation to water stress were redrawn onto Figure 2.8. These results are in agreement with relationships reported by Brown *et al.* (2009) for lucerne in the same environment (Figure 6.17). This confirms that LAER was more sensitive to water stress than RUE, however because of the exponential relationship between R/R_o and LAI (Figure 5.13), when LAI fell below full canopy a decrease in RUE would have a greater influence on DM production. It also confirms water stress was most likely underestimated in the mid-summer regrowth phases at Iversen 12 and an E_T/EP_T of ~0.75 was likely for this period.

The results showed crops reduced canopy expansion rates when water stressed and crop water use decreases. Grazing management will be used in Chapter 7 as a strategy to

influence timing of DM production by manipulation of the crop canopy and therefore water use.

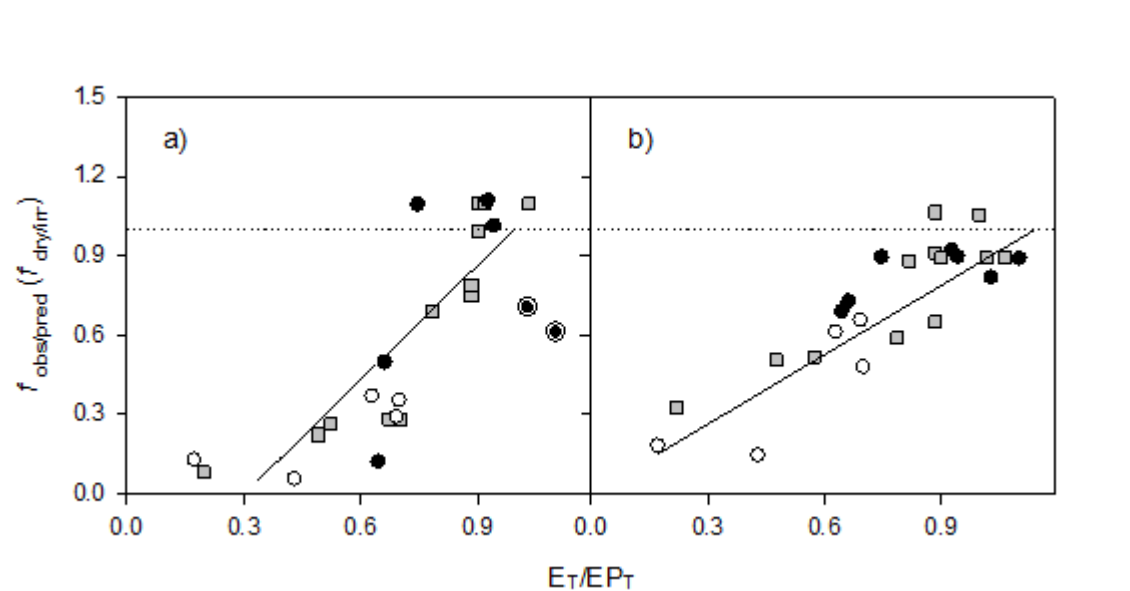


Figure 6.17 Relative effect ($f_{\text{obs/pred}}$) on LAER (a) and $\text{RUE}_{\text{shoot}}$ (b) in lucerne in relation to water stress (E_T/EP_T) in Ashley Dene (\circ) and Iversen 12 (\bullet) from 2011/2012 redrawn with data from Brown *et al.* (2009) of dryland relative to irrigated lucerne ($f_{\text{dry/irr}}$) from 2000/2002 (\blacksquare) at Lincoln University, Canterbury, New Zealand.

Note: Linear regressions (—); a) $y = 1.43x - 0.44$, $R^2 = 0.73$. b) $y = 0.88x + 0.05$, $R^2 = 0.74$. Circled points in Figure 6.17a were omitted from regression analysis as E_T/EP_T was most likely underestimated.

6.5 Conclusions

This chapter quantified crop water demand and supply from the soil. The supply of water available for growth was the result of PAWC in individual soil layers and the rate of extraction by the crops. Water stress was quantified as transpiration in relation to demand and relationships were formed between yield forming factors and water stress. Water stress reduced yield by decreasing the capture of radiation and the efficiency with which it was converted into DM. Specific conclusions are:

- The Ritchie calculation modified to account for soil drying by crop roots gave an accurate description of E_s for the soil-plant combinations in the present study.
- The EFV of lucerne in the establishment season appeared consistent between soil types at ~14 mm/day, but decreased when crop water demand was less than supply.
- Second year crops at Ashley Dene displayed twice the rate of water extraction in individual soil layers and an EFV of 32.6 mm/day compared with 14.2 mm/day at Iversen 12.
- Cumulative WUE was 22 and 29 kg DM/ha/mm at Ashley Dene and Iversen 12, respectively. WUE of individual regrowth phases varied three fold throughout the season. Most likely linked to RUE_{shoot} , which was affected by water stress and partitioning of DM.
- Water stress could be quantified as transpiration in relation to demand (E_T/EP_T), but limitations occur when water stress reduces canopy expansion and therefore apparent EP_T .
- Water stress reduced R/R_o and RUE. LAER was more sensitive to water stress which decreased from $f_{obs/pred}$ of 1.0 to near zero when E_T/EP_T was 0.30 compared with $RUE_{shoot} f_{obs/pred}$ which decreased to 0.30.

7 Lucerne yield and water use after different defoliation regimes

7.1 Introduction

When crop water demand exceeded supply, lucerne reduced leaf area (Chapter 6). Radiation interception regulates transpiration demand as it represents the energy that drives water evaporation, therefore a smaller canopy, lowers water demand and alleviates further effects of water stress (Section 2.5.2). A reduction in leaf canopy through removal by grazing before the onset of water stress may relieve water demand and therefore alter the mechanisms and responses to water stress.

Dryland lucerne does not provide an even feed supply, which was shown for crops at Ashley Dene which grew 60% of total DM in the first two regrowth cycles (Section 4.3.2). The implication of this is that matching feed supply at this time of year with animal demand is perceived as difficult by some farmers (Kirsopp, 2001). Furthermore, often surplus feed in spring is conserved as hay or silage to maintain quality, but as little as one month later the lucerne crop has exhausted the soil moisture, growth ceases and feed demand exceeds supply. Therefore, the aim of this research is to examine if the timing of DM production can be influenced by grazing the crop at different times, through the manipulation of crop water use. For farmers, this would mean greater control of feed supply and the ability to implement grazing strategies to defer the spring surplus to later in the season. Harrison *et al.* (2011) showed that under Australian conditions, removal of the canopy of a wheat (*Triticum aestivum*) crop through grazing before the onset of reproductive development, reduced transpiration and relieved short term water stress. The crop used the water later in the season during grain-fill, so the transferred water maintained photosynthesis levels relative to un-grazed crops.

Results from this chapter are in two parts. Part one examines the influence of three spring grazing treatments on lucerne yield and water use during the grazing period and the remainder of the season. The second part examines how the time of grazing within a six paddock rotationally grazed system affects yield and water use of the individual paddocks.

7.2 Material and methods

Data were collected from two adjacent experiments for one season, June 2011 to June 2012. The experiments were set up in the same area and managed together. The on-going objectives of the experiments are to compare lucerne cultivar production and persistence when subjected to different grazing managements.

7.2.1 Experimental site

These experiments are located at the Lincoln University dryland research farm, Ashley Dene in paddock H7 (43°39'S, 172°19'E, 35 m.a.s.l). Paddock H7 is approximately 0.8 km southwest of Paddock M2B, the Ashley Dene site used in Experiment 1. Paddock H7 is 5.2 ha of flat land, with slight (0.2 m) depressions towards the southwest corner. The two experiments covered a combined area of 2.6 ha.

7.2.1.1 Site history

Prior to the current experiment the paddock was a grazed pasture, sown in annual ryegrass from 2007 to 2008. The paddock was ploughed and then conventionally cultivated in October 2008 in preparation for sowing the current experiments in November 2008.

7.2.1.2 Soil characteristics

The soil is classified as a Lowcliffe stony silt loam (Cox, 1978). This is similar to the Lismore stony silt loam in Paddock M2B (Section 3.1.2). The Lowcliffe has similar horizons as the Lismore series, sandy loam topsoil containing stones overlaying compacted gravels. Lowcliffe soils differ by having a lower percentage of stones in the topsoil and depth of sandy gravels ranges from 0.6 to 1.1 m, compared with less than 0.5 m for Lismore soils. Lowcliffe soils also have a clay/gravel matrix below 1.7 m, (McLenaghan and Webb, 2012). This results in the Lowcliffe soils having a PAWC of about 100 mm/m compared with 60 mm/m for Lismore soils.

7.2.1.3 *Meteorological conditions*

Climate data collected for the Ashley Dene experiment in paddock M2B were used in the current experiment (Section 3.2). In brief, the experiment received 590 mm of rainfall during the measurement period (LTM; 633 mm) and experienced 1100 mm of Penman potential evaporation (LTM; 1094 mm) creating a maximum potential soil moisture deficit of 560 mm in late May (LTM; 520 mm).

Vapour pressure deficit (VPD) was calculated daily as the difference between vapour pressure and saturated vapour pressure at air temperature calculated using wet and dry bulb temperatures obtained from Broadfields meteorological station. Calculations and details are presented in Jenson *et al.* (1990). VPD ranged from 0.4 kPa in July 2011 to 0.8 kPa in January 2012 (Section 3.2.5).

7.2.2 **Agronomic management**

Early in November 2008 inoculated lucerne seed was sown using an Øyjord cone seeder. The grazing treatments for each experiment (described below) were first implemented in year two, from 2 October 2010. The current research occurred in the third season.

7.2.2.1 *Experiment three*

Experiment three was established as a split-plot within a randomised complete block design. The main-plots were two grazing treatments; set stocked and semi-set stocked, and the sub-plots consisted of three cultivars; ‘Stamina 5’, ‘Stamina 6’ and ‘Runner’ (Table 7.1), replicated four times (Appendix 13 and 14). The main-plots were 48 x 89 m, which were divided in half by temporary electric fences. The semi-set stocked plots were then divided in half again. The set-stocked grazing treatment consisted of leaving the grazing sheep in the sub-plot for the duration of the treatment period, which differed from the second grazing treatment which involved alternatively grazing each half of the sub-plot every 10 days, termed semi-set stocking. The grazing treatments were imposed on 27 September 2011 when pre-grazing herbage mass was 2 t DM/ha. Three mixed-age ewes with two week old twin lambs were put on each set stocked sub-plot and one

half of the semi-set stocked sub-plot. The stocking rate was 14.1 ewes/ha. The grazing period finished when lucerne herbage mass decreased to ~500 kg DM/ha and feed supply was well below animal demand. This occurred on 5 December 2011. Lambs were weaned from ewes at this time. This is consistent with commercial farm practices, whereby feed demand is reduced at this time of year by the removal of ewes, and any lambs that have achieved the required liveweight for sale. Following the grazing treatment period the temporary fences dividing the semi-set stocked treatments were removed and various stock classes and numbers were rotationally grazed around the sub-plots with grazing duration no longer than 7 days per sub-plot. Plots were grazed a further three times from 15 December 2011 to 15 May 2012, with a final clean up graze in June. Plots were destocked from 6 March to mid April 2012 to allow six weeks of regrowth to recharge perennial reserves which is consistent with normal commercial farm practice (Moot *et al.*, 2003). Dates of grazing and stock class are summarised in Appendix 15.

Table 7.1 Cultivars and their dormancy ratings used in two experiments in paddock H7 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Cultivar	Experiment	Dormancy rate
<u>Semi-winter active</u>		
‘Kaituna’	4	4-5
‘Stamina 5’	3 and 4	5
‘AgResearch (grazing tolerance)’	2	5
‘Stamina 6’	3 and 4	6
<u>Winter dormant</u>		
‘AgResearch (high preference)’	4	2
‘Rhino’	4	3
‘Runner’	3 and 4	3

7.2.2.2 *Experiment four*

The objective of Experiment four was to implement a rotational grazing system based on six paddocks of equal size. Stock graze each paddock for ~7 days, creating about a 35 to 42 day rotation before the regrowth in the same paddock is grazed again. This system is based on best practice which allows the lucerne time to develop its canopy to maximise yield, while minimum grazing time reduces damage to lucerne crowns and basal buds which affects subsequent regrowth (Moot *et al.*, 2003). The experiment consisted of six 0.46 ha (48 x 89 m) paddocks. Within each paddock seven cultivars were sown (Table 7.1) in sub-plots 6.3 x 24.5 m. Cultivars were replicated four times within each paddock (Appendix 13 and 14). Grazing treatments were first imposed with 34 mixed aged ewes and 60 two week old lambs on 27 September 2011 starting in paddock 1. Stocking rate was 12.3 ewes/ha (over all 6 paddocks), consistent with Experiment 3. Stock were rotated around paddocks 1 to 6 with grazing duration ~7 days per paddock. This was determined by a desired post-grazing residual of 0.4 to 0.8 t DM/ha depending on lucerne maturity, which equates to 50 to 100 mm of low quality mature stem and minimal residual leaf material. Each paddock was grazed twice from 27 September to 5 December 2011 and then a further three times which was consistent with Experiment 3 (Appendix 16).

7.2.2.3 *Soil fertility*

Soil fertility was managed to maximise lucerne yield potential. During the establishment of the experiments in November 2008 2 t/ha lime and 125 kg/ha super sulphur 15 (0,9,0,15) were applied. Based on soil analysis of the topsoil (0-75 mm) in May 2011 (Appendix 17) 2.8 t/ha lime and 500 kg/ha sulphur super 15 were applied in September 2011.

7.2.2.4 *Plant population*

Plant population was affected ($P < 0.05$) by grazing management after the second season (June 2011) with set stocked and rotationally grazed lucerne populations of 150 plant/m² compared with the semi-set stocked treatment with a population of 205/m² (Stocker, 2011). Plant populations were above the critical threshold where yield is

negatively affected of ~50 plants/m² (Teixeira *et al.*, 2007a) and would not have impacted on shoot yield in the following season.

7.2.3 Measurements

Data were collected from one cultivar subplot in Experiment 3, 'Stamina 6' and two cultivar subplots in Experiment 4, 'Stamina 6' and 'Kaituna'. Both cultivars are semi-winter active. 'Kaituna' is the standard New Zealand bred cultivar and has been subjected to the most recent research in New Zealand (Varella, 2002; Brown, 2004; Teixeira, 2006). 'Stamina 6' was included because it was common to both experiments and is comparable to 'Stamina 5' which was studied in the previous chapters. Analysis showed there was no difference between 'Kaituna' and 'Stamina 6' in Experiment 4 for DM yield ($P = 0.096$), radiation use efficiency ($P = 0.133$) and water use efficiency ($P = 0.651$) (Appendix 18), therefore all results for Experiment 2 are presented as paddock means.

All measurements and calculations used are consistent with previous chapters with differences described below.

7.2.3.1 *DM of set stocked and semi-set stocked treatments*

During the first grazing period, shoot DM of set stocked and semi-set stocked plots were measured using exclusion cages. Exclusion cages were 0.7 x 1.1 m which enabled a 0.2 m² quadrat to be taken from within the caged area. Cages were placed within plots and cuts taken from the excluded area and surrounding plot every 10 days, before cages were moved to a new area. DM grown for the 10 day period was the difference between the DM yield from the cage and the pre-grazing cut 10 days earlier. Under the grazing regimes the swards became a mix of; complete shoots, right through a continuum of shoots with decreasing proportion of leaf to bare stems, and senesced material which had been trampled by the grazing stock. DM samples were separated into green and senesced (<50% green) material, with the latter discarded to prevent the higher DM% material influencing yield. This was also important to accurately quantify leaf area index.

7.2.3.2 *Post grazing residual and herbage utilisation*

Post grazing residuals were measured in the rotationally grazed treatments within 24 hours of the removal of sheep. Herbage utilisation was calculated as the percentage difference between final DM yield and the post-grazing residual. Results are only presented from the first regrowth cycle because data from the subsequent cycles were not representative due to the carry over of residual from the previous cycle. This was not evident in the first regrowth cycle because the plots had been hard grazed in winter and no residual was evident.

7.2.3.3 *Leaf area index of set stocked and semi-set stocked treatments*

Leaf area was measured destructively using a sub-sample of shoots and a leaf area meter as described in Section 5.2.2.1. To prevent overestimation of LAI, only those green leaves which were considered to contribute to photosynthesis were measured. Samples were sorted and shoots containing leaves <50% green were discarded, along with shoots containing green leaves which had been trampled and the stem broken.

7.2.3.4 *Soil water*

Neutron probe access tubes were installed in each plot in June 2011. Within replicates access tubes were placed as close together as possible to minimise the effect of variable PAWC between plots (Appendix 14). Soil moisture measurements and a water balance were calculated as described in Chapter 6. The Lowcliffe soil has been described as poorly drained (McLenaghan and Webb, 2012), however the soil water balance showed in the majority of plots (80%) the underlying gravels were very free-draining. Towards the southern end of Experiment 4 (paddock 2, 3 and 6) there was evidence of the water table rising to about 1.8 m below the soil surface from September to late October. This made the crop water use calculation inaccurate for these plots. Therefore, for these plots, soil moisture measurements were excluded from below 1.5 m when the water table was above 2.3 m. Hoffmann *et al.* (2003) showed lucerne was capable of using water preferentially from the water table, however this was not thought to have happened as the water table dropped before the water extraction front reached 1.8 m in

the nearby unaffected plots. Soil water measurements and crop water use calculations were consistent with Chapter 6.

7.2.3.5 *Forage nitrogen and nutritional analysis*

Forage nitrogen and nutritional content were determined for each growth cycle from the final DM harvest. Analysis was conducted on the sub-sample of representative shoots used for determining LAI (Section 5.2.2.1). Samples were ground to pass through a 1 mm sieve (Cyclotec Mill, USA) and near infrared spectroscopy (NIR; Foss NIR Systems 5000 Rapid Content Analyser), calibrated using wet chemistry for lucerne forage was used to determine forage quality. Crude protein (CP; %) content was determined by multiplying nitrogen content by a factor of 6.25 (Waghorn *et al.*, 2007) (Equation 7.1). Energy content (ME; MJ ME/kg DM) was determined by multiplying digestible organic matter contained in the dry matter content (DOMD; %) by a factor of 0.16 (Freer *et al.*, 2007) (Equation 7.2).

Equation 7.1 $CP = N\% \times 6.25$

Equation 7.2 $ME = DOMD \times 0.16$

7.2.3.6 *Leaf and stem separation*

The leaf and stem fractions were measured at the final harvest date for each regrowth period. A sub-sample of 20 representative stems was taken from the quadrat harvested for DM. Each sample was then separated using the ‘breaking-point method’, where the top of each stem was bent and pulled down the stem until it broke. Leaf and stem above the breaking point was considered the leaf fraction, and below it was defined as stem. Brown (2004) showed this method of separation was effective in defining the leaf and stem fractions of lucerne which correlated with contrasting protein and energy levels (Section 2.1.3). It also reflected livestock grazing preference and utilisation and therefore the post-grazing residual.

7.2.3.7 *Canopy height*

Canopy height was measured in the set stocked and semi-set stocked grazing treatments from September 27 to 5 December 2011. Canopy height was measured from within the quadrat taken for DM assessment. The height was determined from the ground to the apical bud.

7.2.4 **Statistical analysis**

Statistical analysis was conducted in GENSTAT (version 14.1) (Lawes Agricultural Trust, IACR, Rothamsted, U.K.). Experiment 4 was analysed using one-way analysis of variance (ANOVA). For the analysis of cultivar, paddocks were used as replicates (6), because there was no cultivar effect, cultivar was then used as replicates (2) for analysis of paddock differences. Experiments 3 (four replicates) and 4 (two replicates) were compared using an unbalanced one-way ANOVA. Means were separated by Fishers protected l.s.d ($P \leq 0.05$) when significant.

7.3 Results

Results are presented in two parts. The first part examines the effect of the method of grazing; set stock, semi-set stock and rotational grazing on DM yield, forage quality and water use. Emphasis is on early season results, when grazing treatments were imposed, as well as annual results. The second part of the results examines the effect of the time of grazing in the six paddock rotation (Experiment 4) on DM yield, formation of yield processes and water use.

7.3.1 The effect of grazing management on DM yield, forage quality and water use

Results presented in the first part of this chapter are from the set stocked and semi-set stock treatments in Experiment three. These are compared solely with the ‘Kaituna’ and ‘Stamina 5’ treatments in paddock 1 of Experiment four. Only Paddock 1 was used because its grazing dates were consistent with those used in Experiment three. Data from the first grazing period is from 27 September 2011 to 5 December 2011 and annual results from the start to July 2012.

7.3.1.1 *DM yield*

Shoot DM yield was not different between all grazing treatments ($P = 0.067$) during the initial grazing period from 27 September to 5 December 2011 with a mean yield of 6.3 t DM/ha (Table 7.2). By the end of the season, June 2012, the annual yield was greatest ($P < 0.05$) under rotational grazing with 12.1 t DM/ha, compared with the set stocked and semi-set stocked treatments which had an annual yield of 10.6 t DM/ha, or 12% less.

Table 7.2 Accumulated DM yield (t DM/ha) of dryland lucerne from June 2011 to 5 December 2011 (Spring DM) and then in total to 13 June 2012 when subjected to three grazing managements at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Grazing treatment	Spring DM	Total DM
Set stocked	6.1	10.6 _b
Semi-set stocked	5.9	10.5 _b
Rotational	6.8	12.1 _a
<i>P</i>	0.067	<0.05
SEM	ns	0.33

Note: Means within a column with different letters are significantly different (l.s.d $P = 0.05$). SEM = standard error of the mean, ns = not significant.

7.3.1.2 *Crop mass*

The crop mass was ~2 t DM/ha for all treatments when grazing commenced on 27 September (Figure 7.1). Under rotational grazing paddock 1 had three growth phases. The regrowth duration was 36 and 28 days for the second and third regrowth phase, respectively. The crop mass at grazing increased in the first rotation from 2 t DM/ha to 2.7 t DM/ha in the third regrowth phase. Crop cover continued to be maintained for both the set and semi-set stocked treatments at 2 to 2.5 t DM/ha until early November. After this DM cover decreased to 0.5 t DM/ha by 5 December when all treatments were destocked.

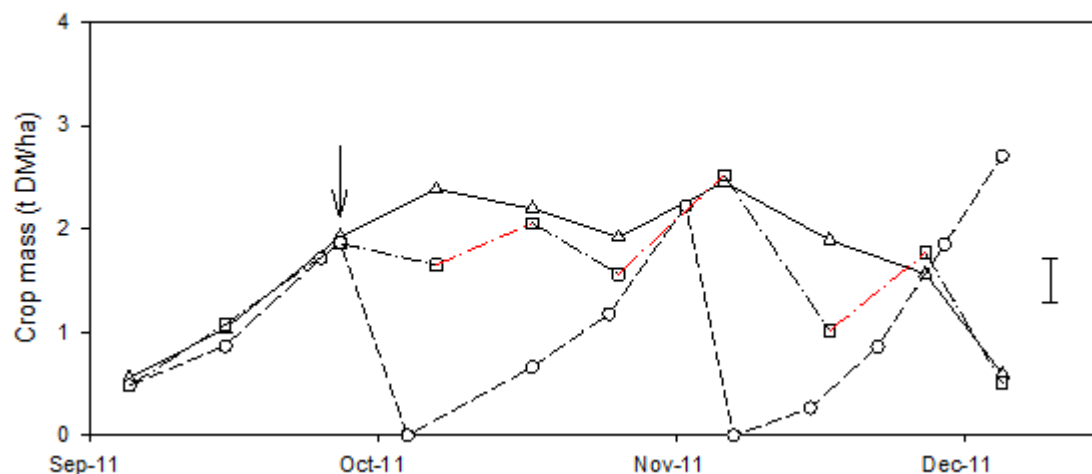


Figure 7.1 Crop mass of dryland lucerne subjected to three grazing managements from 27 September to 5 December 2011; set stocked (Δ), semi-set stocked (\square) and rotationally grazed (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Bar represents l.s.d ($P = 0.05$) at end of grazing period. Arrow indicates start of grazing treatments.

(---) Indicates the 10 day recovery period (ungrazed) for semi-set stocked treatments.

7.3.1.3 Leaf area index and radiation interception

At the start of the grazing period LAI was ~ 2.5 for all treatments, indicating incomplete canopy cover (Figure 7.2). LAI continued to increase under set stocking to 3.2 by early October but then decreased to 0.7 by the 5 December. Rotational grazed crops reached canopy closure, LAI ~ 3.5 in Rotations 2 and 3. The smaller canopy for rotationally grazed crops intercepted 950 MJ/m^2 of total solar radiation, or 30% less ($P < 0.05$) than the set and semi-set stocked crops which intercepted 1400 MJ/m^2 (Figure 7.3). $\text{RUE}_{\text{shoot}}$ was 0.73 g DM/MJ , and consistent for all treatments until the grazing commenced on 27 September. $\text{RUE}_{\text{shoot}}$ for the rotational grazed crop remained at this level until 5 December, but $\text{RUE}_{\text{shoot}}$ for both the set and semi-set stocked crops decreased to 0.37 g DM/MJ , 50% less.

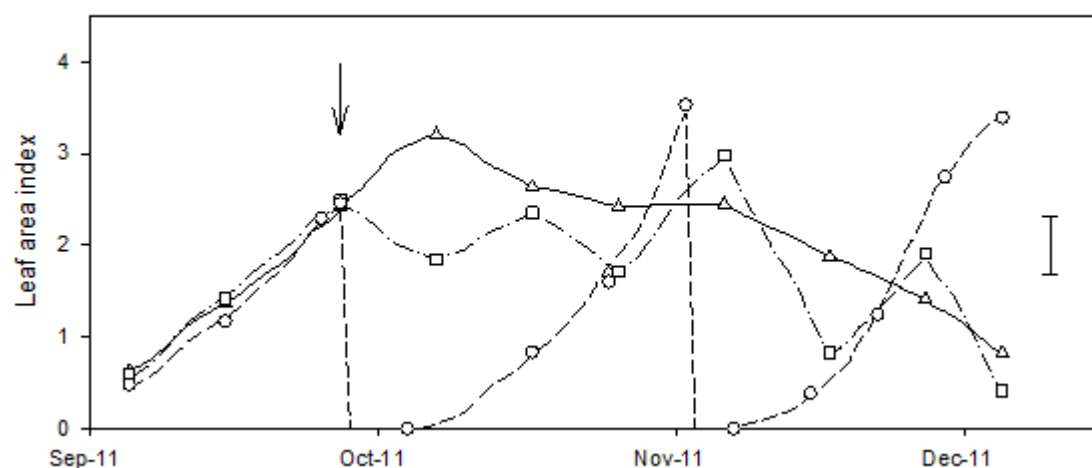


Figure 7.2 Leaf area index of dryland lucerne subjected to three grazing managements from 27 September to 5 December 2011; set stocked (Δ), semi-set stocked (\square) and rotationally grazed (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Bar represents l.s.d ($P = 0.05$) at end of grazing period. Arrow indicates start of grazing treatments.

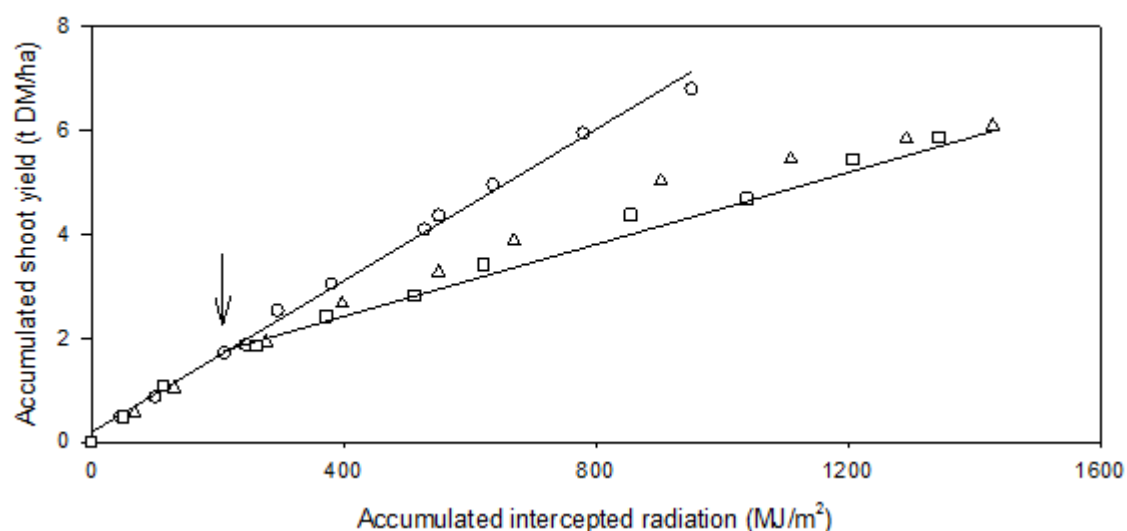


Figure 7.3 Relationship between accumulated shoot yield and accumulated total intercepted radiation of dryland lucerne subjected to three grazing management treatments from 27 September to 5 December 2011; set stocked (Δ), semi-set stocked (\square) and rotational (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Linear regressions (—); ($\Delta \square$) $y = 0.37x + 1070$, $R^2 = 0.98$, (\circ) $y = 0.73x + 181$, $R^2 = 0.99$. Note: Arrow indicates start of grazing treatments.

7.3.1.4 Canopy nitrogen content

Crop nitrogen (N) uptake showed a strong linear increase in relation to LAI with an R^2 of 0.88 which was unaffected ($P = 0.36$) by treatment. A constant N uptake of 31 kg N per unit of LAI was estimated. N uptake was consistently above the critical threshold for maximum leaf are expansion presented by Lemaire *et al.* (2007).

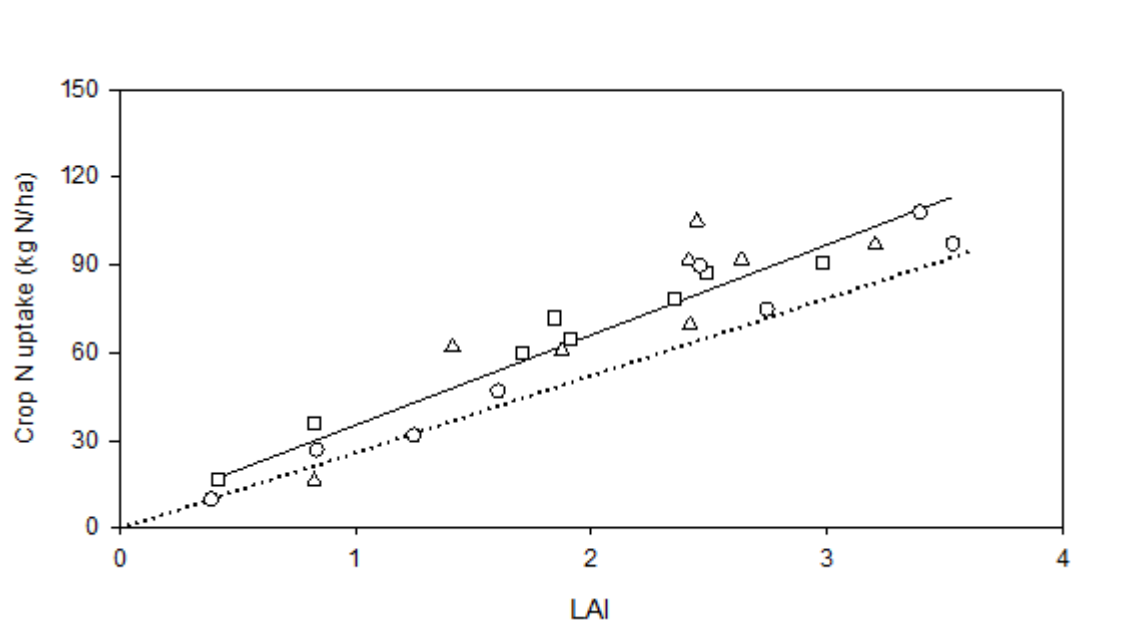


Figure 7.4 Canopy nitrogen (N) uptake in relation to leaf area index (LAI) of dryland lucerne subjected to three grazing managements from 27 September to 5 December 2011; set stocked (\triangle), semi-set stocked (\square) and rotational (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Linear regressions (—); $y = 30.8x + 4.48$, $R^2 = 0.88$. Critical N uptake curve (····); $y = 25.4x^{1.03}$, for lucerne grown in a temperate environment adapted from Lemaire *et al.* (2007).

7.3.1.5 Water use

Crop water use was calculated using a daily water budget which accounted for losses from soil evaporation (Section 6.2.2.1) and drainage (Section 6.2.1.6) which is consistent with Chapter 6. Some variation in soil within the experiments was evident as maximum SWD was 237 mm for the rotationally grazed crops compared with 220 mm for set and semi-stocked crops (Table 7.3), although this was not statistically different ($P = 0.76$) due to the highly variable spatial distribution of these alluvial soils.

Maximum SWD varied ± 118 mm. Crop water use was 290 mm in set and semi-stocked crops, 20% higher ($P < 0.05$) than rotationally grazed crops. However, rotationally grazed crops experienced 128 mm of soil water evaporation compared with 77 mm for the other crops, therefore total water use was consistent among treatments. Accumulated WU in relation to DM up to 5 December 2011 displayed a constant linear relationship ($R^2 > 0.98$; data not shown). WUE was 21.3 kg DM/ha/mm for the set and semi-set stocked crops which was 30% less ($P < 0.05$) than the rotationally grazed crop (Table 7.3).

Table 7.3 Maximum soil water deficit (SWD_{max}; mm), crop water use (E_T; mm), water use efficiency (WUE; kg DM/ha/mm) and soil evaporation (E_S; mm) of dryland lucerne from 8 June 2011 to 5 December 2011 subjected to three grazing managements at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Paddock	SWD _{max}	E _T	WUE	E _S
Set stocked	215	297 _a	21.6 _b	77 _b
Semi set stocked	220	282 _a	20.9 _b	76 _b
Rotational	237	231 _b	30.5 _a	128 _a
<i>P</i>	0.775	0.047	0.033	0.032
SEM	ns	10.58	1.43	7.96

Note: Means within a column with different letters are significantly different (l.s.d $P = 0.05$). SEM = standard error of the mean, ns = not significant. PAWC determined to 2.3 m.

Figure 7.5 shows patterns of accumulated crop WU and soil evaporation differed amongst treatments but the two were balanced resulting in a mean total WU of 360 mm ($P = 0.896$). Monthly rainfall for September was 20 mm, compared with the long term mean of ~50 mm. October received twice the average rainfall and regular rainfall events occurred during November and December which both received ~60 mm. Crop WU was reduced for periods of ~10 days following grazing events in the rotationally

grazed crops. Manipulating crop WU through timing of grazing is examined in detail in Section 7.3.2 using data from Experiment 2.

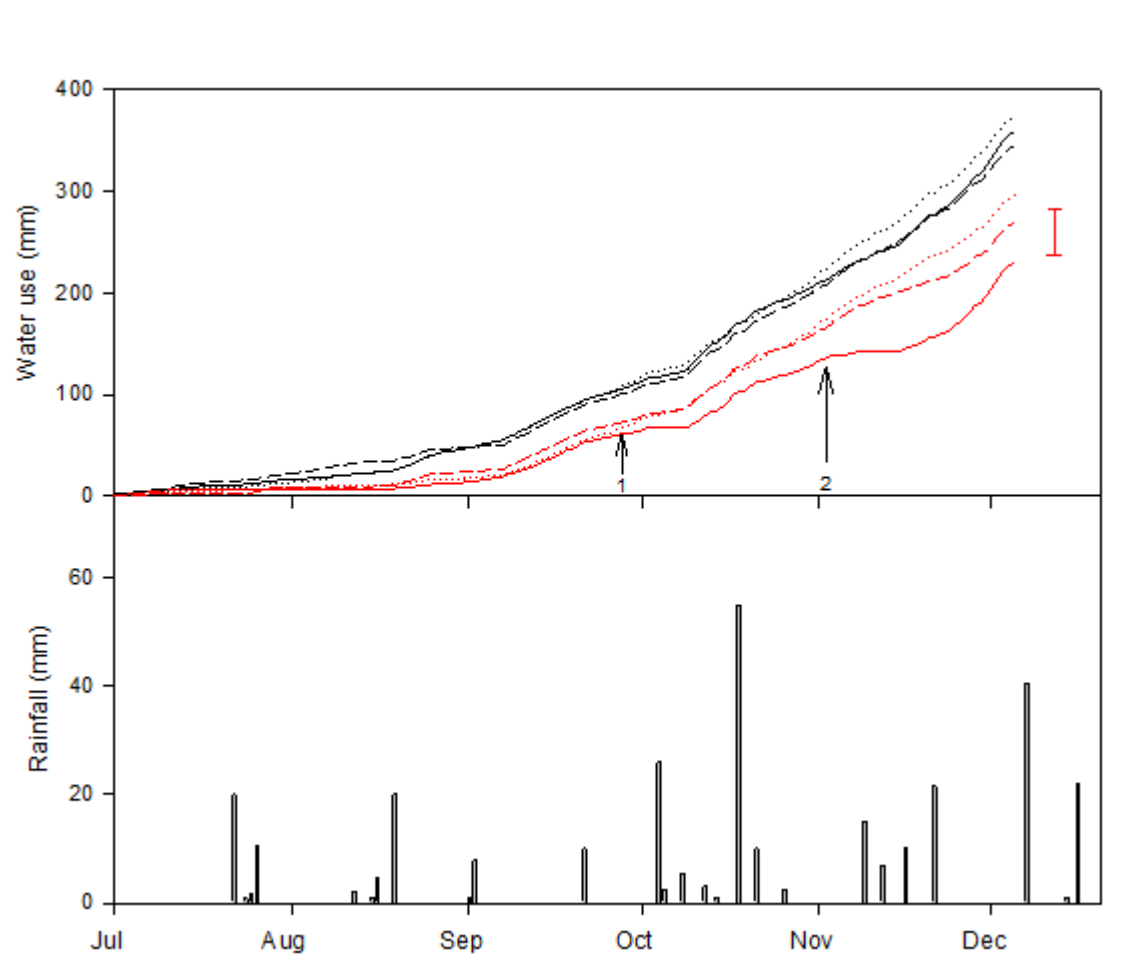


Figure 7.5 Accumulated crop water use (red), total water use (black) and daily rainfall (■) of dryland lucerne subjected to three grazing managements; set- stocked (····), semi set-stocked (---) and rotational grazing (—) from July to December 2012 at Lincoln University, Canterbury, New Zealand.

Note: ¹ indicates start of grazing period.

² indicates the time of the second grazing round for the rotationally grazed treatment.

7.3.1.6 Water use in relation to intercepted radiation

Crop transpiration (E_T) showed a strong linear increase in relation to intercepted radiation with an R^2 of 0.99 (Figure 7.6), which was unaffected ($P = 0.21$) by grazing treatment. The slope of the relationship (E_T/R_i) described the WU per unit of intercepted radiation which was 0.19 mm/MJ/m^2 .

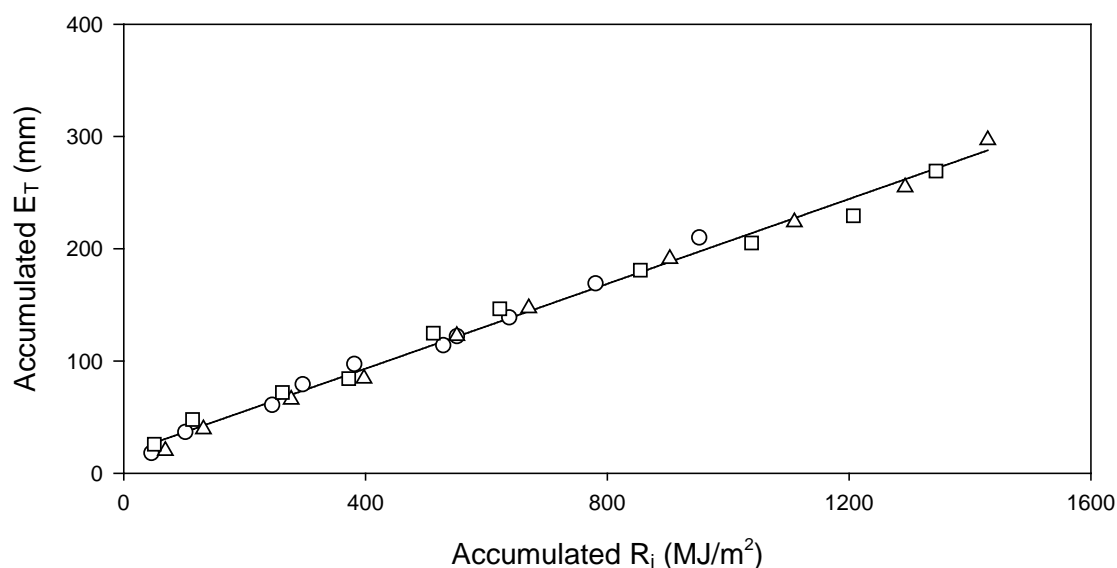


Figure 7.6 Transpiration (E_T) in relation to intercepted radiation (R_i) accumulated from 1 July to 5 December 2011 for dryland lucerne subjected to three grazing management treatments from 27 September to 5 December 2011; set stocked (\triangle), semi-set stocked (\square) and rotational (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Linear regressions (—); $y = 0.19x + 17.6$, $R^2 = 0.99$.

7.3.1.7 Annual DM yield

Following the final grazing from the previous season in June 2011, growth did not occur until the first week of September, with DM accumulating linearly during the first grazing period (Figure 7.7). Following the end of the first grazing period the rotationally grazed treatment maintained growth rates of 60 kg DM/ha/day and by mid-January had a 2 t DM/ha yield advantage over the set and semi set stocked treatments,

which was consistent until the end of the season. The objective of the following analysis is to determine the cause of the yield difference, and if the first grazing period did have a residual effect on the remainder of the season.

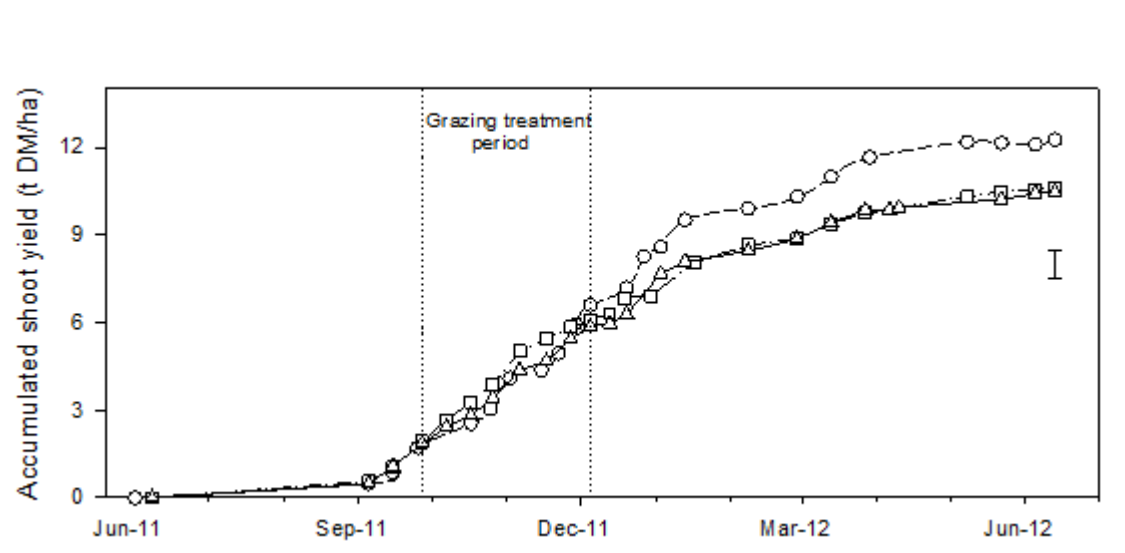


Figure 7.7 Accumulated shoot yield of dryland lucerne from June 2011 to June 2012 subjected to three grazing managements from 27 September to 5 December 2011; set stocked (\triangle), semi-set stocked (\square) and rotational grazed (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Bar represents l.s.d ($P = 0.05$).

7.3.1.8 Soil water deficit

Soil water deficit at the end of the first grazing period was ~120 mm (Figure 7.8). The maximum soil water deficit occurred on 22 February 2012 with the highest deficit in the rotationally grazed crops of 240 mm and lowest, 215 mm in the set stocked crops. The difference in maximum deficit is associated with soil type and PAWC (Table 7.3).

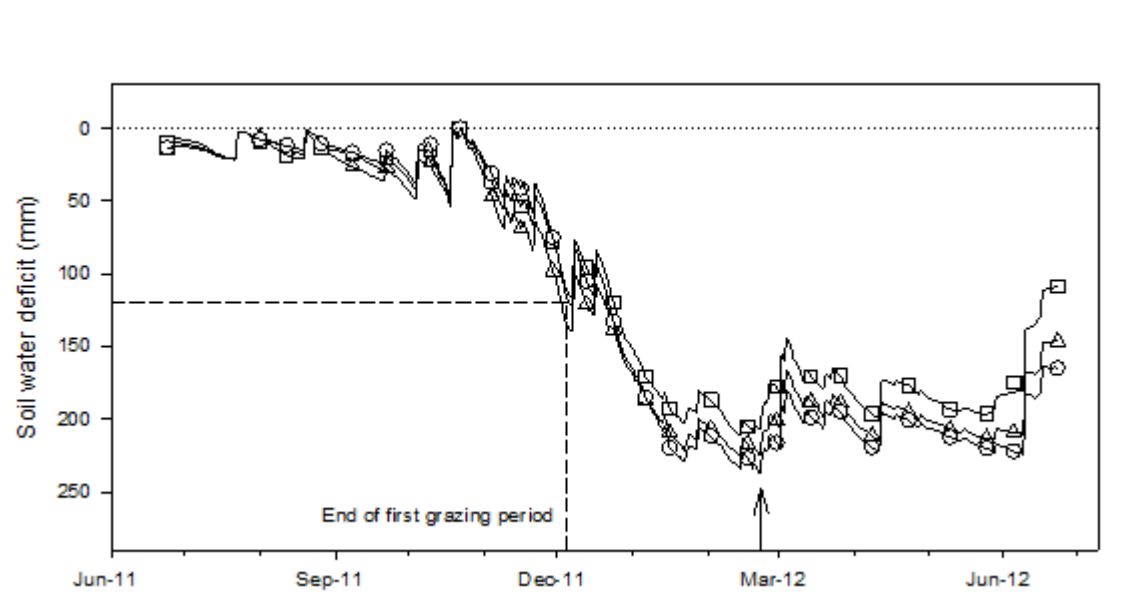


Figure 7.8 Soil water deficit to 2.3 m for June 2011 to July 2012 for dryland lucerne subjected to three grazing managements; set stocked (△), semi-set stocked (□) and rotational grazing (○) at Lincoln University, Canterbury, New Zealand.

Note: Arrow indicates date of maximum soil water deficit.

7.3.1.9 Intercepted radiation

The set and semi-set stocked crops maintained RUE_{shoot} of 0.35 g DM/MJ for the remainder of the season, intercepting 2800 MJ/m² by June 2012 (Figure 7.9). Intercepted radiation demonstrated a bi-linear relationship with accumulated DM for rotationally grazed crops with a total intercepted radiation of 2130 MJ/m² by June. Crops maintained a RUE_{shoot} of 0.72 g DM/MJ until early January which then decreased to 0.40 g DM/MJ, and was consistent with the set and semi-set stocked crops.

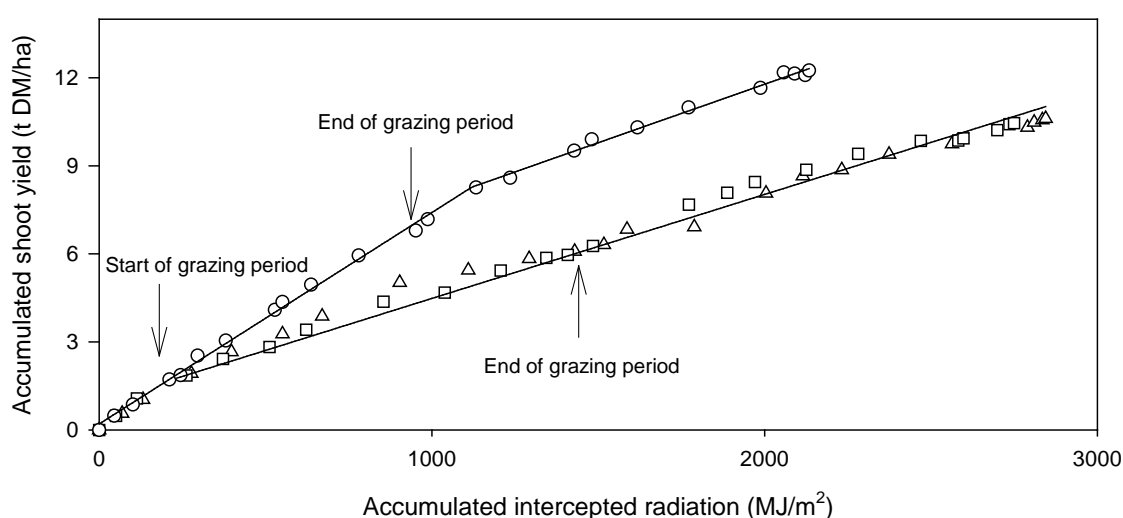


Figure 7.9 Relationship between accumulated shoot yield and accumulated total intercepted radiation of dryland lucerne from June 2011 to June 2012 subjected to three grazing managements; set stocked (\triangle), semi-set stocked (\square) and rotational grazing (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Linear regression; (\triangle , \square); $y = 0.35x + 941$, $R^2 = 0.99$. Broken stick regression; (\circ); $y = 0.72 \cdot (x < 1121)$, $0.40 \cdot (x > 1121)$, $R^2 = 0.99$. 1121 MJ/m² occurred on 5 January 2012.

7.3.1.10 Crop water use

Crops displayed a constant linear relationship ($R^2 = 0.99$) between accumulated DM and E_T (Figure 7.10). Rotationally grazed crops used 460 mm by June 2012 with a WUE of 25.5 kg DM/ha/mm. Set and semi-set stocked crops used 530 mm of water, 15% more with a WUE of 19.3 kg DM/ha/mm, or 24% less.

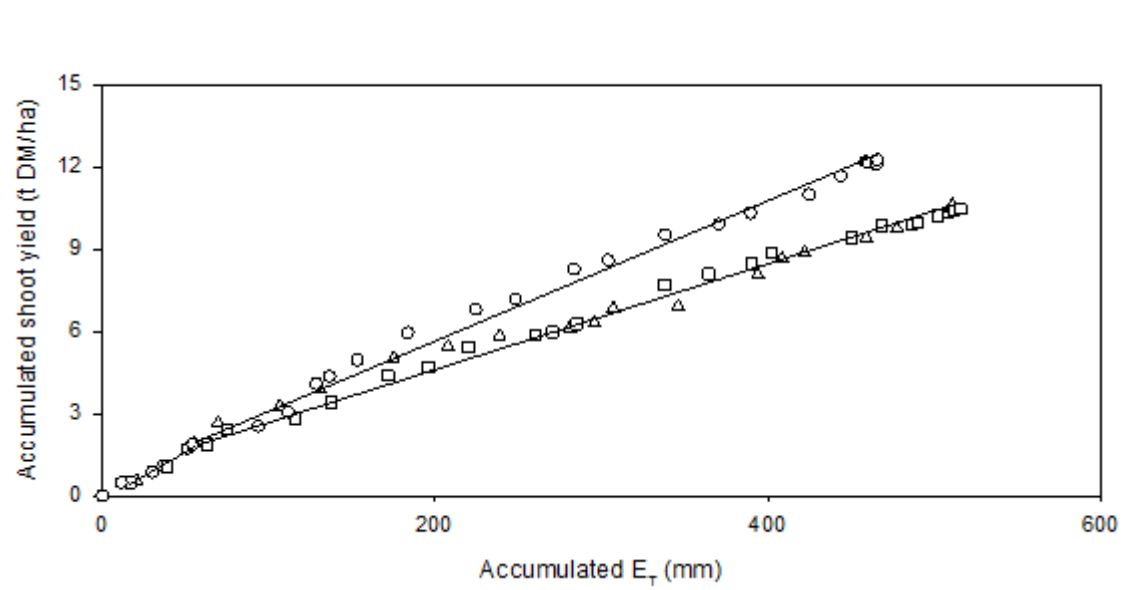


Figure 7.10 Accumulated shoot yield in relation to accumulated crop water use (E_T) for dryland lucerne from June 2011 to June 2012 subjected to three grazing managements treatments; set stocked (\triangle), semi-set stocked (\square) and rotationally grazed (\circ) at Lincoln University, Canterbury, New Zealand.

Note: Broken-stick regressions; ($\triangle \square$) $y = 32.1 * (x < 56)$, $19.3 * (x > 56)$, $R^2 = 0.99$. (\circ) $y = 32.1 * (x < 56)$, $25.6 * (x > 56)$, $R^2 = 0.99$.

7.3.2 The effect of timing of grazing on DM yield, forage quality and water use

The objective of the second part of the results was to determine if manipulating the size of the canopy through grazing affected the amount and timing of crop water use. The data presented are from Experiment four, and include all six paddocks in the rotationally grazed treatment. This contrasts part 1 where only paddock 1 was used.

7.3.2.1 DM yield and interception radiation

Annual yield differed ($P < 0.01$) among paddocks with the highest yield attained in paddocks 2, 4, 5 and 6 of 14.3 t DM/ha, and the lowest in paddock 1 with 12.1 t DM/ha (Table 7.4). RUE_{shoot} was consistent between all paddocks with a mean of 0.59 g DM/MJ, therefore greater DM yield was associated with increased intercepted radiation. The highest yielding paddocks intercepted 2600 MJ/m², compared with the lowest (Paddock 1 and 3) which intercepted 2140 MJ/m².

Table 7.4 Annual dry matter yield (DM; t DM/ha), intercepted total radiation (R_i ; MJ/m²) and shoot radiation use efficiency (RUE_{shoot} ; g DM/MJ) of dryland lucerne within a rotationally grazed six paddock system from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Paddock	DM	R_i	RUE_{shoot}
1	12.1 _c	2144 _{cd}	0.57
2	14.7 _a	2406 _b	0.60
3	12.7 _{bc}	2137 _d	0.60
4	14.4 _a	2276 _{bc}	0.65
5	13.7 _{ab}	2601 _a	0.55
6	14.5 _a	2603 _a	0.58
P	0.006	<0.001	ns
SEM	0.284	37.6	

Note: Means within a column with different letters are significantly different (l.s.d $P = 0.05$). SEM = standard error of the mean, ns = not significant. PAWC determined to 2.3 m.

The pattern of DM accumulation displayed a sigmoidal relationship which was consistent among paddocks (Figure 7.11). Growth started in the first week of September and DM accumulated linearly until early January when about three quarters of total DM had been grown. A further ~ 3 t DM/ha was accumulated over the summer and autumn months.

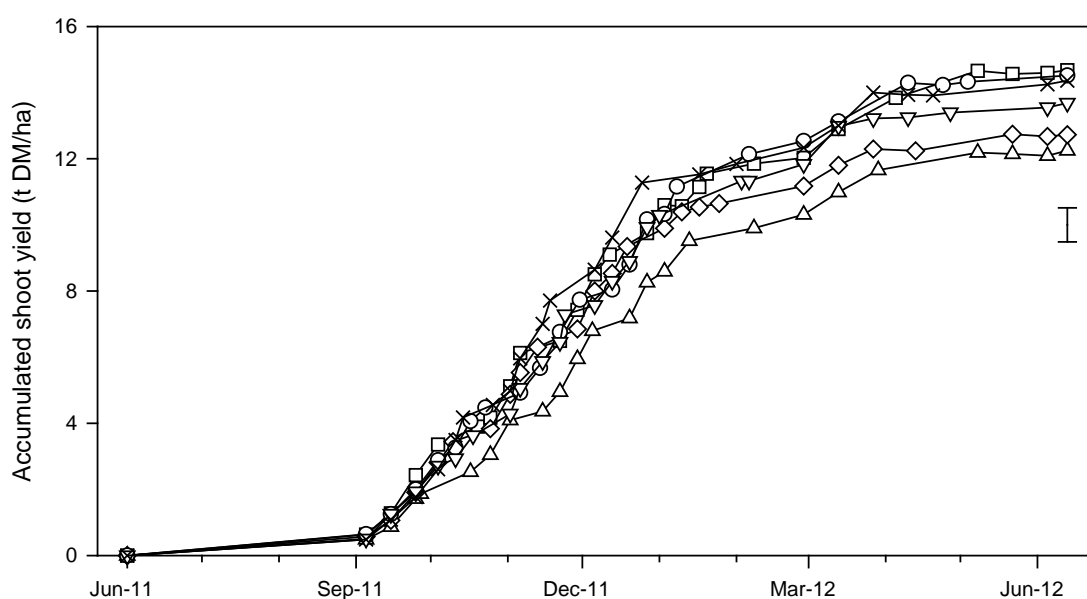


Figure 7.11 Accumulated shoot yield of dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

There was a strong ($R^2 = 0.97$) linear relationship between accumulated shoot yield and intercepted radiation. A broken-stick regression improved the relationship ($R^2 = 0.98$) and was consistent with previous results (Figure 7.12). Crops displayed a $\text{RUE}_{\text{shoot}}$ of 0.71 g DM/MJ from June until mid-January when 1405 MJ/m² of radiation had been intercepted. $\text{RUE}_{\text{shoot}}$ then decreased to 0.40 g DM/MJ, or 45% less, until June 2012.

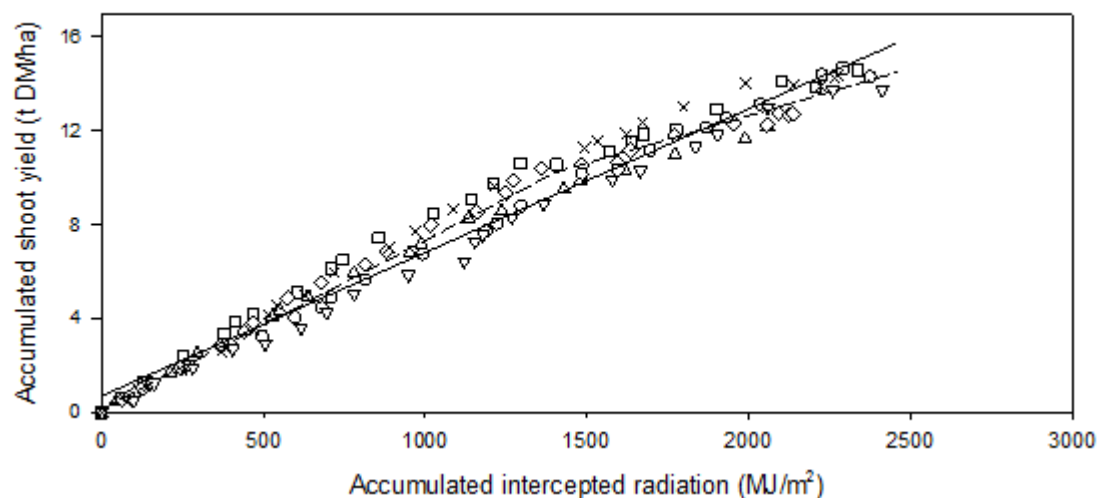


Figure 7.12 Relationship between accumulated shoot yield and accumulated total intercepted radiation of dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Linear regression; (—) $y = 0.61x + 719$, $R^2 = 0.97$. Broken stick regression; (— — —) $y = 0.71*(x < 1405)$, $0.40*(x > 1405)$, $R^2 = 0.98$.

7.3.2.2 Soil water and water use efficiency

The maximum SWD for the six paddocks ranged from 224 mm in paddock 4 to 288 mm in paddock 2 (Table 7.5). Seasonal WUE was constant ($P = 0.651$) among paddocks with a mean of 26.7 kg DM/ha/mm (Figure 7.13). Crop WU and soil evaporation (E_s) were inversely related, for example paddock 6 had the highest ($P = 0.046$) crop WU of 560 mm but the lowest ($P = 0.006$) E_s of 210 mm (Table 7.5). In contrast, paddock 1 had the lowest crop WU of 460 mm and highest E_s of 288 mm.

Table 7.5 Maximum soil water deficit (SWD_{max}; mm), crop water use (E_T; mm), water use efficiency (WUE; kg DM/ha/mm) and soil evaporation (E_s; mm) of dryland lucerne grown within a rotationally grazed six paddock system from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Paddock	SWD _{max}	E _T	WUE	E _s
1	237	460 _c	26.5	288 _a
2	288	521 _{ab}	27.2	280 _{ab}
3	266	468 _c	27.0	259 _{ab}
4	224	513 _b	28.0	247 _{bc}
5	247	502 _b	26.0	205 _d
6	272	559 _a	25.5	216 _{cd}
P	0.749	0.046	0.651	0.006
SEM	ns	19.5	ns	10.5

Note: Means within a column with different letters are significantly different (l.s.d $P = 0.05$). SEM = standard error of the mean, ns = not significant. PAWC determined to 2.3 m.

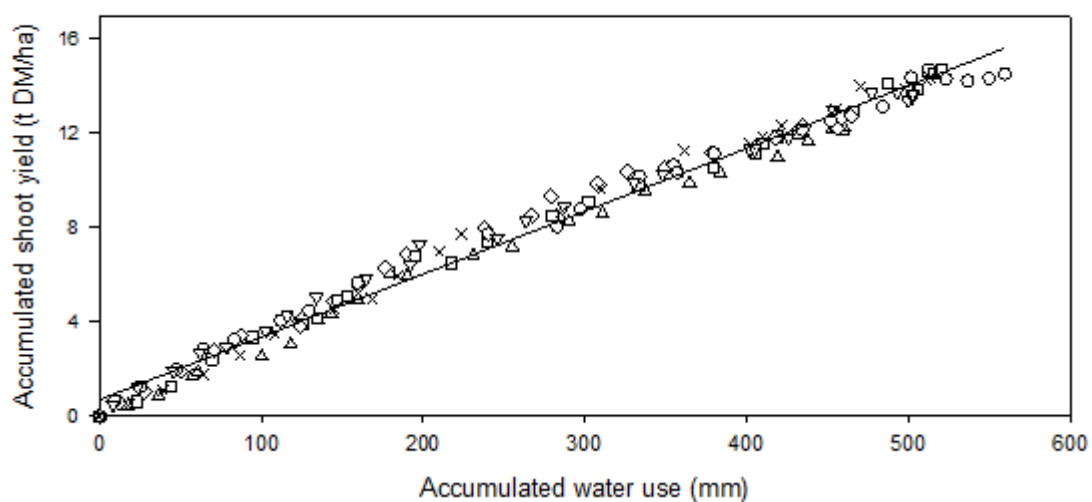


Figure 7.13 Accumulated shoot yield in relation to accumulated water use of dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Linear regression; (—) $y = 26.7x + 711$, $R^2 = 0.99$.

7.3.2.3 Water use and intercepted radiation

There was a strong ($R^2 = 0.97$) linear relationship between accumulated E_T and R_i in all paddocks (Figure 7.14). The mean E_T/R_i was 0.22 mm/MJ/m^2 , which was consistent among paddocks. The analysis of individual paddocks showed the response of E_T in relation to R_i was curvilinear (data not shown), as the E_T/R_i differed between individual regrowth phases. An example of this relationship is shown in Figure 7.15 for paddock one. The E_T/R_i generally decreased for regrowth phases as the season progressed. E_T/R_i was 0.22 mm/MJ/m^2 in the first cycle which decreased to 0.10 mm/MJ/m^2 in the final regrowth phase.

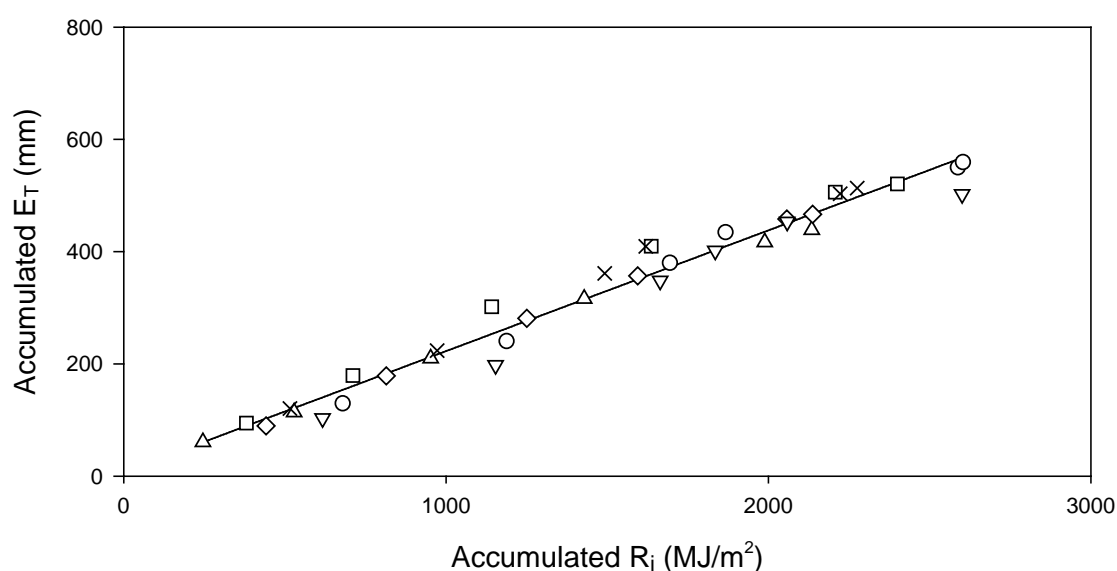


Figure 7.14 Transpiration (E_T) in relation to intercepted radiation (R_i) accumulated for dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Linear regression; (—) $y = 0.22x + 7.6$, $R^2 = 0.97$.

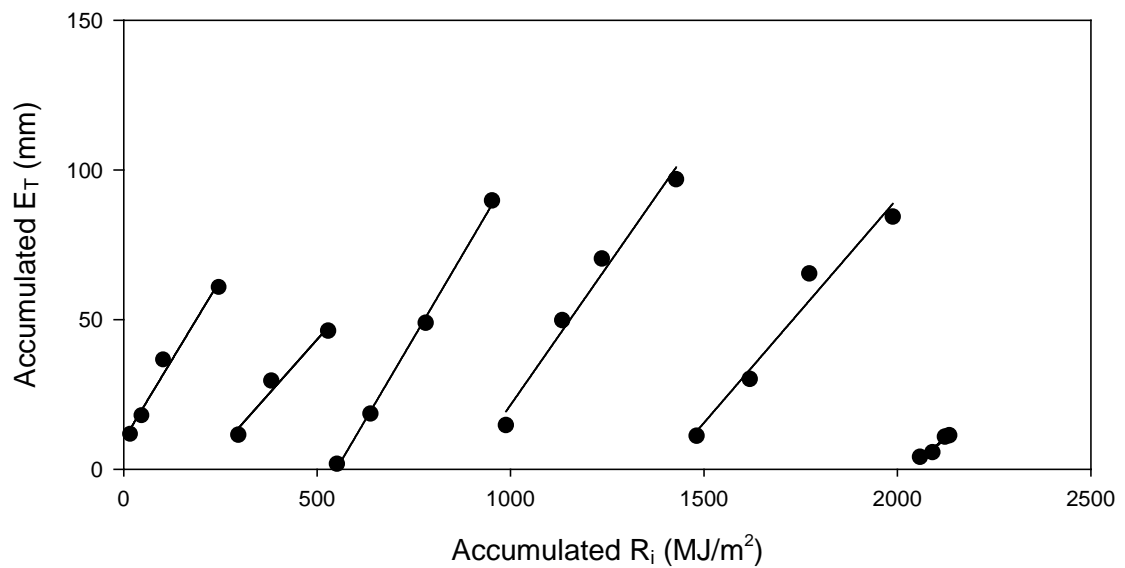


Figure 7.15 Transpiration (E_T) in relation to intercepted radiation (R_i) accumulated within regrowth periods for dryland lucerne within a rotationally grazed six paddock system (paddock one shown) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

The E_T/R_i was plotted against mean vapour pressure deficit (VPD) for individual regrowth phases to explain seasonal variation for all six paddocks. There was no consistent relationship between E_T/R_i and VPD (Figure 7.16), but most values fell below the relationship determined for irrigated lucerne at Lincoln by Brown *et al.* (2012). Values that were consistent with the relationship presented were from the first regrowth phases in spring. These crops displayed an E_T/R_i of ~ 0.21 mm/MJ/m² when the VPD was 0.48 kPa, similar to that of fully irrigated crops shown by Brown *et al.* (2012).

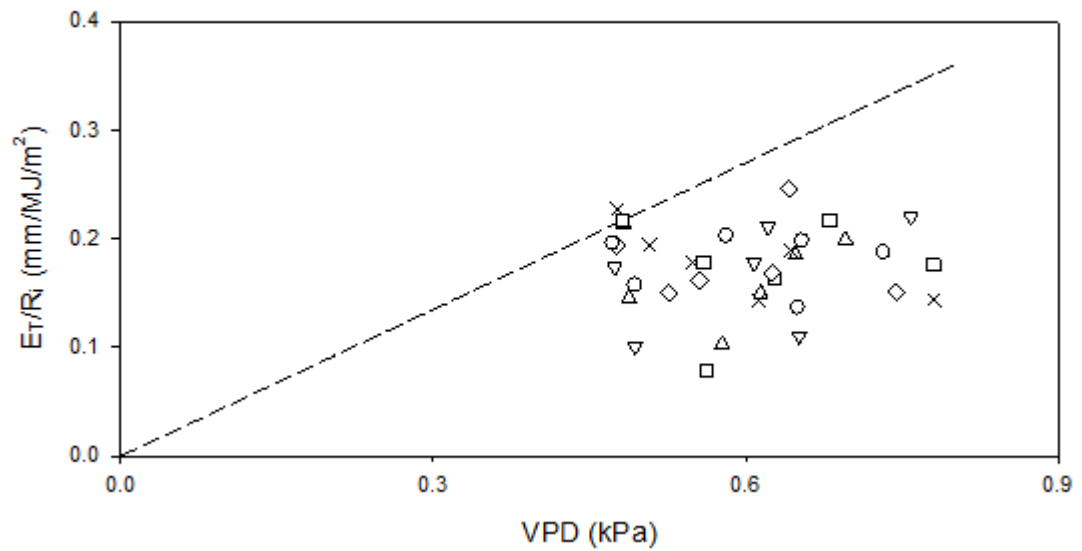


Figure 7.16 Transpiration per unit of intercepted radiation (E_T/R_i) in relation to mean vapour pressure deficit (VPA) for dryland lucerne within a rotationally grazed six paddock system; paddock 1 (\triangle), 2 (\square), 3 (\diamond), 4 (\times), 5 (∇) and 6 (\circ) from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Linear regression; (— — —) $y = 0.45x$, E_T/R_i for irrigated lucerne grown at Lincoln from Brown *et al.* (2012).

7.3.2.4 Forage energy and protein content and leaf percentage

Mean annual lucerne energy and protein content did not differ ($P>0.29$) among the six paddocks under rotational grazing management (Table 7.6). Annual mean energy content was 10.7 MJ ME/kg DM with a total of 146 GJ ME/ha grown for the season. Annual mean CP content was 18.4% with a total of 2.44 t CP/ha accumulated from June 2011 to June 2012.

Table 7.6 Mean and total annual energy and crude protein content of six dryland lucerne paddocks in a rotationally grazed system over six growth cycles from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Paddock	Energy		Crude protein	
	Mean MJ ME/kg DM	Annual GJ ME/ha	Mean (%)	Annual (t CP/ha)
1	11.0	134	20.4	2.45
2	10.9	158	19.0	2.78
3	10.7	136	17.4	2.21
4	10.7	154	18.6	2.63
5	10.4	141	16.5	2.11
6	10.6	150	18.8	2.43
Mean	10.7	146	18.4	2.44
P	ns	ns	ns	ns
SEM	0.312	18.8	1.59	0.27

The percentage of leaf, energy and CP content of DM at final harvest differed ($P<0.05$) among growth cycles and displayed similar seasonal trends over the six regrowth phases (Figure 7.17). The percentage of leaf was 90% in spring which decreased to 70% in the third cycle in mid-summer. Leaf percentage then increased to 85% in autumn (Figure 7.17a). Mean energy content of spring grown lucerne was 11 MJ ME/kg DM which

decreased to 10 MJ ME/kg DM in mid-summer. Energy content then increased to 11 MJ ME/kg DM in autumn (Figure 7.17b). Early season CP content was ~20% in spring which decreased to ~16% by the third regrowth cycle. CP increased to 22% by late autumn (Figure 7.17c).

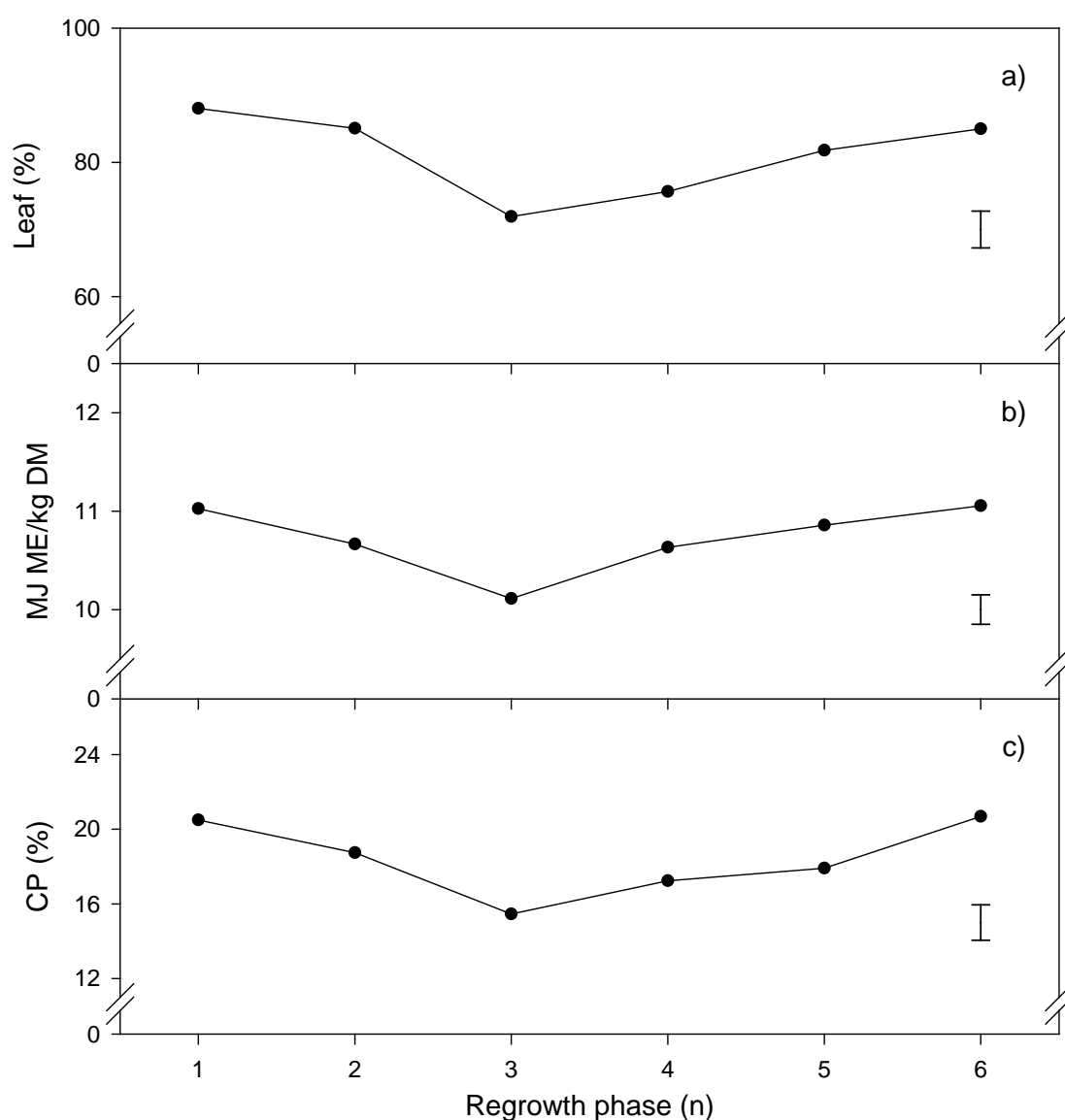


Figure 7.17 Leaf percentage (a), energy content (MJ ME/kg DM ;b) and crude protein content (CP; c) of dryland lucerne at final harvest in a rotationally grazed system over 6 growth cycles from June 2011 to June 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Bar represents l.s.d ($P = 0.05$).

7.3.2.5 *DM yield and utilisation*

Final shoot yield at grazing differed ($P < 0.001$) with date of grazing for the first regrowth cycle (Table 7.7). Shoot yield in paddock 1 was 1.9 t DM/ha when grazing first commenced, which increase to 4.5 t DM/ha in paddock 6, which was grazed 26 days later. The post-grazing residual differed ($P < 0.001$) among paddocks. The residual was lowest in paddock 1 with a mass of 0.3 t DM/ha, which increased to 2.4 t DM/ha in paddock 6. The DM consumed by the ewes and lambs did not differ ($P = 0.15$) among paddocks, but the trend showed up to 2.5 t DM/ha was consumed when shoot yield ranged from 3.4 to 4.1 t DM/ha.

Table 7.7 Date of grazing, DM yield (t DM/ha) and post-grazing residual (t DM/ha), DM consumed (t DM/ha) and utilisation (%) for the first regrowth phase from September to October 2012 for six paddocks within a rotationally grazed system at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Paddock	Start of grazing	DM yield	Residual	Consumed	Utilisation
1	27 Sep	1.87 _c	0.30 _f	1.57	84.0 _a
2	4 Oct	3.36 _b	0.96 _e	2.40	71.5 _b
3	10 Oct	3.44 _b	1.04 _d	2.40	69.8 _b
4	14 Oct	3.68 _b	1.14 _c	2.54	68.9 _b
5	18 Oct	4.13 _{ab}	1.56 _b	2.57	62.3 _c
6	23 Oct	4.47 _a	2.42 _a	2.05	46.7 _d
P		<0.001	<0.001	ns	<0.001
SEM		0.21	0.03	0.29	2.30

Note: Means within a column with different letters are significantly different (l.s.d $P = 0.05$). SEM = standard error of the mean.

Utilisation of DM showed a decrease in relation to shoot yield at grazing (Table 7.7). Utilisation decreased from 85% when shoot yield was 2 t DM/ha to 45% when yield increased to 4.5 t DM/ha. Energy consumption increased from 20 GJ ME/ha to 30 GJ ME/ha when pre-grazing shoot yield doubled from 2 to 4 t DM/ha (Figure 7.18). DM

utilisation and energy consumption were maximised when grazing occurred when shoot yield was ~3.5 t DM/ha.

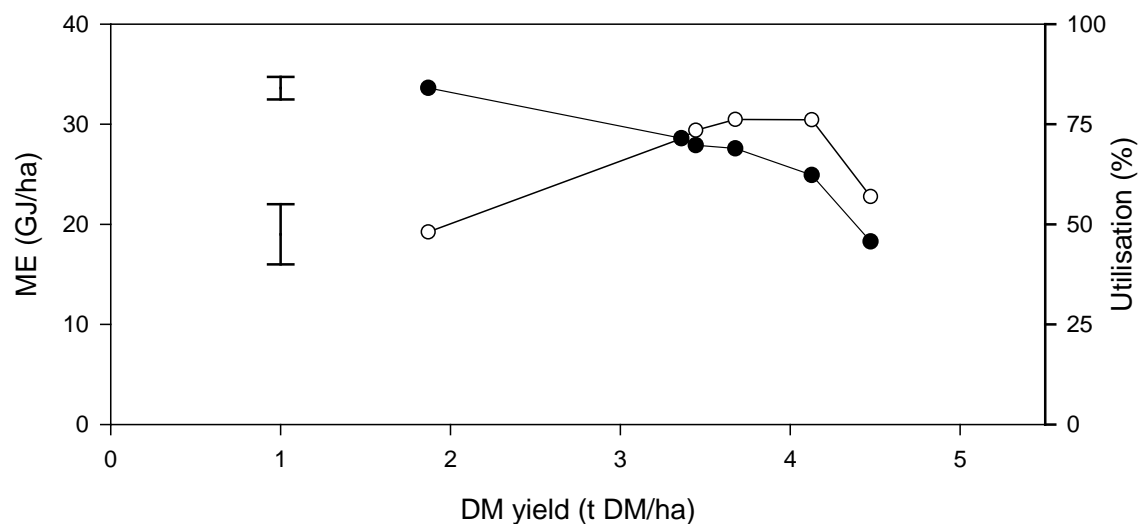


Figure 7.18 Energy (GJ ME/ha; ○) consumption and DM utilisation (●) in relation to DM yield for the first regrowth phase from September to October 2012 for six paddocks within a rotationally grazed system at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Note: Bar represents l.s.d ($P = 0.05$). Energy consumption was calculated based on the assumption the energy content of the residual fraction was 9.4 MJ/kg DM (Brown, 2004).

7.4 Discussion

7.4.1 The effects of grazing management on DM yield

7.4.1.1 *DM yield in relation grazing management*

These results show lucerne can be continuously grazed in early spring. Early season grazing management did not influence DM yield during the grazing period with 6.3 t DM/ha attained in all three grazing treatments; set stocked, semi-set stocked and rotational (Table 7.2). This was achieved because the grazing treatments were imposed when DM cover was ~2 t/ha (Figure 7.1) and crops were experiencing linear growth rates of ~70 kg DM/ha/day (Figure 7.7). Stock density in the continuous grazing treatments was set so maximum feed demand when lambs were close to weaning matched DM supply. A 65 kg ewe with twin lambs growing at 400 grams/day requires ~50 ME MJ/day (Nicol and Brookes, 2007). Lucerne energy content was ~10.8 ME MJ/ kg DM (Figure 7.17), and utilisation of 75% would be expected to maintain this growth rate on a DM cover of ~2.5 t DM/ha (Figure 7.18). This shows an appropriate stocking rate is 11 to 12 ewes/ha. This is lower than the stocking rate used in experiment three (14 ewes/ha), which was limited by the plot size as 1 ewe per plot equated to ~5 ewes/ha. However, this methodology of determining stocking rate means feed demand exceeds supply when grazing is initiated. In the present study DM cover increased to 2.5 t DM/ha in the set stocked plots 10 days after grazing was imposed (Figure 7.1). The result of this was that LAI of 2 to 3 was maintained in the set stocked and semi-set stocked plots throughout the grazing period (Figure 7.2). This meant these plots continued to intercept radiation and growth rates were maintained, relative to rotationally grazed plots. This differed from Janson (1974) who set stocked at about 23 ewes/ha which resulted in forage demand exceeding supply. As a consequence DM cover was ~50% less relative to rotationally grazed lucerne after four weeks, which meant their set stocked plots had to be destocked 10 days earlier than the rotationally grazed lucerne. Which resulted in their rotationally grazed lucerne yielding 30% more than lucerne set stocked in spring.

The results show set stocking is a viable spring grazing management option, but should not be continuously grazed for longer than the spring period. The rotationally grazed

plots intercepted 30% less radiation than both the set stocked and semi-set stocked lucerne but displayed a RUE_{shoot} of 0.73 g DM/MJ compared with 0.37 g DM/MJ in the set stocked and semi-set stocked lucerne (Figure 7.3). This was associated with greater respiration and/or partitioning of DM to the root mass due to the continual initiation of new shoots from basal buds which requires the remobilisation of assimilates stored within the taproot and crown (Avice *et al.*, 1996). Current literature advises against set stocking lucerne as continuous grazing prevents the canopy from expanding, reducing light interception and therefore yield. Also the removal of apical stems requires the continuous formation of basal shoots which depletes root reserves and reduces stand persistence (Section 2.1.4.1). This was observed in the current research and reported in similar aged lucerne subjected to short (28 day) and long (42 day) grazing regimes by Teixeira *et al.* (2007c). The short rotation crop experienced reduced canopy expansion rates which intercepted 45% less radiation which resulted in a corresponding decrease in DM yield.

Intercepted radiation was calculated from a constant extinction coefficient (k) (Equation 2.3). A possible limitation to this is that k was not quantified for set stocked or semi-set stocked lucerne. This was because a large overestimation of LAI occurred when the canopy was measured using the Sunscan canopy analyser due to high levels of residual DM, not associated with leaf area due to trampling by stock. It was assumed that k was unaffected by grazing, and the value of 0.89 measured in Chapter 5 was used to calculate intercepted radiation. Varella (2002) reported a constant k of 0.82 in lucerne subjected to different light regimes. This suggests that the changes in light environment induced by grazing would not be expected to affect k values. For the RUE_{shoot} of the continuously grazed lucerne to equal that of the rotationally grazed crops, k would need to decrease to 0.35, which indicates very erect leaves, which has not been reported in the literature for lucerne, and was not observed in the current research.

Most likely RUE_{total} was consistent among grazing treatments. RUE_{shoot} differed due to differences in the partitioning of DM to root biomass and/or respiration losses associated with increased remobilisation of root biomass when continuously grazing. There is no literature on the effects of set stocking lucerne on RUE_{shoot} . There are two

hypotheses associated with the decrease in RUE_{shoot} under continuous grazing; i) removal of upper canopy layers by grazing resulted in lower, less efficient leaves intercepting the majority of the radiation, or ii) lucerne increased partitioning below ground and/or respiration in response to faster depletion of perennial reserves from continuous grazing.

LAI expansion was proportional to canopy N uptake which was above the critical threshold for maximum LAER (Figure 7.4). This suggests photosynthetic capacity was unaffected by grazing management. Lower layers of the canopy have been shown to contain older leaves (Brown *et al.*, 1966) with lower nitrogen content (Lemaire *et al.*, 1991). Brown *et al.* (1966) reported four week old leaves in the bottom strata of a lucerne canopy were half as efficient in CO_2 uptake as the top leaves when subjected to full radiation. Nitrogen distribution in a canopy is non-uniform and tends to follow the distribution of light (Hay and Walker, 1989). This was shown in lucerne by Lemaire *et al.* (1991) who reported nitrogen content of the leaf decreased exponentially from 0.3 to 0.05 mg/cm² leaf from the top strata of the canopy (0.8 m) to ground level. It is therefore suggested one possibility of the lower RUE_{shoot} in the present study occurred from preferential grazing by sheep, which were observed to remove the upper layers of the canopy first. This may have resulted in the lower canopy layers, which were less efficient converters of radiation into biomass, intercepting a larger proportion of radiation relative to the complete canopy under rotational grazing. This hypothesis is discounted as canopy height measurements showed maximum canopy height was 0.25 m, which decreased to 0.05 m in early December (Appendix 19). The shorter canopy relative to that of Lemaire *et al.* (1991) crops meant the canopy did not experience closure, which reduced the shading of lower leaves. The effect of this was canopy N content was maintained among treatments (Section 7.3.1.4) which is suggested not to affect photosynthetic capacity of the crop under continuous grazing.

The second suggestion is RUE_{total} was constant, however due to higher perennial reserve depletion under continuous grazing, crops experienced higher maintenance respiration, and may also have experienced greater assimilate partitioning below ground to compensate for this. Therefore apparent RUE_{shoot} would decrease. This means lucerne

should not be set stocked for longer than the spring period, and allowed ~6 weeks of uninterrupted growth following the period of continuous grazing, in summer to recharge the perennial reserves (Moot *et al.*, 2003). This is a key determinant of subsequent crop productivity and stand persistence (Teixeira *et al.*, 2007c). Janson (1974) reported a lag period in DM growth following set stocking of lucerne as apical meristems were removed and new growth did not occur until new basal buds were initiated. This constant renewal of basal buds was shown to deplete perennial reserves in lucerne by Teixeira *et al.* (2007b) who reported perennial DM under long grazing rotation (42 day) was ~5 t DM/ha in spring compared with short grazing rotation (28 days) of ~3 t DM/ha. Root mass continued to decline under the short grazing rotation. Root sampling of the current research by Speedy (2012) on November 10 2011 showed perennial DM differed between grazing treatment ($P<0.006$). Rotationally grazed plots had 4.7 t DM/ha compared with set stocked and semi-set stocked which had 3.4 t DM/ha. The increase in annual DM yield of rotationally grazed crops was 1.3 t DM/ha (Table 7.2), which is consistent with the loss in below ground DM of continuously grazed crops. Chapter 4 suggested lucerne had an optimum root mass of ~5 t DM/ha which supports the hypothesis that the continuously grazed crops had lower root biomass and compensated for this by increasing below ground partitioning of assimilate.

7.4.1.2 *DM yield in relation to timing of grazing*

The timing of grazing did not influence annual DM yield. Differences in DM yields were explained by the PAWC of the soil profile, which differed among paddocks (Table 7.5). Annual mean paddock DM yield of the rotationally grazed crops was 13.7 t DM/ha (Table 7.4). This result is consistent with yields attained from the same experiment in the previous season (Stocker, 2011) and within the range of 12 to 18 t DM/ha reported for dryland lucerne in a similar environment (Brown *et al.*, 2006a; Mills *et al.*, 2008b; Moot *et al.*, 2008). Annual yield was almost twice that of the second year crops in Chapter 4. This is a reflection of the higher PAWC of ~250 mm (Table 7.5) compared with 130 mm. The further extraction of 120 mm of would equate to an extra ~3 t DM/ha based on a WUE of 25 kg DM/ha/mm (Table 7.5).

7.4.2 The effects of grazing management on forage quality

Grazing method and timing did not affect lucerne energy or protein content (Figure 7.17). Forage quality displayed a seasonal trend with a decrease in both energy (11.5 to 10 MJ ME/kg DM) and CP (25 to 15%) from spring to summer. This trend was consistent with the fraction of leaf material which decreased from 90% to 70% from spring to summer (Figure 7.17a). Brown *et al.* (2005a) reported lucerne had relatively stable leaf and stem ME and CP contents, and forage quality was predominantly driven by the leaf to stem ratio. A decrease in both quality parameters occurred when SWD was ~120 mm (Figure 7.8), which was ~50% of PAWC (Table 7.3) which indicates the lucerne was under water stress. Chapter 6 showed water stressed lucerne experienced lower LAER and reduced LAI, this would reduce the leaf to stem ratio and therefore forage quality. This was shown in the current research with maximum forage quality attained when the leaf contributed >90% of total shoot DM which declined when leaf content decreased to ~70% (Figure 7.17a).

Optimum grazing duration can be determined using the ‘breaking point method’ (Section 7.2.3.6). This method gives a suitable indication of proportion of stem hence the lower quality forage which should not be grazed to maximise liveweight gain in lambs. There was a strong positive linear relationship ($R^2 = 0.81$) between stem content and post grazing residual in the rotationally grazed crops (Appendix 20). However the stem content, measured by the ‘breaking point method’, systemically underestimated the residual by ~0.3 t DM/ha. This supports Brown (2004) suggestion that the ‘breaking point method’ (Section 7.2.3.6) can give a good representation of the stem fraction. This means as pre grazing mass increases so does the residual (Table 7.7) and the optimum pre-grazing mass is ~3.5 t DM/ha when both DM utilisation and energy consumption are maximised (Figure 7.18).

Lucerne is a quality forage and maintains superior livestock production when compared with ryegrass based pastures in the same dryland environment. Annual ME and CP was 150 GJ/ha and 2.5 t/ha, respectively (Figure 7.5) which is comparable to that reported for dryland lucerne by Brown (2004). This result is higher than that reported for dryland grass based pasture by Mills (2007) which showed N deficient cocksfoot

produced ~50% less DM than that of the lucerne in the present study and had an annual ME and CP content of 50 GJ/ha and 0.6 t/ha, respectively. The consistent seasonal quality of lucerne in the current research supported total annual liveweight gains of ~900 kg/ha, 60% more than that of a dryland grass based pasture in the same environment and season (Speedy, 2012). This was consistent with that of Brown *et al.* (2006a) which reported annual LWG of 950 kg/ha, 50% higher than a cocksfoot based pasture.

7.4.3 The effects of grazing management on water use

7.4.3.1 Water use in relation to grazing management

Grazing management did influence crop water use, but annual yield was unaffected because total water use (transpiration and soil evaporation) was consistent among crops. The lower crop WU for rotationally grazed lucerne was off-set by higher soil evaporative losses of 128 mm compared with 76 mm for set and semi-set stocked crops (Table 7.3). This resulted in total water use of ~360 mm for all grazing treatments from June 2011 to 5 December 2011 (Figure 7.5). Set stocked and semi-set stocked crops used 290 mm, 20% more water than the rotationally grazed crop (Table 7.3). But, these crops had a WUE of 21.3 kg DM/ha/mm, compared with 30.5 kg DM/ha/mm with the rotationally grazed crop, therefore arrived at similar DM yields for the same period. Most likely the lower WUE shown by the continuously grazed crops is a reflection of the lower shoot yield due to greater respiration costs associated with continual shoot production. These WUE values were in the range reported in Chapter 6 and the upper value is consistent for dryland lucerne (Brown, 2004; Tonmukayakul *et al.*, 2009).

Crop WU among the grazing treatments was explained by the pattern of LAI, but E_T and E_S were inversely related, therefore there was no net effect on total WU with grazing management. Crop water demand is driven by evapotranspiration and is proportional to canopy size (French and Legg, 1979) as intercepted radiation (R_i) provides the energy for water evaporation (Asseng and Hsiao, 2000). E_T increased linearly in response to R_i at 0.19 mm/MJ/m² which was consistent among grazing treatments. The rotationally grazed crops which had a mean LAI of 1.1 compared with

set stocked and semi-set stocked crops which had an LAI of 2.1 for the duration of the grazing period (Figure 7.2), intercepted 30% less radiation (Figure 7.3) and therefore E_T was proportionally reduced. But, the smaller canopy of rotationally grazed crops exposed the soil surface to higher evaporative losses as per the soil evaporation (E_S) model when soil moisture was above the lower limit of extraction (Ritchie, 1972). Rainfall twice the long term monthly mean in October and regular rainfall events in November and December (Figure 3.2) maintained the soil water content of the top layer of ~20%. This resulted in higher E_S experienced in these crops, and therefore a consistent total WU. The results from this study suggest grazing management did not affect the temporal pattern of water use, however the relationship between E_T and E_S is an important result. If E_S was reduced and more water was lost via transpiration yield gains could be made. This may occur in a drier climate, where the soil surface is dry and E_S is minimised, however Harrison *et al.* (2011) showed in Australian conditions, where annual rainfall is half of that in the present study total WU was maintained by increased E_S when a wheat crop was defoliated.

7.4.3.2 *Water use in relation to time of grazing*

Timing of grazing manipulated the pattern of leaf area and influenced crop water use. Crop WU was driven by intercepted radiation, therefore grazing removed leaf area which lowered the water loss through transpiration. But, similarly to Experiment 3 total water use was unchanged as E_S increased proportionally. WUE was 26.7 kg DM/ha/mm and unaffected by time of grazing (Figure 7.13). Differences in DM yields attained (Table 7.4) were related to differences in PAWC of the soil within individual plots and the proportion of this water which was transpired by the canopy (Table 7.5). Generally, the later grazed plots in spring had a longer duration of the canopy above the LAI_{crit} which increased water loss through E_T , compared with E_S . Grazing reduced leaf area which lowered water loss through transpiration, however total water use was unchanged as E_S increased proportionally.

Canopy expansion and duration explained E_T as the relationship between R_i and E_T was consistent among paddocks (Figure 7.14). E_T/R_i of individual regrowth phases ranged from 0.10 to 0.22 mm/MJ/m² (Figure 7.15), and there was no apparent relationship

between E_T/R_i and VPD (Figure 7.16). VPD is the difference in the saturated vapour pressure at a given temperature and actual vapour pressure which creates the difference in water vapour concentration between stomata and the external air that drives E_T (Tanner and Sinclair, 1983). When VPD increases, E_T increases but there is no associated increase in photosynthesis, therefore the transpiration efficiency (TE) decreases. Brown *et al.* (2012) showed for lucerne, when the reciprocal of TE ($1/TE$) was regressed against VPD for individual regrowth phases the relationship was inconsistent ($R^2 = 0.19$). But, when $1/TE$ was plotted against air temperature there was a linear increase ($R^2 = 0.64$) from 1.5 Pa at 7 °C to 3.0 Pa at 17 °C. This implies DM yield would be maximised in crops that experience greater E_T at lower VPD. Therefore in the current research, greater yield would be associated in the crops where grazing was delayed as these experienced a higher proportion of E_T during the early spring when VPD was the lowest. However this was not evident. The E_T/R_i in relation to VPD was below the threshold presented by Brown *et al.* (2012) for fully irrigated lucerne in the same environment which suggests E_T was restricted by supply, rather than demand. This represents stomata closure in response to high radiation load was due to water stress when water demand exceeds supply. This is consistent with the results in Chapter 6, which showed on a similar soil type E_T was limited by PAWC of the soil. Therefore the manipulation of LAI through timing of grazing did not have a significant effect on yield as E_T was restricted by water supply rather than the demand from the canopy.

Grazing management did not significantly influence the timing of DM production and the spring feed surplus could not be transferred to later in the season. In fact, the results showed an increase in WUE would be expected with greater spring production due to a higher proportion of water lost via E_T when VPD is lowest. Grazing removes leaf area which reduces crop water use, however the trade-off is an increase in E_s , and total WU is unchanged. Lucerne can be set stocked in spring, this is an important result because it increases the flexibility of lucerne management. The cost of set stocking is greater demand on perennial reserves, this has to be replenished to maintain stand productivity and persistence.

7.5 Conclusions

These results suggest the alternative grazing strategies investigated do not compromise DM yield or quality. However, longer term analysis, particularly of lucerne root biomass is required to determine the effects of these strategies on lucerne stand productivity and persistence. Grazing management did influence crop water use by manipulating canopy size, however due to regular rainfall the trade-off of a smaller canopy was met with proportional increases in soil evaporation. Specific conclusions are:

- Spring grazing management from September to early December did not influence DM yield, 6.3 t DM/ha was achieved from set stocked, semi-set stocked and rotationally grazed lucerne. But, annual yield was 1.5 t DM/ha greater in the rotationally crop by June.
- Grazing management did not influence DM quality, however quality decreased from September to December; ME decreased from 11 to 10.5 MJ/kg DM and CP from 25 to 15%.
- Crop water use was 0.19 mm/MJ of intercepted radiation for the spring grazing treatments. Continuously grazed crops had a larger canopy throughout the grazing period, which intercepted 30% more radiation than the rotationally grazed crops.
- Annual WUE was 26.7 kg DM/ha/mm for the six paddock rotation regardless of timing of grazing. Early grazing reduced LAI, which reduced E_T . However because crop water use and soil evapotranspiration were inversely related, total WU was consistent.

8 General Discussion

8.1 Introduction

The aim of this thesis (Section 1.3) was to refine best management practices for dryland lucerne crops in relation to water extraction. The general discussion summaries key physiological results from individual results chapters and uses these to discuss their implications for best management practices for lucerne. Opportunities for further research are also highlighted.

8.2 Lucerne establishment and yield

To maximise DM yield lucerne should be spring sown, however from the 20 lucerne crops established over two seasons at two different sites all crops established with >200 seedlings/m² within one month after sowing (Figure 4.2). DM yield in the establishment year was reduced by 16 kg/ha/day at Ashley Dene and 114 kg/ha/day at Iversen 12 when sowing was delayed from December to February (Figure 4.5). The delayed sowing means crops intercepted less radiation which is a key driver of yield (Equation 2.1). Furthermore, partitioning of DM between shoot and root compounded the decrease in yield with delayed sowing. For example, at Iversen 12 the October sown crop partitioned 30% of total DM below ground which increased to 50% when sown in February (Table 4.6). Results suggest the root has a greater sink strength for assimilates compared with the shoot, and crop ontogeny overrode environmental signals to maintain allocation of DM below ground to meet a biomass requirement of 4 to 5 t/ha (Figure 4.11). This explained the decrease in shoot yield with delayed sowing in the second season. At Iversen 12 the early sown crop had an annual DM yield in the second season of 21.5 t DM/ha compared with 15.8 t DM/ha for the late sown crops (Table 4.4). However, the late sown crops partitioned ~2.5 t DM/ha more below ground than the early sown crop, thus total DM was more comparable. This apparent level of desired root mass supports other studies of lucerne grown at Iversen Field (Brown, 2004; Teixeira, 2006) and Ashley Dene (Speedy, 2012) and in other temperate environments (Thiebeau *et al.*, 2011). These results show the establishment phase was not limited solely to seedling lucerne, rather it appears to be strongly influenced by the

crops demand to meet this biomass. This is an important result for crop physiologists. It explains the observation lucerne can take up to 12 months to reach full production (Moot *et al.*, 2012) and challenges the suggestion that defoliation triggers lucerne to change its physiology between seedling and regrowth crops (Teixeira *et al.*, 2011; Thiebeau *et al.*, 2011). Further data are required to build stronger relationships between the allocation of DM during establishment and yield forming components, such as canopy development and LAER (Appendix 12), which would further add to the current partitioning framework presented for regrowth crops (Figure 2.7).

Lucerne should be spring sown to maximise potential yield in the establishment and subsequent season. When confronted with a February sowing date, an alternative species with greater cool season growth such as forage cereal or brassica would be expected to increase production three fold in this environment (Figure 4.13). This could increase feed supply over the autumn and winter period when lucerne growth rates are minimal ($<3 \text{ kg DM}/^{\circ}\text{Cd}$; Figure 4.8) and should not be grazed (Moot *et al.*, 2003). Sowing lucerne in the following spring is then recommended. Results from the present study highlights the importance of quantifying below ground DM in physiological studies as it appears crop ontogeny prioritised root growth over shoot DM, which would influence shoot yield.

8.3 Water supply and demand

When PAWC is known, yield can be predicted and management decisions can be made to increase crop productivity in a water scarce environment. One recommendation is to time the final grazing to coincide with maximum SWD to reduce the impacts of water stress and loss in yield and forage quality through crop senescence. A second inference is that lucerne can be strategically sown to provide a feed supply when established stands have exhausted soil water and growth has ceased. In this study, yield was largely determined by the amount of water extracted from the soil. Crops at Ashley Dene extracted 130 mm to depth of $\sim 2.3 \text{ m}$ (Figure 6.4) and crops at Iversen 12 extracted 360 mm (Figure 6.5). Water supply is determined by the PAWC of the soil profile, the EFV and $-k_l$ (Section 2.5.1). Seedling crops displayed a consistent EFV of 14 mm/day. The constant EFV of seedling lucerne between sites shows water supply had little influence

on root growth and it was most likely under genetic control of the crop at this stage. This explains the consistent DM yields of crops in the establishment season at Ashley Dene of ~1 t DM/ha per growth cycle (Figure 4.6). The advancing root front accessed about 0.85 mm of stored water per day, water used is the minimum of supply and demand (Equation 6.1), therefore this determined yield. This result increases reliability of predicting WU for first year crops. This can be used strategically within a farm system to provide feed at key times. For example, dryland lucerne growth normally ceases mid-summer on light soils where all stored water is exhausted. This was shown in the second year crop in the present study at Ashley Dene. For the regrowth crop at Ashley Dene, which had an EFV of 32 mm/day (Figure 6.8) and a maximum extraction depth of ~2.5 m, this would be expected to occur ~2.5 months after growth initiated. In a normal year this would be mid-December. Lucerne can be sown in spring to provide feed during these times, particularly when quality feed is required such as mating of ewes in late summer.

A single EFV and $-kl$ were inappropriate when predicting water extraction rate among crops. The EFV for second year crops at Ashley Dene was 32 mm/day, or double that of crops at Iversen 12. This explains why stored water was exhausted mid-summer and growth ceased for these crops. This shows the EFV of regrowth crops was influenced by water supply and demand, and the crops at Ashley Dene compensated for the lower PAWC by doubling the rate of extraction down the soil profile. The soil could only supply about 70% of crop demand when SWD was minimal (Figure 6.13), which means, although the crop compensated by doubling the EFV the soil still could not supply water to meet demand and water stress developed. This is an important finding, as there are few reports on the influence of stones in the soil profile and the effect on water extraction. More data are required to confirm this finding. To do this, the transpiration of fully watered lucerne crops grown on both soil profiles should be compared. If the hypothesis holds, then the transpiration would be lower on stony soil and represent water supply from the soil compared with the crop on the deep soil where transpiration would represent crop demand.

8.4 Mechanisms responsible for a reduction in yield under water stress

Future research should use the supply and demand method rather than the site and crop specific critical limiting deficit framework to quantify water stress. Water stress can be quantified as transpiration (E_T) in relation to demand (EP_T) and related to yield forming components to allow comparisons between crops and sites. This is important because the critical limiting deficit method is site and species specific. This method uses SWD as a measure of water stress and relates it to yield to define a critical level where yield is decreased (Penman, 1971). Furthermore, it offers no explanation of the mechanisms responsible for the yield decrease. A reduction in LAER was the main mechanism to reduce intercepted radiation which drives transpiration. This result supports the hypothesis of Chapter 7, that grazing could be used to manipulate crop water use, and therefore a management tool to alter the timing of DM production and water stress in dryland environments. LAER decreased to 10% of the expected maximum rate when water supply was less than 60% of crop demand (Figure 6.16a). A reduction in LAER was attributed to both a decrease in leaf number and size. Leaf number was decreased due to; a reduction in mainstem node appearance (Figure 6.14), branching rate (Figure 6.15) and stem number (Section 5.3.1.7). Individual leaf size for crops at Ashley Dene was on average 75 mm², or 60% smaller than for crops at Iversen 12 (Figure 5.16). Leaf size explained 82% of the variation in LAER which increased linearly at a rate of 0.00008/°Cd per mm² when individual leaf size increased from 20 to 150 mm² (Figure 5.17). This result shows consistent relationships between water stress for crops grown on both sites and supports the framework for quantifying water stress for lucerne presented by Brown *et al.* (2009). This was shown when data from the current research were redrawn on their results (Figure 6.17), showing the mechanisms responsible for yield loss do not change between seasons and sites, rather the level of stress.

When describing crop partitioning dynamics in relation to environmental factors (Figure 2.7), the relationships are likely only relevant where crop ontogeny does not take priority. This was shown first by crop ontogeny prioritising DM allocation to the roots during the establishment phase and, secondly at Ashley Dene where crops displayed a high level of partitioning to the roots throughout the entire season. These results

suggest that the current framework for the prediction of shoot yield based on RUE_{total} of 1.6 g DM/MJ, adjusted for temperature and then partitioning (Section 2.4) is unsuitable for establishing and water stressed crops. An alternative could be to describe partitioning in relation to the root mass. Partitioning was maintained at the maximum rate until the root mass is satisfied, thereafter the current framework is used. However, the majority of root sampling occurred in the establishment season in the present study and therefore the results are compounded by sowing date. Further data linking absolute root mass and partitioning are required to confirm the proposed relationship.

8.5 Grazing management

These results showed set stocking lucerne did not influence DM yield during the spring grazing period (Table 7.2). This increases the flexibility of spring lucerne management for farmers. Many farmers see the need to rotationally graze lucerne in early spring as a major disadvantage as this coincides with lambing where it is preferable to set stock ewes to minimise disturbance (Kirsopp, 2001). The key outcome of this part of the research was that by understanding the formation of yield (Section 2.2), grazing management could be refined to minimise the loss in yield reported in the literature. To do this, set stocked crops needed to maintain a canopy close to full, around 2.5 t DM/ha, to maximise intercepted radiation, and therefore potential yield. Stocking rate should be based on lucerne growth rate and maximum animal demand at the end of the grazing period. This means initial feed supply exceeds demand, which allows the crop canopy to expand, and maintains radiation interception. The results explain the failure of previous set stocking experiments, which often resulted in continuously grazed lucerne yields up to 75% less than rotationally grazed crops (Section 2.1.4.1). However, lucerne should not be grazed from July until mid-September (Moot *et al.*, 2003), which means farmers who rely on lucerne for a large (30-40%) proportion of feed during spring report lambing two to three weeks later compared with ryegrass based pastures (Kirsopp, 2001; Moot, 2012). This is seen as a major disadvantage of lucerne, with the perception that later lambing reduces the number of early lambs sold at a premium, and increases the risk of lower sale weights due to the onset of drought. But, farmers report liveweight gains for lambs from birth to weaning of 250 to 400 g/head/day when grazing lucerne compared with 150-250 g/head/day when grazing ryegrass/cocksfoot

pastures (Avery *et al.*, 2008; Mills *et al.*, 2008a; Ates, 2009). The high growth rates on lucerne allows farmers to finish stock earlier and at higher weights (Avery *et al.*, 2008), albeit with a later lambing date, compared with ryegrass pastures.

Lucerne should not be set stocked for longer than the early spring period. An implication of set stocking for the entire spring period is crops are more susceptible to invasion by weeds. This is because frequent rains and the incomplete canopy allows seeds to germinate and compete for light (Palmer, 1982). A more appropriate duration could be to set stock for 6 weeks, or about the expected length of one grazing rotation in a 6 paddock system. Set stocked and semi-set stocked crops displayed a RUE_{shoot} about half of that for rotationally grazed crops. This was associated with greater respiration and/or partitioning of DM to the root mass due to the continual initiation of new shoots from basal buds which requires the remobilisation of assimilates stored within the taproot and crown (Avice *et al.*, 1996). Perennial reserves are a key determinant of subsequent crop productivity (Thiebeau *et al.*, 2011) spring productivity (Teixeira *et al.*, 2007c) and stand persistence. Therefore, it is suggested lucerne should not be continuously set stocked all year, but allowed ~6 weeks of uninterrupted growth, following the period of continuous grazing, in summer to recharge the perennial reserves (Moot *et al.*, 2003).

8.5.1 Grazing management and water use

Crop water use was influenced by spring grazing management, but annual yield was unaffected because total water use (transpiration and soil evaporation) was consistent among crops. WU per unit of intercepted radiation (E_T/R_i) was 0.19 mm/MJ/m² and consistent among crops (Figure 7.6). This means grazing removed leaf area which decreased crop transpiration, and therefore would alleviate the impact of water stress. However, this did not influence DM yield because intercepted radiation did not limit yield, rather water supply did. Total water use was consistent among crops because transpiration and soil evaporation (E_s), were inversely related. Therefore, mitigating E_s losses, and increasing the proportion of water lost via transpiration would increase yield. Grass based pastures often have complete ground cover and E_s is minimal and disregarded from the water balance (Mills, 2007). This study should be repeated on a

lucerne/grass mixed pasture to limit E_s and on a deep soil where transpiration is not limited by water supply which would maximise the amount of water available for crop use.

In spring, delayed grazing maximised yield for crops in the first rotation (Table 7.7), but the optimum yield for grazing, when utilisation and energy intake were maximised was ~3.5 t DM/ha. Delayed grazing increased intercepted radiation, when water supply did not constrain transpiration and E_T/R_i was similar to that of a fully irrigated crop (Figure 7.16). This meant a larger proportion of water was transpired when VPD was the lowest which increased WUE, and yield. However, as yield increases the proportion of leaf to stem decreases, which reduces forage quality (Section 2.1.3). This reduces utilisation of DM by livestock. For example, in the first rotation, paddock one yielded 1.9 t DM/ha and had an utilisation of 85%. Paddock 6, grazed about one month later yielded 4.5 t DM/ha and utilisation was 45% (Table 7.7). The optimum grazing time was when shoot yield was about 3.5 t DM/ha, and utilisation of DM and energy intake were maximised (Figure 7.18). In a rotational grazing situation, the first paddock needs to be grazed before this optimum yield to maintain the quality of the following paddocks, particularly at the end of the rotation. The timing of the start of grazing and the stocking rate at which to graze is a key decision which depends on lucerne growth rate, which is driven by environmental variables, but regulated by available water in a dryland situation. Physiological relationships formed in this thesis could be used in future research to validate agronomic recommendations, to maximise the productivity of lucerne in regard to WU, in dryland farm systems. For example, often one paddock is removed from the grazing rotation to be conversed as hay or silage. This often occurs later in the season, however an improved use of water may be to cut the last paddock in the first rotation, paddock six in the present study. This would allow maximum WUE from greater transpiration when VPD is lowest, and high utilisation would be maintained from mechanic defoliation.

8.6 Conclusions

The research presented in this study has refined best management practices for dryland lucerne crops in relation to water extraction. This was achieved by quantifying the development and growth of dryland lucerne in relation to the availability of water as influenced by soil PAWC, sowing date and grazing management. The availability of water affected canopy development and expansion and therefore radiation interception. Yield was explained by differences in intercepted radiation and the efficiency with which it was converted into biomass. Specific conclusions were:



- Lucerne should be spring sown. When sown in October, crops produced 2.5 t DM/ha and 12 t DM/ha at Ashley Dene and Iversen 12, respectively. Delayed sowing beyond December reduced yield by 16 kg DM/ha/day at Ashley Dene and 114 kg DM/ha/day at Iversen 12.
- The EFV for lucerne in the establishment year was ~14 mm/day, but decreased when crop water demand was less than supply. The PAWC of the soil influenced the EFV of second year crops, which doubled at Ashley Dene. Further research is required to fully understand the influence on water demand and supply on the EFV.
- The low PAWC soil at Ashley Dene appeared to be insufficient to supply water to meet crop demand at any time. This requires further research. Understanding the influence of water stress on yield is most important to refine best management practices for these crops.
- The effect of water stress on crop canopy development, expansion and RUE, displayed consistent relationships between sites. Water stress was quantified as transpiration (E_T) in relation to demand (EP_T) which was EP adjusted for R/R_o . E_T/EP_T was compared with yield forming processes.

- Lucerne can be set stocked in spring. Lucerne should be set stocked at a rate to maintain a canopy cover of ~2.5 t DM/ha to maximise radiation interception. Set stocking appears to deplete root reserves faster than rotationally grazing lucerne, which resulted in annual yields of continuously grazed crops 1.5 t DM/ha less than when rotationally grazed.
- Grazing management did not influence total water use. Transpiration and soil water evaporation were inversely related. Additional research is required to determine strategies to reduced soil evaporation in dryland lucerne systems which may result in yield increases.

Appendices

Appendix 1 Experimental plan for Ashley Dene and Iversen 12.

Rep 1					Rep 2				
SD5	SD2	SD1	SD3	SD4	SD4	SD1	SD2	SD5	SD3
1 CS	2 AS	3 BS	4 BS	5 AS	86 SD9	87 SD6	88 SD7	89 SD10	90 SD8
6 BS	7 PS	8 CS	9 AS	10 BS	21 CS	22 PS	23 AS	24 PS	25 AS
11 AS	12 BS	13 AS	14 PS	15 CS	26 BS	27 AS	28 BS	29 BS	30 CS
16 PS	17 CS	18 PS	19 CS	20 PS	31 PS	32 CS	33 CS	34 CS	35 BS
81 SD10	82 SD7	83 SD6	84 SD8	85 SD9	46 AS	37 BS	38 PS	39 AS	40 PS
Rep 3					Rep 4				
SD2	SD5	SD4	SD3	SD1	SD4	SD3	SD1	SD2	SD5
41 AS	42 PS	43 BS	44 CS	45 AS	61 AS	62 PS	63 BS	64 AS	65 BS
91 SD7	92 SD10	93 SD9	94 SD8	95 SD6	66 PS	67 CS	68 AS	69 CS	70 AS
46 PS	47 CS	48 PS	49 PS	50 CS	71 CS	72 AS	73 CS	74 PS	75 PS
51 CS	52 AS	53 CS	54 BS	55 BS	96 SD9	97 SD8	98 SD6	99 SD7	100 SD10
56 BS	57 BS	58 AS	59 AS	60 PS	76 BS	77 BS	78 PS	79 BS	80 CS

	Plots sown 2010/11	Method of inoculation	
	Plots sown 2011/12	AS	ALOSCA
		BS	Bare
		CS	Coated
		PS	Peat

Appendix 2 Soil test results for paddock M2B at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Sowing		pH ¹	P	K	Ca	Mg	Na	S(SO ₄)	N ²
date	Date		Mg/L	-----Me/100g-----				Mg/kg	Kg/ha
Initial	29 Sep 10	5.5	16	0.41	9.1	0.58	0.12	7	-
1	21 Oct 10	6.0	14	0.24	9.3	0.54	0.16	10	42
2	9 Nov 10	6.0	14	0.26	11.3	0.61	0.17	10	44
3	8 Dec 10	6.0	15	0.22	12.2	0.55	0.18	11	71
4	13 Jan 11	5.9	14	0.22	11.9	0.51	0.20	10	102
5	3 Feb 11	6.1	17	0.25	14.7	0.55	0.20	13	100
1-5	10 Jun 11	6.5	12	0.21	11.8	0.49	0.15	10	-
6	10 Oct 11	6.6	27	0.35	15.7	0.63	0.18	65	31
7	7 Nov 11	6.5	31	0.30	12.7	0.55	0.15	34	25
8	9 Dec 11	6.7	28	0.22	12.8	0.46	0.13	35	27
9	10 Jan 12	6.1	24	0.32	11.2	0.50	0.14	41	47
10	17 Feb 12	6.6	29	0.27	14.7	0.45	0.15	50	67
1-5	11 Jul 12	6.3	14	0.26	10.9	0.46	0.12	17	116
6-10	11 Jul 12	6.4	17	0.21	10.2	0.44	0.11	19	30
Lower optima		5.3	20	0.26	-	0.34	-	11	-

Note: Samples from sowing date 1-5 treatments were pooled at the end of the first (10 June 2011) and second (11 July 2012) season and sowing date 6-10 treatments were pooled at the end of the second season (11 July 2012). Soil tests were carried out using the Ministry of Agriculture and Fisheries Quick test (MAF QT). Lower optima for plant growth from Morton and Roberts (1999).

¹Soil pH determined by H₂O extraction.

²Mineral nitrogen is the sum of nitrate and ammonium nitrogen, calculated on a dry weight basis, with bulk density of cultivated soil at 1.2 g/cm³ (McLaren and Cameron, 1990) and adjusted for stone content of 38% in the 0-150 mm layer.

Appendix 3 Soil test results for Iversen Field paddock 12 in the Field Service Centre, Lincoln University, Canterbury, New Zealand.

Sowing		pH ¹	P	K	Ca	Mg	Na	S(SO ₄)	N ²
date	Date		Mg/L	-----Me/100g-----				Mg/kg	Kg/ha
Initial	14 Sep 10	6.0	17	0.70	8.7	1.14	0.31	3	97
1	9 Oct 10	5.8	17	0.44	-	-	-	-	71
2	2 Nov 10	5.7	20	0.53	-	-	-	-	67
3	8 Dec 10	5.5	19	0.64	-	-	-	-	109
4	9 Jan 11	5.5	19	0.53	-	-	-	-	161
5	-	-	-	-	-	-	-	-	-
1-5	10 Jun 11	6.0	11	0.41	7.3	.99	0.16	12	20
6	10 Oct 11	5.7	23	0.72	7.7	1.02	0.16	27	86
7	7 Nov 11	5.7	23	0.65	8.9	1.05	0.16	23	79
8	9 Dec 11	5.7	25	0.62	7.7	0.93	0.12	20	81
9	10 Jan 12	5.6	25	0.90	7.4	0.91	0.12	24	128
10	17 Feb 12	5.6	23	0.55	7.3	0.83	0.14	22	160
1-5	11 Jul 12	5.8	15	0.43	7.5	0.91	0.12	14	58
6-10	11 Jul 12	5.8	19	0.48	7.6	0.87	0.12	15	50
Lower optima		5.3	20	0.26	-	0.34	-	11	-

Note: Samples from sowing date 1-5 treatments were pooled at the end of the first (10 June 2011) and second season (11 July 2012) and sowing date 6-10 treatments were pooled at the end of the second season (11 July 2012). Soil tests were carried out using the Ministry of Agriculture and Fisheries Quick test (MAF QT). Lower optima for plant growth from Morton and Roberts (1999).

¹Soil pH determined by H₂O extraction

²Mineral nitrogen is the sum of nitrate and ammonium nitrogen, calculated on a dry weight basis, with bulk density of cultivated soil at 1.2 g/cm³ (McLaren and Cameron, 1990).

Appendix 4 Regrowth cycle start and defoliation date and method, and regrowth and grazing duration for lucerne crops grown on 10 sowing dates from October 2010 to July 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Season	Sowing date	Regrowth	Start date	Defoliation Date	Regrowth Days	Defoliation method	Grazing days
2010/11	1	1	21 Oct	24 Jan	95	Mown	-
		2	24 Jan	25 Mar	60	Mown	-
		3	25 Mar	14 Jun	81	Grazed	5
	2	1	9 Nov	11 Feb	94	Mown	-
		2	11 Feb	27 Apr	75	Mown	-
		3	27 Apr	14 Jun	48	Grazed	5
	3	1	8 Dec	25 Mar	107	Mown	-
		2	25 Mar	14 Jun	81	Grazed	5
	4	1	13 Jan	5 May	112	Mown	-
		2	5 May	14 Jun	40	Grazed	5
	5	1	3 Feb	14 Jun	131	Grazed	5
2011/12	1-5	1	20 Jun	27 Oct	129	Grazed	7
		2	3 Nov	15 Dec	42	Grazed	8
		3	23 Dec	29 Feb	68	Grazed	4
		4	4 Mar	20 April	47	Grazed	4
		5	25 Apr	11 Jul	77	Grazed	5
	6	1	10 Oct	11 Jan	93	Mown	-
		2	11 Jan	28 Mar	77	Mown	-
		3	28 Mar	13 Jun	77	Grazed	5
	7	1	7 Nov	1 Feb	86	Mown	-
		2	1 Feb	11 Apr	70	Mown	-
		3	11 Apr	13 Jun	63	Grazed	5
	8	1	9 Dec	21 Mar	103	Mown	-
		2	21 Mar	14 May	54	Mown	-
		3	14 May	13 Jun	30	Grazed	5
	9	1	10 Jan	25 Apr	106	Mown	-
		2	25 Apr	13 Jun	49	Grazed	5
	10	1	17 Feb	13 Jun	117	Grazed	5

Appendix 5 Post-grazing residuals for sowing date treatments 1 to 5 for regrowth period 1 (3 November 2011) and regrowth period 2 (23 December 2011) at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Sowing date	Post-grazing residual (kg DM/ha)	
	Regrowth 1	Regrowth 2
21 Oct 10	810 _c	754 _{abc}
9 Nov 10	955 _c	821 _{bc}
8 Dec 10	757 _{bc}	830 _c
13 Jan 11	473 _a	598 _{ab}
3 Feb 11	466 _a	556 _a
P	0.05	0.05
SEM	261	103

Means within a column with different letters are significantly different (l.s.d $\alpha = 0.05$)

Appendix 6 Regrowth cycle start and defoliation date and method, and regrowth and grazing duration for lucerne crops grown on 10 sowing dates from October 2010 to July 2012 at Iversen 12, Lincoln University, Canterbury, New Zealand.

Season	Sowing date	Regrowth	Start date	Defoliation Date	Regrowth Days	Defoliation method	Grazing days
2010/11	1	1	4 Oct	28 Dec	85	Mown	-
		2	28 Dec	8 Feb	42	Mown	-
		3	8 Feb	20 Apr	71	Mown	-
		4	20 Apr	13 Jun	54	Grazed	7
	2	1	4 Nov	17 Jan	74	Mown	-
		2	17 Jan	10 Mar	52	Mown	-
		3	10 Mar	13 May	64	Mown	-
		4	13 May	13 Jun	31	Grazed	7
	3	1	2 Dec	15 Feb	75	Mown	-
		2	15 Feb	20 Apr	64	Mown	-
		3	20 April	13 Jun	54	Grazed	7
	4	1	10 Jan	5 May	115	Mown	-
		2	5 May	13 Jun	39	Grazed	-
2011/12	1-5	1	20 Jun	11 Oct	113	Mown	-
		2	11 Oct	17 Nov	37	Mown	-
		3	17 Nov	20 Dec	33	Mown	-
		4	20 Dec	26 Jan	37	Mown	-
		5	26 Jan	15 Mar	49	Mown	-
		6	15 Mar	1 May	47	Mown	-
		7	1 May	11 Jul	71	Grazed	5
	6	1	10 Oct	4 Jan	86	Mown	-
		2	4 Jan	21 Feb	48	Mown	-
		3	21 Feb	4 Apr	43	Mown	-
		4	4 Apr	13 Jun	70	Grazed	5
	7	1	7 Nov	25 Jan	79	Mown	-
		2	25 Jan	12 Mar	47	Mown	-
		3	12 Mar	2 May	51	Mown	-
		4	2 May	13 Jun	42	Grazed	5
	8	1	9 Dec	27 Feb	80	Mown	-
		2	27 Feb	11 Apr	44	Mown	-
		3	11 Apr	13 Jun	63	Grazed	5
	9	1	10 Jan	25 Apr	106	Mown	-
		2	25 Apr	13 Jun	49	Grazed	5
	10	1	17 Feb	13 Jun	117	Grazed	5

Appendix 7 The coefficients, coefficients of determination (R^2) and standard error of the mean (SEM) for Gompertz curves fitted to cumulative emergence data for lucerne sown in the field at different times at Ashley Dene and Iversen 12, Lincoln University, Canterbury, New Zealand.

Site	Sowing date	<i>B</i>	<i>M</i>	<i>C</i>	R^2	SEM
<u>Ashley Dene</u>	21 Oct 10	0.26	6.90	347.6	0.95	28.4
	9 Nov 10	0.26	6.38	248.6	0.96	18.4
	8 Dec 10	0.31	11.25	208.2	0.98	13.5
	13 Jan 11	0.94	8.61	280.7	0.99	10.3
	3 Feb 11	1.17	6.75	371.1	0.99	2.51
	10 Oct 11	1.76	5.72	254.8	0.96	20.7
	7 Nov 11	2.00	6.53	240.0	0.99	7.9
	9 Dec 11	0.53	4.63	276.1	0.96	21.1
	10 Jan 12	0.25	14.40	232.8	0.96	16.2
	17 Feb 12	0.76	6.99	312.2	0.99	11.4
<u>Iversen 12</u>	4 Oct 10	0.21	8.72	323.6	0.99	7.66
	4 Nov 10	0.20	9.70	328.5	0.98	16.4
	2 Dec 10	0.40	5.54	321.6	0.97	23.0
	10 Jan 11	0.83	9.11	327.7	0.99	0.4
	7 Feb 11	0.76	3.38	383.7	0.98	24.2
	10 Oct 11	1.75	5.69	215.4	0.96	16.9
	7 Nov 11	1.73	6.25	294.0	0.99	6.9
	9 Dec 11	0.60	4.38	262.0	0.99	20.1
	10 Jan 12	0.16	7.44	275.1	0.96	21.7
	17 Feb 12	1.25	4.47	335.5	0.99	10.3

Note: Gompertz functions described in Equation 4.1.

Appendix 8 Ashley Dene (SD1-5) DM accumulation in relation to thermal time.

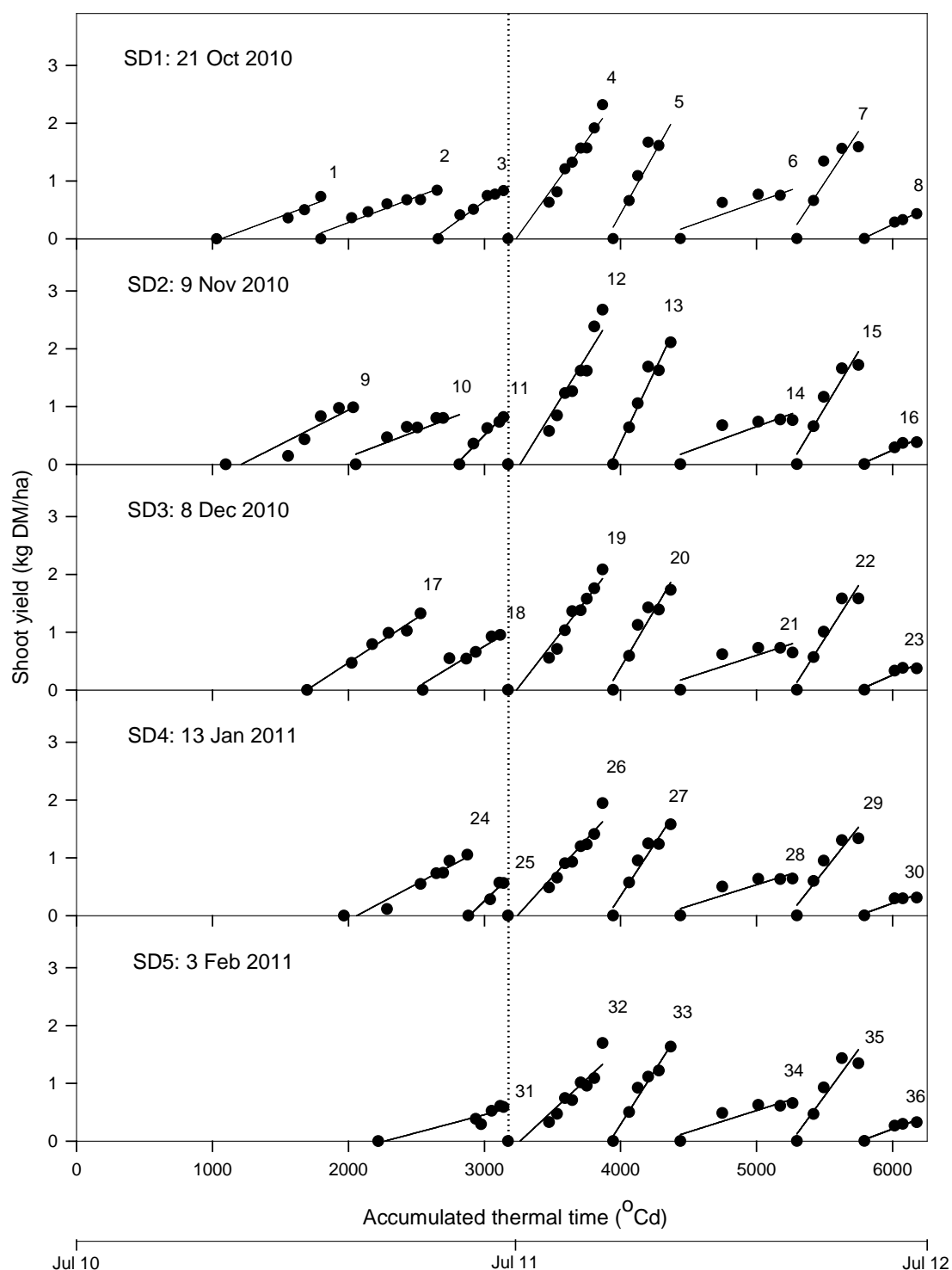


Figure 0.1 Shoot dry matter (DM) in relation to accumulated thermal time of lucerne grown on five dates at Ashley Dene Lincoln University, Canterbury, New Zealand.

Note: The slope of the regressions represent growth rate (kg DM/ $^{\circ}\text{Cd}$) which are described in Table 0.1.

Table 0.1 The coefficient (Y), coefficients of determination (R^2) and standard error of the mean (SEM) for shoot dry matter (DM) in relation to accumulated thermal time of lucerne grown on five dates (SD) at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Regression ¹	SD	Season	Rotation	Y	R^2 (%)	SEM
1	SD1	2010/11	1	0.88	0.94	0.149
2			2	0.89	0.94	0.103
3			3	1.72	0.97	0.167
4		2011/12	1	3.27	0.96	0.264
5			2	4.21	0.88	0.774
6			3	0.83	0.75	0.275
7			4	3.56	0.84	0.904
8			5	1.12	0.99	0.751
9	SD2	2010/11	1	1.19	0.85	0.247
10			2	0.90	0.73	0.246
11			3	2.42	0.97	0.246
12		2011/12	1	3.82	0.91	0.468
13			2	4.70	0.96	0.541
14			3	0.86	0.76	0.279
15			4	3.92	0.92	0.169
16			5	1.05	0.94	0.193
17	SD3	2010/11	1	1.54	0.98	0.107
18			2	1.44	0.90	0.216
19		2011/12	1	3.04	0.96	0.248
20			2	4.01	0.92	0.595
21			3	0.76	0.70	0.287
22			4	3.70	0.92	0.613
23			5	1.04	0.88	0.274
24	SD4	2010/11	1	1.25	0.94	0.139
25			2	2.29	0.96	0.343
26		2011/12	1	2.59	0.93	0.274
27			2	3.60	0.94	0.454
28			3	0.74	0.82	0.201
29			4	2.98	0.90	0.576
30			5	0.85	0.86	0.245
31	SD5	2010/11	1	0.62	0.87	0.119
32		2011/12	1	2.19	0.87	0.320
33			2	3.70	0.96	0.333
34			3	0.74	0.84	0.187
35			4	3.22	0.89	0.657
36			5	0.88	0.93	0.167

Note: ¹Regression numbers refer to Figure 0.1.

Appendix 9 Iversen 12 (SD1-5) DM accumulation in relation to thermal time.

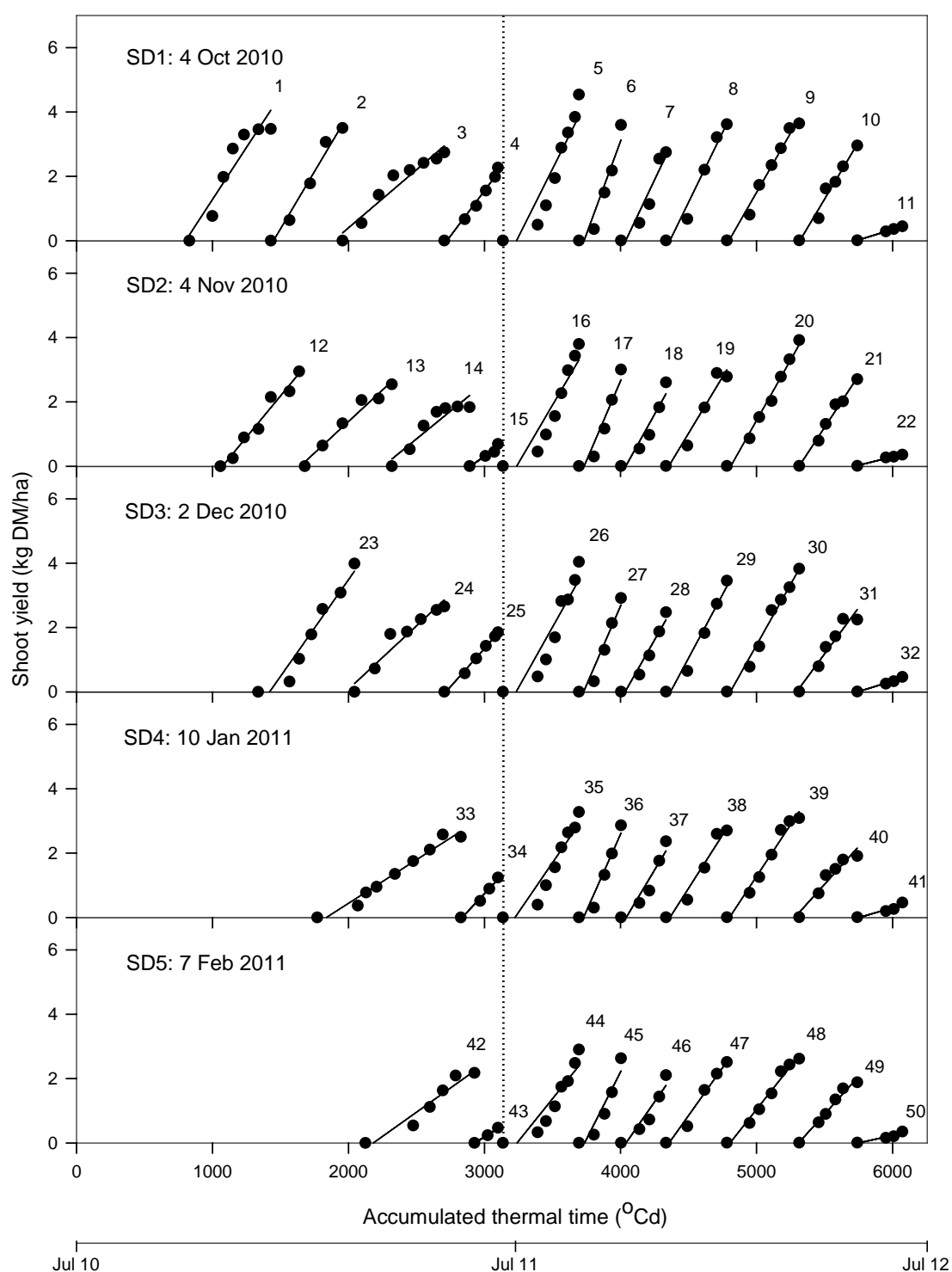


Figure 0.2 Shoot dry matter (DM) in relation to accumulated thermal time of lucerne grown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand.

Note: The slope of the regressions represent growth rate (kg DM/°Cd) which are described Table 0.2.

Table 0.2 The coefficient (Y), coefficients of determination (R^2) and standard error of the mean (SEM) for shoot dry matter (DM) in relation to accumulated thermal time of lucerne grown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand.

Regression ¹	Sowing date	Season	Rotation	Y	R^2 (%)	SEM
1	SD1	2010/11	1	6.47	0.89	1.019
2			2	7.12	0.98	0.624
3			3	3.61	0.94	0.385
4			4	5.62	0.98	0.378
5		2011/12	1	8.43	0.86	1.387
6			2	11.52	0.91	2.046
7			3	8.90	0.91	1.602
8			4	8.68	0.97	0.901
9			5	7.38	0.98	0.441
10			6	7.11	0.97	0.605
11			7	1.31	0.99	0.455
12	SD2	2010/11	1	5.12	0.97	0.406
13			2	3.91	0.97	0.345
14			3	3.45	0.87	0.590
15			4	2.99	0.94	0.518
16		2011/12	1	7.20	0.86	1.194
17			2	9.90	0.92	1.727
18			3	7.61	0.91	1.348
19			4	7.02	0.95	0.946
20			5	7.51	0.99	0.404
21			6	6.44	0.99	0.399
22			7	1.05	0.98	0.970
23	SD3	2010/11	1	6.01	0.94	0.671
24			2	3.93	0.93	0.477
25			3	4.77	0.99	0.168
26		2011/12	1	7.52	0.96	1.247
27			2	9.80	0.94	1.494
28			3	7.44	0.95	1.015
29			4	7.90	0.97	0.794

Regression ¹	Sowing date	Season	Rotation	Y	R ² (%)	SEM
30			5	7.54	0.98	0.478
31			6	5.73	0.93	0.760
32			7	1.31	0.98	0.129
33	SD4	2010/11	1	2.71	0.97	0.179
34			2	4.50	0.99	0.385
35		2011/12	1	6.17	0.89	0.909
36			2	9.52	0.94	1.447
37			3	7.07	0.91	1.325
38			4	6.62	0.96	0.813
39			5	6.42	0.97	0.477
40			6	4.68	0.93	0.627
41			7	1.23	0.90	0.293
42	SD5	2010/11	1	3.01	0.93	0.401
43			2	2.69	0.99	0.188
44		2011/12	1	5.26	0.85	0.911
45			2	8.35	0.89	1.679
46			3	6.09	0.90	1.182
47			4	5.95	0.98	0.544
48			5	5.34	0.98	0.361
49			6	4.68	0.98	0.358
50			7	0.94	0.92	0.199

Note: ¹Regression numbers refer to Figure 0.2.

Appendix 10 Model parameterisation.

Following crop emergence, leaf area expansion rate (LAER) was described by logistic function in relation to temperature (Table 0.3). Radiation was intercepted using Beer's Law and the appropriate extinction coefficient (k). Intercepted radiation was converted to yield using constant radiation use efficiencies for the crops. Parameters are from crops grown at Lincoln University under non-limiting conditions with similar sowing dates to the February sown lucerne.

Table 0.3 Potential yield model parameters; emergence ($^{\circ}\text{Cd}$), leaf area expansion rate (LAER; $\text{LAI}/^{\circ}\text{Cd}$), extinction coefficient (k) and shoot radiation use efficiency ($\text{RUE}_{\text{shoot}}$; $\text{g DM}/\text{MJ}$) for oats, annual ryegrass and kale at Lincoln University, Canterbury, New Zealand.

Crop	Emergence	LAER			k	$\text{RUE}_{\text{shoot}}$	Reference
		a	b	m			
Oats	132	4.59	244.9	734.8	0.77	1.38	1,2
Annual ryegrass							
1 st growth	132	8.52	304.0	1025.3	0.72	1.23	2
2 nd growth		5.14	93.8	1390.0	0.72	1.23	2
Kale	300	4.60	0.16	40.0	0.90	1.56	3,4
References:	¹ (Martini <i>et al.</i> , 2009) ² (Martini, 2012) ³ (Chakwizira, 2008) ⁴ (Chakwizira <i>et al.</i> , 2011)						

Appendix 11 Canopy Development of lucerne grown at Ashley Dene

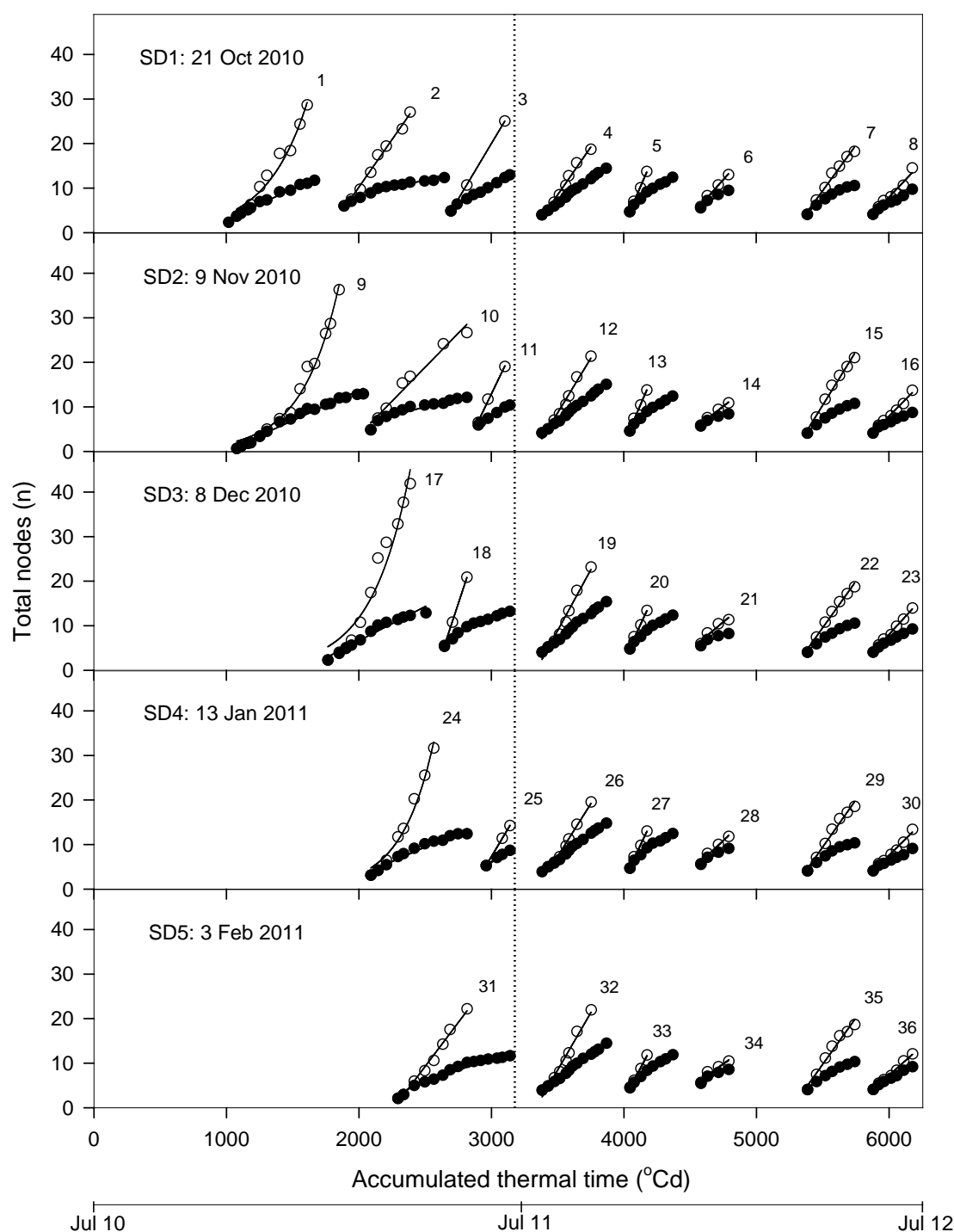


Figure 0.3 The number of mainstem (●) and total (○) nodes in relation to thermal time accumulation for lucerne grown at Ashley Dene subjected to five sowing dates at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Form of the regressions described in Table 0.4.

Table 0.4 The coefficient (M, B), coefficients of determination (R^2) and standard error of the mean (SE) for mainstem node number (phyllochron) and total leaf number (branching) in relation to accumulated thermal time of lucerne grown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Regression ¹	Sowing date	Phyllochron			Branching			
		R^2 (%)	M	SE	R^2 (%)	M	B	SE
1	SD1	98.3	0.014	0.0006	98.8	1.221	3.392	0.0197
2		90.0	0.008	0.0008	99.0	0.043		0.0017
3		99.2	0.017	0.0006	99.0	0.050		0.0004
4		99.7	0.022	0.0004	98.3	0.043		0.0023
5		96.5	0.023	0.0018	99.7	0.069		0.0025
6		95.3	0.018	0.0028	98.7	0.033		0.0027
7		95.6	0.018	0.0017	98.3	0.041		0.0024
8		98.5	0.018	0.0010	95.6	0.031		0.0030
9	SD2	97.6	0.014	0.0006	98.5	1.221	0.060	0.0197
10		89.3	0.008	0.0009	97.1	0.031		0.0024
11		99.5	0.019	0.0007	99.6	0.062		0.0040
12		99.8	0.023	0.0003	97.9	0.049		0.0029
13		97.1	0.023	0.0017	99.5	0.069		0.0035
14		92.8	0.012	0.0025	98.6	0.023		0.0020
15		97.0	0.019	0.0015	98.5	0.048		0.0026
16		96.7	0.015	0.0012	98.5	0.030		0.0016
17	SD3	95.6	0.015	0.0010	95.2	1.004	0.001	0.0002
18		94.2	0.015	0.0013	96.8	0.055		0.0041
19		99.6	0.024	0.0004	99.4	0.064		0.0035
20		96.7	0.023	0.0017	93.0	0.025		0.0048
21		97.1	0.012	0.0014	98.6	0.042		0.0022
22		98.7	0.017	0.0009	99.4	0.032		0.0011
23		94.2	0.015	0.0013	99.9	0.090		0.0016

Regression ¹	Sowing date	Phyllochron			Branching			
		R ² (%)	M	SE	R ² (%)	M	B	SE
24	SD4	95.6	0.013	0.0009	97.7	1.004	0.001	0.0003
25		98.9	0.019	0.0015	99.9	0.050		0.0007
26		99.6	0.023	0.0004	98.5	0.047		0.0026
27		95.2	0.023	0.0021	99.3	0.063		0.0036
28		94.5	0.016	0.0028	97.5	0.028		0.0032
29		95.2	0.018	0.0018	97.9	0.042		0.0028
30		98.5	0.016	0.0009	98.3	0.029		0.0017
31	SD5	94.5	0.011	0.0007	94.7	1.003	0.003	0.0003
32		99.6	0.022	0.0004	97.4	0.051		0.0035
33		98.0	0.023	0.0013	99.6	0.056		0.0024
34		90.9	0.014	0.0031	92.0	0.021		0.0044
35		97.4	0.017	0.0013	97.0	0.042		0.0033
36		99.0	0.017	0.0007	98.9	0.027		0.0013

Note: ¹Regression numbers refer to Figure 0.3

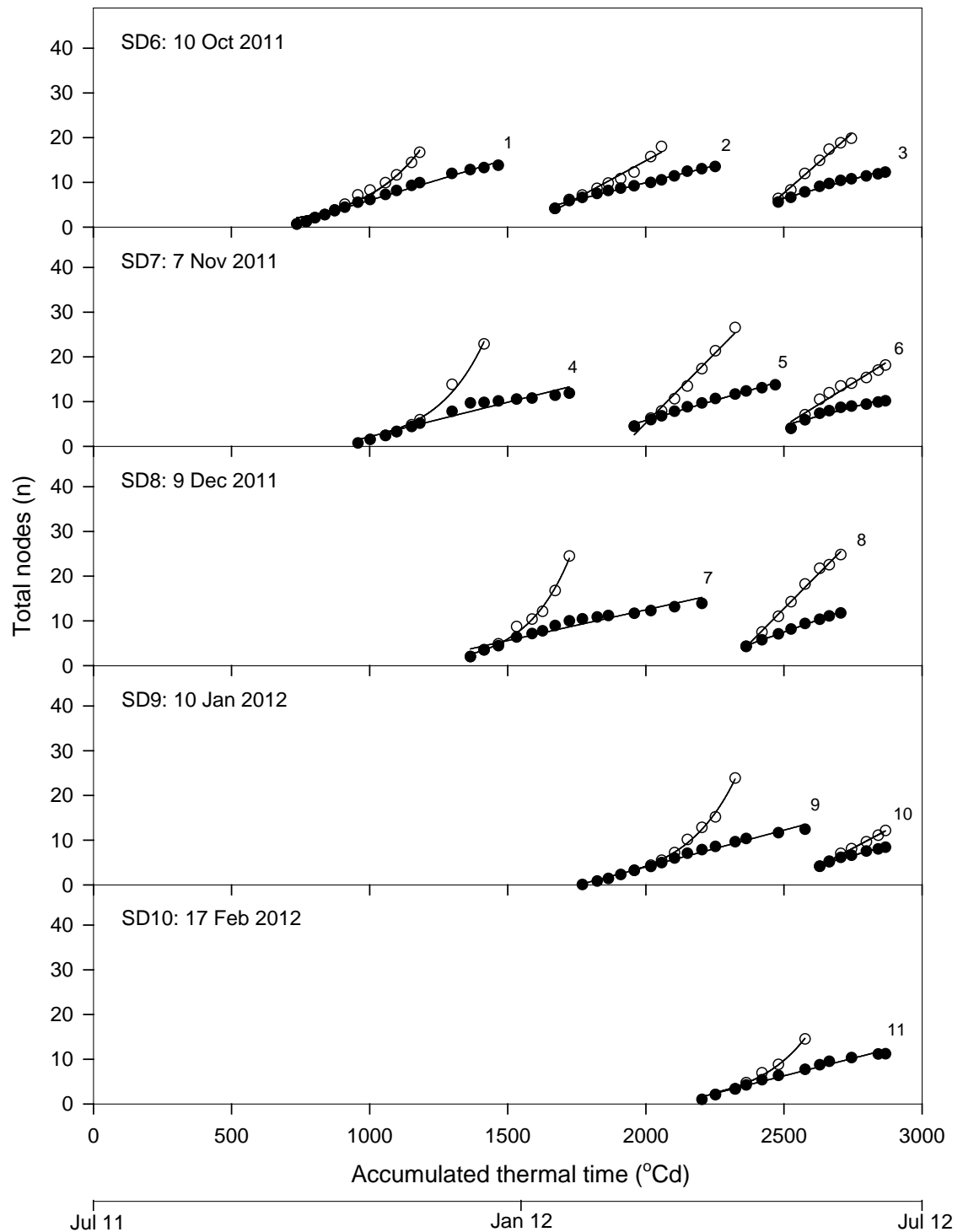


Figure 0.4 The number of mainstem (●) and total (○) nodes in relation to thermal time accumulation for lucerne grown at Ashley Dene subjected to five sowing dates at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Form of the regressions are described in Table 0.5.

Table 0.5 The coefficient (M, B), coefficients of determination (R^2) and standard error of the mean (SE) for mainstem node number (phyllochron) and total leaf number (branching) in relation to accumulated thermal time of lucerne grown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Regression ¹	Sowing date	Phyllochron			Branching			
		R^2 (%)	M	SE	R^2 (%)	M	B	SE
1	SD6	98.9	0.018	0.0005	97.6	0.062	5.140	0.0208
2		98.9	0.015	0.0005	97.1	0.034		0.0022
3		97.0	0.017	0.0010	98.5	0.054		0.0030
4	SD7	94.2	0.015	0.0011	98.6	0.007	2.780	0.0042
5		99.0	0.018	0.0006	98.0	0.062		0.0037
6		91.5	0.016	0.0019	96.0	0.038		0.0029
7	SD8	93.2	0.014	0.0010	99.0	0.001	0.226	0.0003
8		99.6	0.022	0.0005	99.4	0.062		0.0020
9	SD9	98.8	0.016	0.0005	99.5	0.000	0.267	0.0001
10		97.8	0.017	0.0012	99.7	0.033		0.0008
11	SD10	98.2	0.016	0.0007	99.2	0.000	1.391	0.0001

Note: ¹Regression numbers refer to Figure 0.4

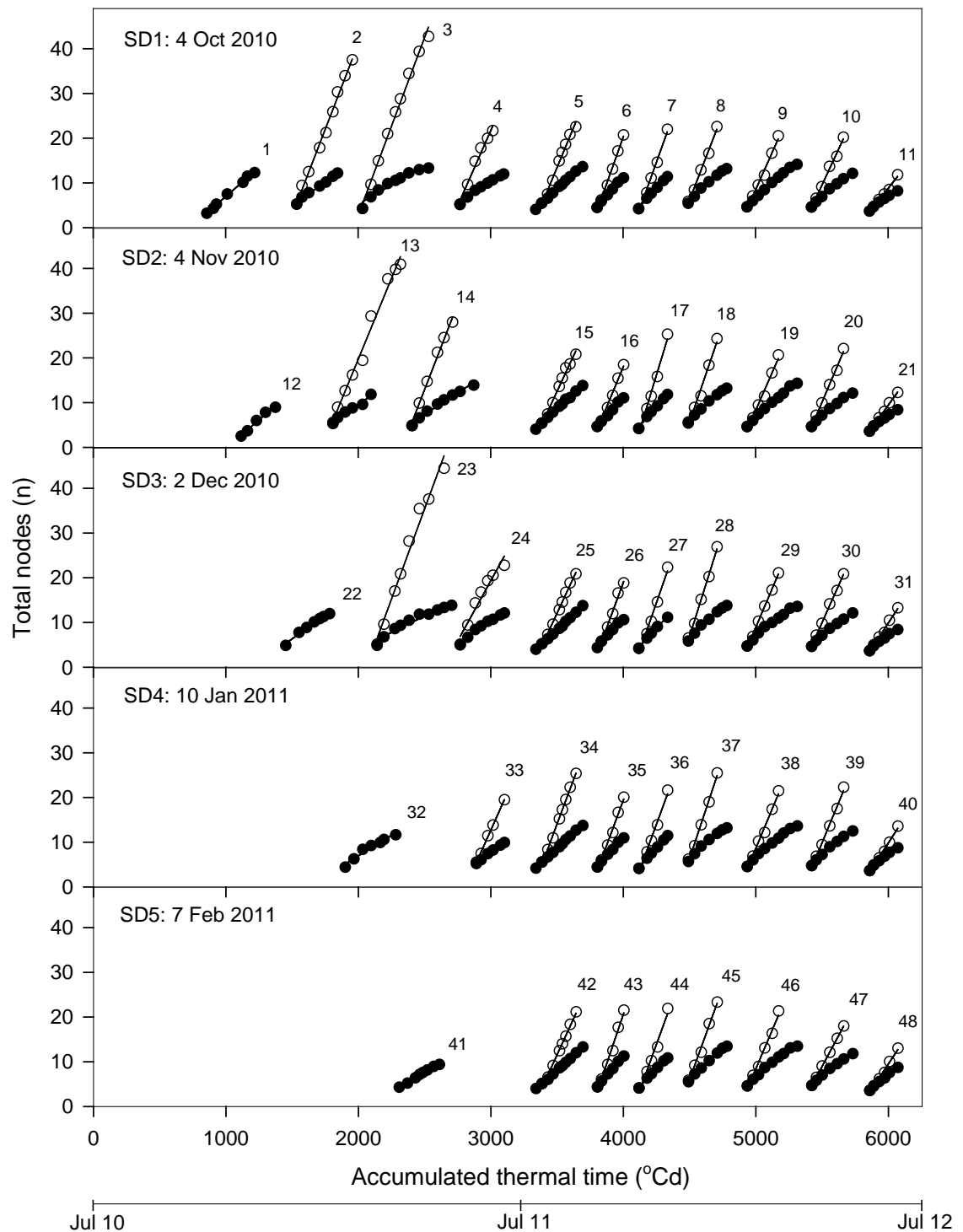


Figure 0.5 The number of mainstem (●) and total (○) nodes in relation to thermal time accumulation for lucerne grown at Iversen 12 subjected to five sowing dates at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Form of the regressions are described in Table 0.6.

Table 0.6 The coefficient (M, B), coefficients of determination (R^2) and standard error of the mean (SE) for main-stem node number (phyllochron) and total leaf number (branching) in relation to accumulated thermal time of lucerne grown on five dates at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Regression ¹	Sowing date	Phyllochron			Branching			
		R^2 (%)	M	SE	R^2 (%)	M	B	SE
1	SD1	99.5	0.026	0.0008	-	-	-	-
2		99.0	0.021	0.0009	99.5	0.077		0.0020
3		93.1	0.017	0.0018	99.3	0.079		0.0025
4		98.4	0.020	0.0010	97.8	0.067		0.0051
5		99.8	0.027	0.0044	98.9	0.072		0.0032
6		99.5	0.033	0.0012	99.3	0.083		0.0036
7		99.7	0.033	0.0008	99.1	0.083		0.0046
8		98.9	0.027	0.0013	99.2	0.077		0.0040
9		99.3	0.026	0.0008	98.7	0.067		0.0038
10		98.9	0.024	0.0011	99.4	0.064		0.0025
11		98.4	0.021	0.0013	98.2	0.038		0.0030
12	SD2	98.9	0.026	0.0020	-	-	-	-
13		98.3	0.020	0.0019	98.6	0.072		0.0033
14		96.8	0.019	0.0012	99.3	0.077		0.0032
15		97.9	0.028	0.0006	98.7	0.064		0.0029
16		99.8	0.033	0.0018	99.0	0.071		0.0037
17		99.5	0.034	0.0014	98.4	0.098		0.0071
18		99.3	0.027	0.0012	98.2	0.087		0.0067
19		99.1	0.026	0.0008	98.3	0.068		0.0045
20		99.3	0.024	0.0012	99.5	0.070		0.0024
21		98.7	0.022	0.0014	99.8	0.041		0.0009
22	SD3	98.4	0.021	0.0012	-	-	-	-

Regression ¹	Sowing date	Phyllochron			Branching			
		R ² (%)	M	SE	R ² (%)	M	B	SE
23		98.4	0.015	0.0013	98.1	0.081		0.0046
24		94.5	0.021	0.0014	94.6	0.054		0.0058
25		97.5	0.028	0.0003	99.4	0.064		0.0020
26		99.9	0.032	0.0017	98.8	0.081		0.0051
27		98.9	0.032	0.0014	98.3	0.085		0.0065
28		99.4	0.027	0.0014	99.6	0.095		0.0036
29		98.7	0.024	0.0012	99.7	0.070		0.0018
30		98.1	0.024	0.0011	99.9	0.066		0.0012
31		99.0	0.022	0.0014	98.7	0.045		0.0026
32	SD4	98.3	0.019	0.0018	-	-	-	-
33		95.4	0.022	0.0007	99.9	0.067		0.0013
34		99.6	0.027	0.0004	99.7	0.080		0.0018
35		99.9	0.033	0.0012	99.0	0.080		0.0041
36		99.5	0.033	0.0660	98.7	0.081		0.0054
37		99.8	0.026	0.0016	99.4	0.089		0.0040
38		98.2	0.024	0.0010	98.8	0.071		0.0039
39		98.8	0.025	0.0012	99.4	0.072		0.0029
40		98.9	0.024	0.0017	98.9	0.046		0.0025
41	SD5	98.1	0.018	0.0006	-	-	-	-
42		99.2	0.027	0.0299	99.3	0.065		0.0023
43		99.9	0.035	0.0009	98.4	0.088		0.0055
44		99.8	0.031	0.0010	97.8	0.082		0.0071
45		99.6	0.028	0.0009	99.1	0.082		0.0044
46		99.4	0.024	0.0011	98.6	0.070		0.0042
47		98.6	0.023	0.0010	99.9	0.055		0.0003
48		99.0	0.024	0.0011	98.8	0.045		0.0025

Note: ¹Regression numbers refer to Figure 0.5

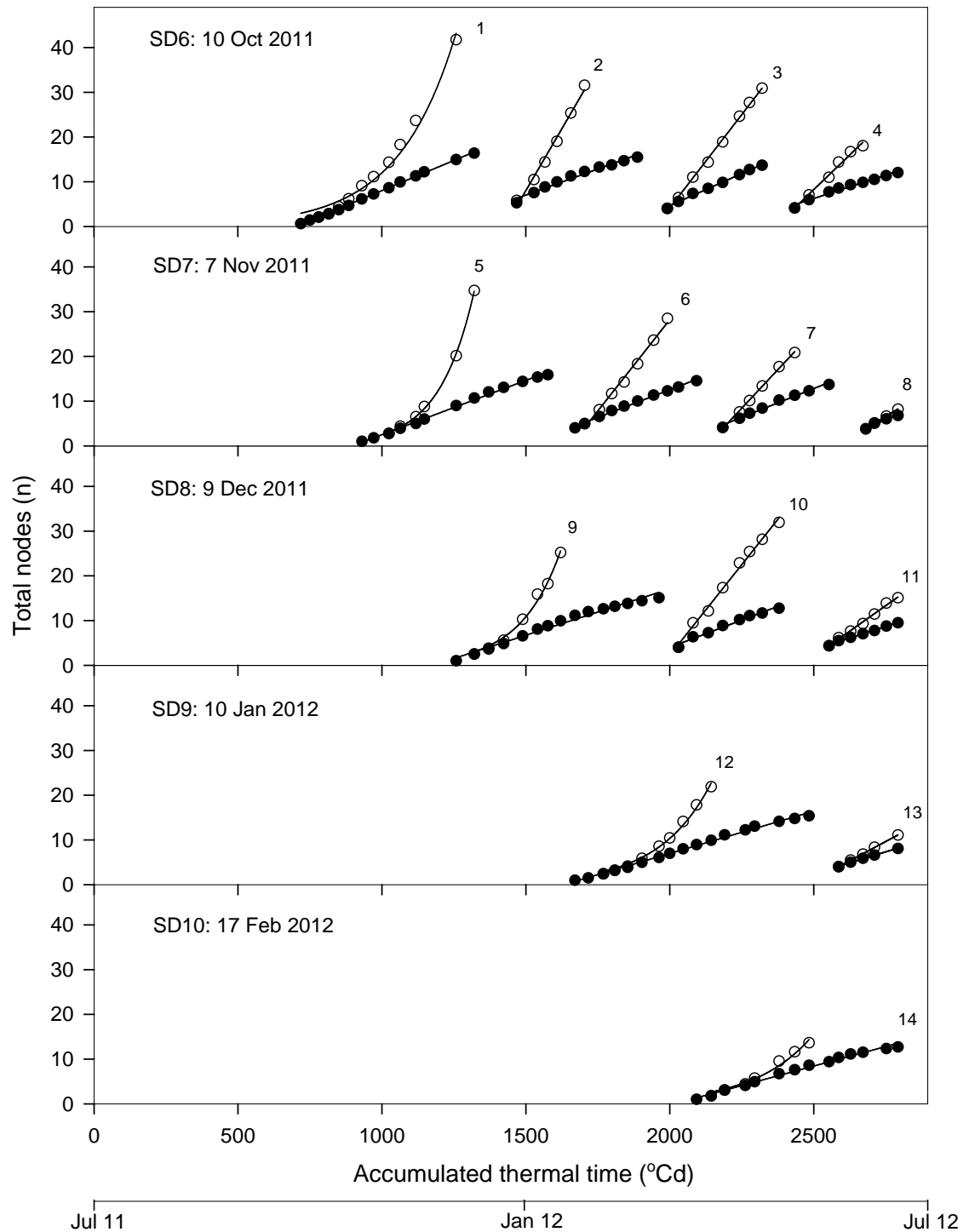


Figure 0.6 The number of mainstem (●) and total (○) nodes in relation to thermal time accumulation for lucerne grown at Iversen 12 subjected to five sowing dates at Lincoln University, Canterbury, New Zealand.

Note: Thermal time accumulated using air temperature ($T_b = 1^\circ\text{C}$) as per Teixeira *et al.* (2011). Form of the regressions are described in Table 0.7.

Table 0.7 The coefficient (M, B), coefficients of determination (R^2) and standard error of the mean (SE) for mainstem node number (phyllochron) and total leaf number (branching) in relation to accumulated thermal time of lucerne grown on five dates at Iversen 12, Lincoln University, Canterbury, New Zealand.

Regression ¹	Sowing date	Phyllochron			Branching			
		R^2 (%)	M	SE	R^2 (%)	M	B	SE
1	SD6	99.9	0.027	0.0003	98.1	1.004	1.574	0.0002
2		97.5	0.023	0.0013	99.0	0.111		0.0058
3		99.5	0.029	0.0008	99.7	0.083		0.0018
4		97.6	0.021	0.0012	98.8	0.062		0.0034
5	SD7	99.6	0.024	0.0005	99.9	1.008	0.333	0.0002
6		99.5	0.025	0.0006	99.3	0.082		0.0031
7		98.7	0.026	0.0012	99.8	0.069		0.0016
8		96.8	0.026	0.0034	99.9	0.039		0.0009
9	SD8	98.1	0.021	0.0008	99.2	1.005	1.025	0.0004
10		97.9	0.024	0.0015	99.3	0.081		0.0027
11		99.4	0.021	0.0007	99.4	0.045		0.0016
12	SD9	99.5	0.019	0.0003	99.4	1.004	0.815	0.0002
13		99.6	0.020	0.0007	99.9	0.034		0.0004
14	SD10	98.9	0.017	0.0005	97.8	1.005	1.199	0.0003

Note: ¹Regression numbers refer to Figure 0.6.

Appendix 12 Phyllochron and leaf area expansion rate in relation to DM partitioning.

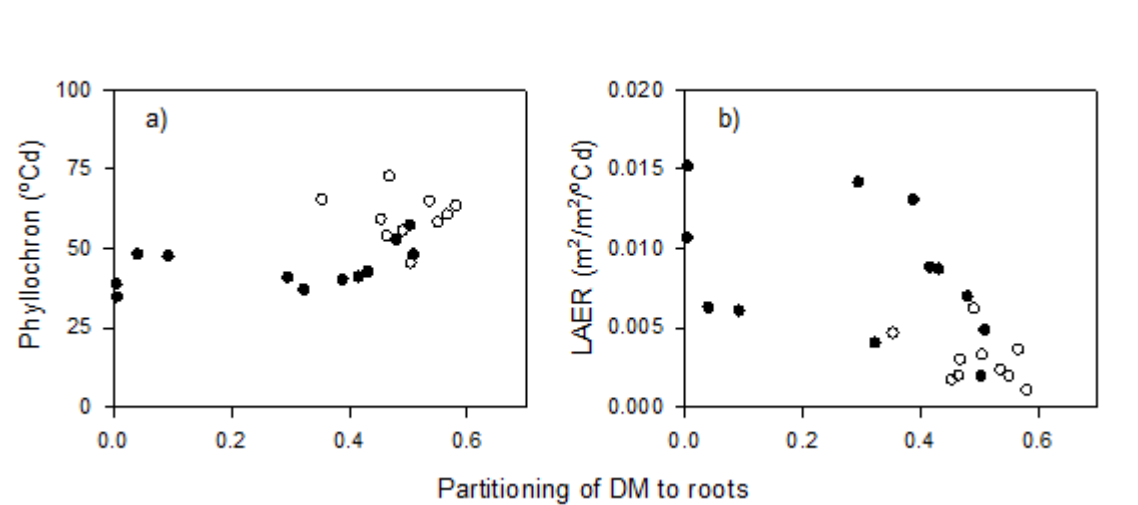
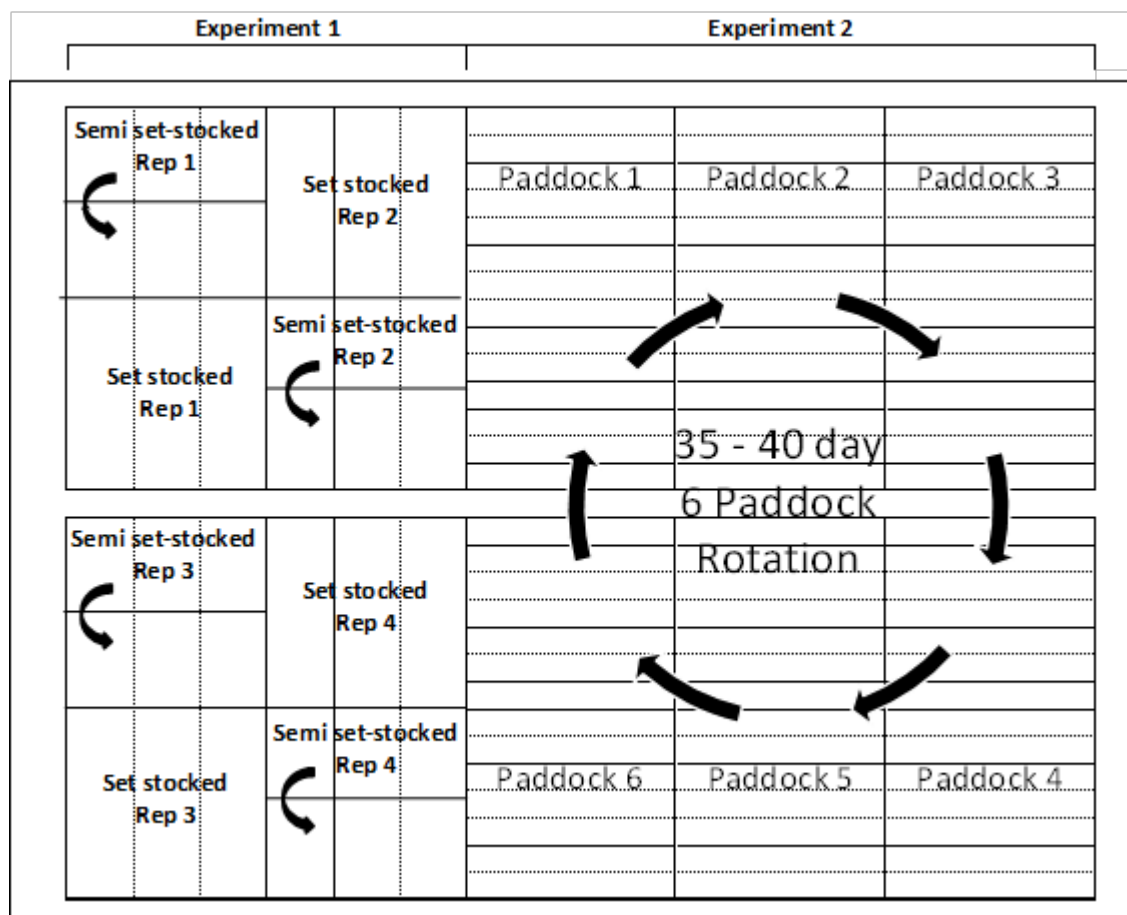


Figure 0.7 Mainstem node appearance (phyllochron) (a) and leaf area expansion rate (LAER) (b) in relation to the proportion of dry matter (DM) partitioned to the root fraction of dryland lucerne in the establishment season at Ashley Dene (○) and Iversen 12 (●) at Lincoln University, Canterbury, New Zealand.

Appendix 13 Trial plan for Experiment 3 and 4 showing grazing management treatments in paddock H7, Ashley Dene, Canterbury, New Zealand.



Arrows in experiment 1, indicate stock moved alternatively between sub-plot halves every 10 days, creating a 20 day rotation. Arrows in experiment 2 indicate the direction stock were moved grazing each paddock. Grazing started in paddock 1. Grazing duration target was 5 to 7 days per paddock, creating a 35 to 40 day rotation.

Appendix 14 Trial plan for Experiment 3 and 4 showing cultivar treatments in paddock H7, Ashley Dene, Canterbury, New Zealand.

Experiment 1						Experiment 2					
Stamina 6	Runner	Stamina 5	Stamina 5	Stamina 6	Runner	Rhino	Stamina 6	Kaltuna	Runner	AgR (graz tol)	AgR (hi pref)
						AgR (hi pref)	Stamina 5	AgR (hi pref)	Stamina 5	Runner	AgR (graz tol)
						AgR (graz tol)	Kaltuna	Stamina 6	Stamina 6	Rhino	Runner
						Runner	AgR (graz tol)	Stamina 5	Kaltuna	AgR (hi pref)	Rhino
						Kaltuna	AgR (hi pref)	Runner	Rhino	Stamina 5	Stamina 5
						Stamina 6	Rhino	AgR (graz tol)	AgR (hi pref)	Stamina 6	Kaltuna
						Stamina 5	Runner	Rhino	AgR (graz tol)	Kaltuna	Stamina 6
						AgR (graz tol)	Kaltuna	Rhino	Stamina 6	Runner	Stamina 5
						AgR (hi pref)	AgR (hi pref)	AgR (graz tol)	Runner	Stamina 5	Stamina 6
						Stamina 5	Stamina 6	Kaltuna	AgR (graz tol)	AgR (hi pref)	Rhino
						Rhino	AgR (graz tol)	Stamina 5	Kaltuna	Stamina 6	Runner
						Kaltuna	Runner	Stamina 6	AgR (hi pref)	Rhino	AgR (hi pref)
						Stamina 6	Rhino	Runner	Stamina 5	AgR (graz tol)	Kaltuna
						Runner	Stamina 5	AgR (hi pref)	Rhino	Kaltuna	AgR (graz tol)
Stamina 5	Runner	Stamina 6	Stamina 6	Runner	Stamina 5	Runner	Rhino	Stamina 5	Stamina 6	Runner	AgR (hi pref)
						AgR (hi pref)	Runner	Runner	AgR (graz tol)	AgR (graz tol)	Kaltuna
						Stamina 6	AgR (graz tol)	AgR (graz tol)	Stamina 5	Stamina 5	Rhino
						Rhino	AgR (hi pref)	Stamina 6	Rhino	Kaltuna	Stamina 6
						Stamina 5	Kaltuna	Rhino	Runner	AgR (hi pref)	AgR (graz tol)
						Kaltuna	Stamina 6	Kaltuna	AgR (hi pref)	Rhino	Stamina 5
						AgR (graz tol)	Stamina 5	AgR (hi pref)	Kaltuna	Stamina 6	Runner
						AgR (hi pref)	Kaltuna	Kaltuna	AgR (graz tol)	AgR (graz tol)	Stamina 5
						AgR (graz tol)	Rhino	AgR (hi pref)	Stamina 6	Rhino	AgR (graz tol)
						Stamina 5	Runner	Stamina 5	Rhino	AgR (hi pref)	AgR (hi pref)
						Stamina 6	Stamina 6	Runner	Runner	Stamina 5	Kaltuna
						Runner	Stamina 5	AgR (graz tol)	Kaltuna	Stamina 6	Rhino
						Rhino	AgR (graz tol)	Stamina 6	AgR (hi pref)	Kaltuna	Runner
						Kaltuna	AgR (hi pref)	Rhino	Stamina 5	Runner	Stamina 6

Yellow shading indicates plots which data was collected from. The cultivar ‘Stamina 6’ was measured in experiment 3 and cultivars ‘Stamina 6’ and ‘Kaituna’ in Experiment 4. Red circles indicate placement of neutron probe access tubes.

Appendix 15

Table 0.8 Summary of grazing periods and stock class in Experiment 3 for set stock (SS) and semi-set stocked (semi SS) grazing treatments at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Treatment	Rep	Stock class	Total stock	Date on	Date off
SS	1-4	Ewes + lambs	9	27 Sep 11	5 Dec 11
Semi SS _a	1-4	Ewes + lambs	9	27 Sep 11	7 Oct 11
Semi SS _b	1-4	Ewes + lambs	9	7 Oct 11	17 Oct 11
Semi SS _a	1-4	Ewes + lambs	9	17 Oct 11	27 Oct 11
Semi SS _b	1-4	Ewes + lambs	9	27 Oct 11	7 Nov 11
Semi SS _a	1-4	Ewes + lambs	9	7 Nov 11	17 Nov 11
Semi SS _b	1-4	Ewes + lambs	9	17 Nov 11	27 Nov 11
Semi SS _a	1-4	Ewes + lambs	9	27 Nov 11	5 Dec 11
Semi SS	1	Lambs	29	15 Dec 11	19 Dec 11
SS	1	Lambs	29	19 Dec 11	23 Dec 11
Semi SS	3	Lambs	29	23 Dec 11	30 Dec 11
SS	3	Lambs	29	30 Dec 11	4 Jan 12
Semi SS	4	Lambs	29	4 Jan 12	9 Jan 12
SS	4	Lambs	29	9 Jan 12	13 Jan 12
Semi SS	2	Lambs	35	13 Jan 12	20 Jan 12
SS	2	Lambs	35	20 Jan 12	25 Jan 12
Semi SS	1	Lambs	35	25 Jan 12	1 Feb 12
SS	1	Lambs	35	1 Feb 12	3 Feb 12
Semi SS	3	Lambs	35	3 Feb 12	5 Feb 12
SS	3	Lambs	35	5 Feb 12	6 Feb 12
SS	3	Hoggets	21	29 Mar 12	6 Apr 12
Semi SS	4	Hoggets	21	6 Apr 12	13 Apr 12
SS	4	Hoggets	21	13 Apr 12	19 Apr 12
Semi SS	2	Hoggets	21	19 Apr 12	24 Apr 12
SS	2	Hoggets	21	24 Apr 12	30 Apr 12
Semi SS	1	Hoggets	21	30 Apr 12	6 May 12
SS	1	Hoggets	21	6 May 12	12 May 12
Semi SS	3	Hoggets	21	12 May 12	15 May 12
All	All	100 ewes (clean up graze)		14 Jun 12	20 Jun 12

Note: Semi SS_a and _b refers to alternative halves of semi SS plots.

Appendix 16

Table 0.9 Summary of grazing dates and stock class for the six paddocks in Experiment 4 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Rotation	Paddock	Stock class	Ewes (n)	Lambs (n)	Date on	Date off
1	1	Ewes + lambs	34	60	27 Sep 11	4 Oct 11
1	2	Ewes + lambs	34	60	4 Oct 11	10 Oct 11
1	3	Ewes + lambs	34	60	10 Oct 11	14 Oct 12
1	4	Ewes + lambs	49	89	14 Oct 11	18 Oct 11
1	5	Ewes + lambs	49	89	18 Oct 11	25 Oct 11
1	6	Ewes + lambs	34	60	25 Oct 11	2 Nov 11
2	1	Ewes + lambs	34	60	2 Nov 11	7 Nov 11
2	2	Ewes + lambs	34	60	7 Nov 11	13 Nov 11
2	3	Ewes + lambs	34	60	13 Nov 11	18 Nov 11
2	4	Ewes + lambs	34	60	18 Nov 11	24 Nov 11
2	5	Ewes + lambs	34	60	24 Nov 11	30 Nov 11
2	6	Ewes + lambs	34	60	30 Nov 11	5 Dec 11
3	1	Lambs		84	6 Dec 11	12 Dec 11
3	2	Lambs		84	12 Dec 11	19 Dec 11
3	3	Lambs		55	19 Dec 11	25 Dec 11
3	4	Lambs		55	25 Dec 11	1 Jan 12
3	5	Lambs		55	1 Jan 12	8 Jan 12
3	6	Lambs		55	8 Jan 12	13 Jan 12
4	1	Lambs		60	13 Jan 12	20 Jan 12
4	2	Lambs		60	20 Jan 12	25 Jan 12
4	3	Lambs		60	25 Jan 12	1 Feb 12
4	4	Lambs		60	1 Feb 12	3 Feb 12
4	5	Lambs		60	3 Feb 12	6 Feb 12
4	6	Lambs		60	6 Feb 12	7 Feb 12
5	1	Hoggets		29	29 Mar 12	5 Apr 12
5	2	Hoggets		29	5 Apr 12	13 Apr 12
5	3	Hoggets		29	13 Apr 12	20 Apr 12
5	4	Hoggets		29	20 Apr 12	27 Apr 12
5	5	Hoggets		29	27 Apr 12	4 May 12
5	6	Hoggets		29	4 May 12	10 May 12
6	1-6	Ewes	100		20 Jun 12	27 Jun 12

Appendix 17

Table 0.10 Soil test results for paddock H7 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

	pH	P	K	Ca	Mg	Na	S(SO ₄)
Date		Mg/L		-----Me/100g-----			Mg/kg
July 2010	5.5	21	0.75	7.1	0.98	0.12	5
May 2011	5.8	16	0.48	6.9	0.98	0.20	14
June 2012	5.9	24	0.72	7.6	0.91	0.12	23
Lower optima	5.3	20	0.26	-	0.34	-	11

Note: Samples were pooled around the two experiments at the end of the second season. Soil tests were carried out using the Ministry of Agriculture and Fisheries Quick test (MAF QT). Lower optima for plant growth from Morton and Roberts (1999).

Appendix 18

Table 0.11 Annual dry matter yield (DM; t DM/ha), intercepted total radiation (R_i ; MJ/m²), shoot radiation use efficiency (RUE_{shoot}; g DM/MJ), water use (WU; mm) and water use efficiency (WUE; kg DM/ha/mm) of ‘Kaituna’ and ‘Stamina 6’ dryland lucerne within a rotationally grazed six paddock system from June 2011 to July 2012 at Ashley Dene, Lincoln University, Canterbury, New Zealand.

Paddock	Cultivar	DM	R_i	RUE _{shoot}	WU	WUE
1	Kaituna	12.0	2129	0.56	430.67	27.45
1	Stamina 6	12.2	2158	0.58	489.20	25.62
2	Kaituna	15.2	2417	0.63	536.55	28.14
2	Stamina 6	14.1	2395	0.57	505.26	26.34
3	Kaituna	13.0	2109	0.62	485.87	25.61
3	Stamina 6	12.4	2165	0.57	449.35	28.29
4	Kaituna	14.9	2515	0.62	549.94	26.93
4	Stamina 6	14.2	2692	0.55	568.57	24.04
5	Kaituna	13.6	2606	0.55	516.20	25.29
5	Stamina 6	13.8	2596	0.55	488.23	26.71
6	Kaituna	14.8	2282	0.66	530.27	27.89
6	Stamina 6	13.9	2269	0.64	496.02	28.13
P	Paddock	0.006	<0.001	0.098	0.046	0.698
	Cultivar	0.096	0.295	0.133	0.117	0.651
l.s.d		1.03			30.8	

Appendix 19 Canopy height of set stocked and semi-set stocked lucerne.

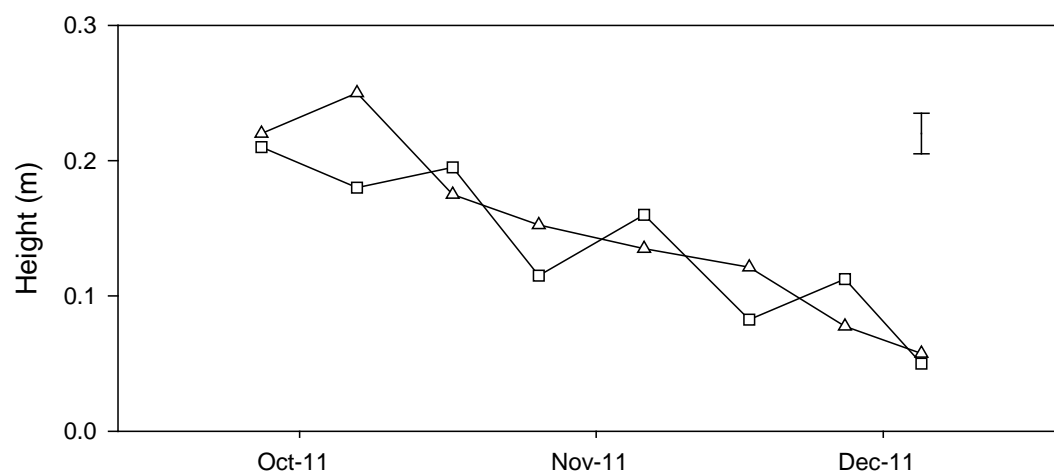


Figure 0.8 Canopy height of dryland lucerne from 27 September to 5 December 2011 subjected to two grazing managements; set stocked (\triangle) and semi-set stocked at Lincoln University, Canterbury, New Zealand.

Note: Bar represents l.s.d ($P = 0.05$) at end of grazing period.

Appendix 20 Post grazing residual in relation to stem content.

The post grazing residual was assessed in the same way as DM, when sheep were removed from plots. The stem DM at grazing explained 81% of the variation in post grazing residual (Figure 0.9). When the stem content was minimal (<100 kg DM/ha) the post grazing residual was ~0.5 t DM/ha, this increased 2.5 t DM/ha when stem content increase to 0.9 t DM/ha.

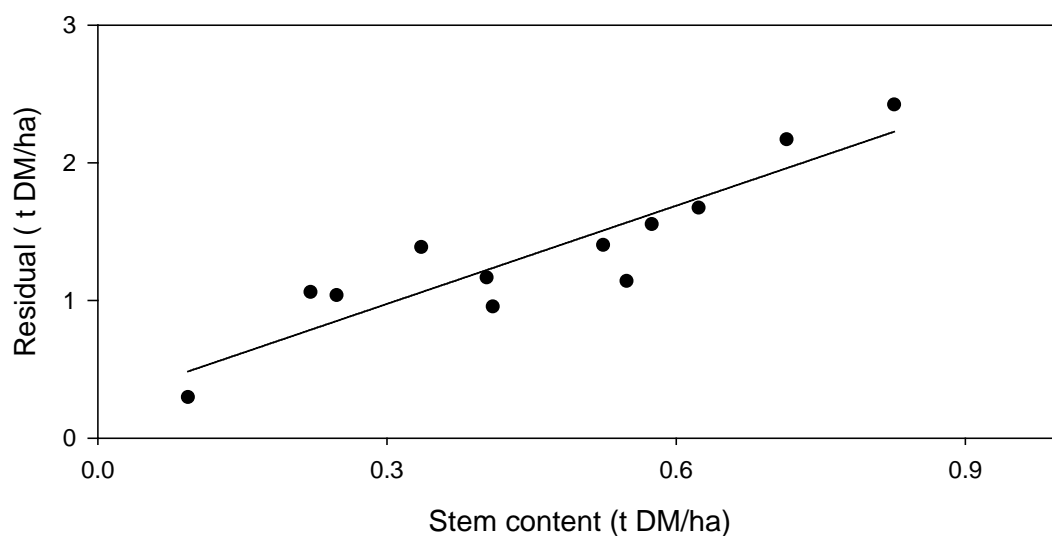


Figure 0.9 The post grazing crop mass (residual) in relation to stem content (t DM/ha) of rotationally grazed dryland lucerne in a 6 paddock rotation for the first two rotations at Lincoln University, Canterbury, New Zealand.

Note: Linear regression; (—) $y = 2.4x + 0.262$, $R^2 = 0.81$.

References

- Allison, R. M. and Vartha, E. W. 1973. Yields of protein extracted from irrigated lucerne. *New Zealand Journal of Experimental Agriculture*, **1**, 35-38.
- Angus, J. F., Cunningham, R. B., Moncur, M. W. and Mackenzie, D. H. 1981. Phasic development in field crops I. Thermal response in the seedling phase. *Field Crops Research*, **4**, 365-378.
- Asseng, S. and Hsiao, T. C. 2000. Canopy CO₂ assimilation, energy balance, and water use efficiency of an alfalfa crop before and after cutting. *Field Crops Research*, **67**, 191-206.
- Asseng, S., Ritchie, J. T., Smucker, A. J. M. and Roberston, M. J. 1998. Root growth and water uptake during water deficit and recovering in wheat. *Plant and Soil*, **201**, 265-273.
- Ates, S. 2009. Grazing management of Subterranean clover (*Trifolium subterraneum* L.) in South Island (New Zealand) summer dry pastures. Ph.D. Thesis, Lincoln University, Lincoln, New Zealand. 288 pp.
- Avery, D., Avery, F., Ogle, I. G., Wills, B. J. and Moot, D. J. 2008. Adapting farm systems to a drier future. *Proceedings of the New Zealand Grassland Association*, **70**, 13-18.
- Avise, J. C., Lemaire, G., Ourry, A. and Boucaud, J. 1997. Effects of the previous shoot removal frequency on subsequent shoot regrowth in two *Medicago sativa* L. cultivars. *Plant and Soil*, **188**, 189-198.
- Avise, J. C., Ourry, A., Lemaire, G. and Boucaud, J. 1996. Nitrogen and carbon flows estimated by ¹⁵N and ¹³C pulse-chase labelling during regrowth of alfalfa. *Plant Physiology*, **112**, 281-290.
- Betteridge, K., Hoogendoorn, C. J., Thorrold, B. S., Costall, D. A. and Ledgard, S. F. 2007. Nitrate leaching and productivity of some farming options in the Lake Taupo catchment. *Proceedings of the New Zealand Grassland Association*, **69**, 123-129.
- Bonhomme, R. 2000. Bases and limits to using "degree-day" units. *European Journal of Agronomy*, **13**, 1-10.
- Brock, J. L. and Hay, M. J. M. 2001. White clover performance in sown pastures: A biological/ecological perspective. *Proceedings of the New Zealand Grassland Association*, **63**, 73-83.
- Brown, C. H. and Green, R. B. 2003. The challenges facing legumes in a dryland environment - a consultant's view. In: D. J. Moot, (ed). *Legumes for Dryland Pastures*. Lincoln University, NZ: New Zealand Grassland Association: Christchurch, 7-12
- Brown, H. E. 2004. Understanding yield and water use of dryland forage crops in New Zealand. Ph.D. Thesis, Lincoln University, Lincoln, New Zealand. 288 pp.
- Brown, H. E., Jamieson, P. D. and Moot, D. J. 2012. Predicting the transpiration of lucerne. *European Journal of Agronomy*, **43**, 9-17.
- Brown, H. E. and Moot, D. J. 2004. Main-stem node appearance of lucerne regrowth in a temperate climate. In: *Proceedings of the 4th International Crop Science Congress*. Australian Agronomy Society, Brisbane, Australia
- Brown, H. E., Moot, D. J., Fletcher, A. L. and Jamieson, P. D. 2009. A framework for quantifying water extraction and water stress responses of perennial lucerne. *Crop and Pasture Science*, **60**, 785-794.

- Brown, H. E., Moot, D. J., Lucas, R. J. and Smith, M. 2006a. Sub clover and lucerne combine to improve dryland stock production. *Proceedings of the New Zealand Grassland Association*, **68**, 109-115.
- Brown, H. E., Moot, D. J. and McKenzie, B. A. 2004. Field Validation of empirical functions used to predict crop water use. *In: Proceedings of the 4th International Crop Science Congress*. Australian Agronomy Society, Brisbane, Australia
- Brown, H. E., Moot, D. J. and Pollock, K. M. 2005a. Herbage production, persistence, nutritive characteristics and water use of perennial forages over 6 years on a Wakanui soil loam. *New Zealand Journal of Agricultural Research*, **48**, 423-439.
- Brown, H. E., Moot, D. J. and Pollock, K. M. 2003. Long term growth rates and water extraction patterns of dryland chicory, lucerne and red clover. *In: Legumes for Dryland Pastures*. (D. J. Moot, ed.), 91-100 pp.
- Brown, H. E., Moot, D. J., Pollock, K. M. and Inch, C. 2000. Dry matter production of irrigated chicory, lucerne and red clover in Canterbury. *Proceedings of the 13th Annual Conference, Agronomy Society of New Zealand, Palmerston North, New Zealand*, **30**, 129-137.
- Brown, H. E., Moot, D. J. and Teixeira, E. I. 2006b. Radiation use efficiency and biomass partitioning of lucerne (*Medicago sativa*) in a temperate climate. *European Journal of Agronomy*, **25**, 319-327.
- Brown, H. E., Moot, D. J. and Teixeira, E. I. 2005b. The components of lucerne (*Medicago sativa*) leaf area index respond to temperature and photoperiod in a temperate climate. *European Journal of Agronomy*, **23**, 348-358.
- Brown, P. W. and Tanner, C. B. 1983. Alfalfa stem and leaf growth during water stress. *Agronomy Journal*, **75**, 799-804.
- Brown, R. H., Cooper, R. B. and Blaser, R. E. 1966. Effects of leaf age on efficiency. *Crop Science*, **6**, 206-209.
- Busari, M. A., Salako, F. K., Tuniz, C., Zuppi, G. M., Stenni, B., Adetunji, M. T. and Arowolo, T. A. 2013. Estimation of soil water evaporative loss after tillage operation using the stable isotope technique. *International Agrophysics*, **27**, 257-264.
- Carter, P. and Sheaffer, C. 1983a. Alfalfa response to soil water deficits. II. Plant water potential, leaf conductance, and canopy temperature relationships. *Crop-Science*, **23**, 679-680.
- Carter, P. and Sheaffer, C. 1983b. Alfalfa response to soil water deficits. I. Growth, forage quality, yield, water use, and water-use efficiency. *Crop-Science*, **23**, 669-675.
- Chakwizira, E. 2008. Growth and development of 'Pasja' and kale crops grown with two methods and four rates of phosphorus (P) application. M.Agr.Sc. Thesis. Lincoln University, Lincoln, New Zealand.
- Chakwizira, E., Moot, D. J., Scoot, W. R., Fletcher, A. L. and Maley, S. 2011. Leaf development, radiation interception and radiation-use efficiency of kale crops supplied with different rates of banded or broadcast phosphorus fertiliser. *Crop and Pasture Science*, **62**, 840-847.
- Clark, D. A. 2011. Changes in pastoral farming practices and pasture persistence - a review. *In: Pasture Persistence Symposium*, 10-11 May 2011, Hamilton. New Zealand Grassland Association: Dunedin. p 7-14.
- Condon, A. G., Richards, R. A., Rebetzke, G. J. and Farquhar, G. D. 2002. Improving Intrinsic Water-use Efficiency and Crop Yield. *Crop Science*, **42**, 122-131.

- Cox, J. E. 1978. Soils and agriculture of Paparua County, Canterbury, New Zealand. New Zealand Soil Bureau Bulletin
- Dardanelli, J. L., Bachmeier, O. A., Sereno, R. and Gil, R. 1997. Rooting depth and soil water extraction patterns of different crops in a silty loam Haplustoll. *Field Crops Research*, **54**, 29-38.
- de Ruiter, J., Fletcher, A., Maley, S., Sim, R. and Fletcher, A. 2009. Aiming for 45 t/ha per annum: Yield of supplementary feed crops grown in sequences designed for maximum productivity. In: Proceedings of the New Zealand Grasslands Association **Vol. 71**. p 107-116.
- Dolling, P. J., Latta, R. A., Ward, P. R., Roberston, M. J. and Asseng, S. 2005. Soil water extraction and biomass production by lucerne in the south of Western Australia. *Australian Journal of Agricultural Research*, **56**, 389-404.
- Douglas, J. 1986. The production and utilization of lucerne in New Zealand. *Grass and Forage Science*, **41**, 81-128.
- Draper, N. and Smith, H. 1998. Applied regression analysis. In. "Wiley series in probability and statistics" 3rd Ed: John Wiley & Sons Inc. ed., New York
- Durand, J. L., Lemaire, G., Gosse, G. and Chartier, M. 1989. An analysis of the conversion of solar energy to dry matter in a lucerne (*Medicago sativa*) population subjected to water deficit. *Agronomie*, **9**, 599-607.
- Elliott, M. G. and Kerse, J. C. 1974. Lucerne in North Otago. *Proceedings of the New Zealand Grassland Association*, **36**, 1-23.
- Evans, D. W. and Peadar, R. N. 1984. Branching as a factor in alfalfa yield. In: Viands, D.R., Elgin, J.H.J. (Eds.), *Report of the 29th Alfalfa Improvement Conference*, Lethbridge, Canada.
- Fick, G. W. 1984. Simple simulation models for yield prediction applied to alfalfa in the northeast. *Crop Science*, **76**, 235-239.
- Fick, G. W., Holt, D. A. and Lugg, D. G. 1988. Environmental physiology and crop growth. In: A. A. Hanson, D. K. Barnes and R. R. J. Hills, (eds). *Alfalfa and alfalfa improvement*. Madison, U.S.A.: American Society of Agronomy, 163-194
- Fletcher, A. L. and Moot, D. J. 2007. Estimating daily solar radiation in New Zealand using air temperatures. *New Zealand Journal of Crop and Horticultural Science*, **35**, 147-157.
- Fletcher, L. 1976. Effect of season and regrowth period on the in vitro digestibility of irrigated lucerne in Canterbury. *New Zealand Journal of Experimental Agriculture*, **4**, 469-471.
- Freer, M., Dove, H. and Nolan, J. V. 2007. Nutrient requirements of domesticated ruminants. Collingwood, Australia: CSIRO Publishing. xxiii-270 pp.
- French, B. K. and Legg, B. J. 1979. Rothamsted irrigation 1964-76. *Journal of Agricultural Science, U.K.*, **92**, 15-37.
- Gallagher, J. and Biscoe, P. 1978. Radiation absorption, growth and yield of cereals. *Journal of Agricultural Science, UK*, **91**, 47-60.
- Gonzalez-Dugo, V., Durand, J. and Gastal, F. 2010. Water deficit and nitrogen nutrition of crops. A review. *Agronomy for Sustainable Development*, **30**, 529-544.
- Harrison, M. T., Evans, J. R., Dove, H. and Moore, A. D. 2011. Recovery dynamics of rainfed winter wheat after livestock grazing 1. Growth rates, grain yields, soil water use and water-use efficiency. *Crop and Pasture Science*, **62**, 947-959.
- Hay, R. K. M. and Walker, A. J. 1989. An introduction to the physiology of crop yield. In. New York: Longman Scientific & Technical, 292

- Hewitt, A. E. 1998. New Zealand soil classification. Landcare Research Science Series No. 1. Lincoln, New Zealand: Manaaki Whenua - Landcare Research Press
- Hoffmann, J. D., Eberbach, P. L., Virgona, J. A. and Katupitiya, A. 2003. Conservative water use by lucerne. *In: Solutions for a better environment: Proceedings of the 11th Australian Agronomy Conference*, Geelong, Victoria, Australia.
- Hoglund, J. H., Dougherty, C. T. and Langer, R. H. M. 1974. Response of irrigated lucerne to defoliation and nitrogen fertilizer. *New Zealand Journal of Experimental Agriculture*, **2**, 7-11.
- Hunt, W. F. and Thomas, V. J. 1985. Growth and Development Responses of Perennial Ryegrass grown at Constant Temperature II.* Influence of Light and Temperature on Leaf, Tiller and Root Appearance. *Australian Journal of Plant Physiology*, **12**, 69-76.
- Iversen, C. E. and Calder, J. W. 1956. Light land pastures. *Proceedings of the New Zealand Grassland Association*, **18**, 78-87.
- Jamieson, P. and Ewert, F. 1999. The role of roots in controlling soil water extraction during drought: an analysis by simulation. *Field Crops Research*, **60**, 267-280.
- Jamieson, P., Francis, G., Wilson, D. and Martin, R. 1995a. Effects of water deficits evapotranspiration from barley. *Agricultural and Forest Meteorology*, **76**, 35-44.
- Jamieson, P. D. 1999. Crop Responses to Water Shortages. *Journal of Crop Production*, **2**, 71-83.
- Jamieson, P. D., Brooking, I. R., Porter, J. R. and Wilson, D. R. 1995b. Prediction of leaf appearance in wheat: a question of temperature. *Field Crops Research*, **41**, 35-44.
- Jamieson, P. D., Porter, J. R., Goudriaan, J., Ritchie, J. T., Keulen, H. v. and Stol, W. 1998. A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Research*, **55**, 23-44.
- Janson, C. G. 1982. Lucerne grazing management research. *In: R. B. Wynn-Williams, (ed). Lucerne for the 80's*. Agronomy Society of New Zealand: Palmerston North, 111-114
- Janson, C. G. 1975. Interaction of maturity stage and defoliation duration in the simulated grazing of irrigated lucerne. *New Zealand Journal of Experimental Agriculture*, **3**, 63-69.
- Janson, C. G. 1974. Lucerne management for the critical spring period under light land grazing. *Proceedings of the New Zealand Grassland Association*, **36**, 66-77.
- Janson, C. G. and Knight, T. L. 1973. Establishment of lucerne with cover crops under different soil moisture conditions. *New Zealand Journal of Experimental Agriculture*, **1**, 243-251.
- Jenson, M. E., Burman, R. D. and Allen, R. G. eds). 1990. Evapotranspiration and irrigation requirements: a manual. New York, U.S.A: American Society of Civil Engineers, pp. 332.
- Jones, C. A. and Kiniry, J. R. 1986. CERES-Maize: a simulation model of maize growth and development. College Station: Texas A&M University Press. 194 pp.
- Juan, N., Sheaffer, C. and Barnes, D. 1993. Temperature and photoperiod effects on multifoliolate expression and morphology of alfalfa. *Crop Science*, **33**, 573-578.
- Justes, E., Thiebeau, P., Avise, J., Lemaire, G., Volenec, J. and Ourry, A. 2002. Influence of summer sowing dates, N fertilization and irrigation on autumn VSP accumulation and dynamics of spring regrowth in alfalfa (*Medicago sativa* L.). *Journal of Experimental Botany*, **53**, 111-121.

- Kearney, J. K., Moot, D. J. and Pollock, K. M. 2010. On-farm comparison of pasture production in relation to rainfall in Central Otago. *Proceedings of the New Zealand Grassland Association*, **72**, 121-126.
- Keoghan, J. M. 1982. Effects of cutting frequency and height on top-growth of pure lucerne stands. In: R. H. M. Langer, (ed). *The Lucerne Crop*. Wellington, 117-128
- Khaiti, M. and Lemaire, G. 1992. Dynamics of shoot and root growth of lucerne after seeding and after cutting. *European Journal of Agronomy*, **1**, 241-247.
- Khumalo, Q. 2012. Lucerne (*Medicago sativa* L.) establishment after inoculation with different carriers of *Ensifer meliloti* sown on five dates at Lincoln University, Unpublished M.Ag.Sc Thesis, Lincoln University, Lincoln, New Zealand
- Kirkham, M. B. 2004. Principles of soil and plant relations. United States of America: Elsevier Academic Press
- Kirsopp, S. 2001. Management techniques to maximise legume production in dryland farming., Masters of Applied Science thesis, Lincoln University, Canterbury, New Zealand.
- Kobayashi, K. and Salam, M. 2000. Comparing simulated and measured values using mean squared deviation and its components. *Agronomy Journal*, **92**, 345-352.
- Kramer, P. J. and Boyer, J. S. 1995. Water Relations of Plants and Soils. London, England: Academic Press Limited
- Langer, R. H. M. 1968. Growth of lucerne. *Proceedings of the New Zealand Grassland Association*, **30**, 12-20.
- Langer, R. H. M. and Steinke, T. D. 1965. Growth of lucerne in response to height and frequency of defoliation. *Journal of Agricultural Science*, **64**, 291-294.
- Lemaire, G., Onillon, B., Gosse, G., Chartier, M. and Allirand, J. M. 1991. Nitrogen distribution within a lucerne canopy during regrowth: relation with light distribution. *Annals of Botany*, **68**, 483-488.
- Lemaire, G., van Oosterom, E., Sheehy, J., Jeuffroy, M., Massignam, A. and Rossato, L. 2007. Is crop N demand more closely related to dry matter accumulation of leaf area expansion during vegetative growth? *Field Crops Research*, **100**, 91-106.
- Martini, M. Y. 2012. Physiological and environmental constraints to winter forage crops production. Ph.D. Thesis. Lincoln University, Lincoln, New Zealand.
- Martini, M. Y., McKenzie, B. A., Moot, D. J., Hill, G. D. and de Ruiter, J. M. 2009. Dry matter accumulation of oats sown at five different sowing dates. *Agronomy New Zealand*, **39**, 71-80.
- Masiunas, J. B. and Carpenter, P. L. 1984. Radicle growth of grasses and legumes in response to temperature. *Horticulture Science*, **19**, 298-300.
- Mattera, J., Romero, L. A., Cuatrin, A. L., Cornaglia, P. S. and Grimoldi, A. A. 2013. Yield components, light interception and radiation use efficiency of lucerne (*Medicago sativa* L.) in response to row spacing. *European Journal of Agronomy*, **45**, 87-95.
- McGowan, A. W., Sheath, G. W. and Webby, R. W. 2003. Lucerne for high quality summer feed in North Island hill country. In: D. J. Moot, (ed). *Legumes for Dryland Pastures*. Lincoln University, New Zealand: New Zealand Grassland Association: Christchurch, 169-174
- McLaren, R. and Cameron, K. 1990. Soil science: an introduction to the properties of New Zealand soils. Auckland, New Zealand: Oxford University Press

- McLenaghan, R. and Webb, T. 2012. Soil properties and fertility of Ashley Dene: the challenge. *In*: Lucas, D., Gow, N. and Nicol, A. (Eds). Ashley Dene Lincoln University farm - the first 100 years: Lincoln University, 17-22.
- Miller, M. G. and Veltman, A. 2004. Proposed Canterbury Natural Resources Plan for river and groundwater allocation policies and the implications for irrigation dependent farming in Canterbury. *Proceedings of the New Zealand Grassland Association*, **66**, 11-23.
- Mills, A. 2007. Understanding constraints to cocksfoot (*Dactylis glomerata* L.) based pasture production. Ph.D. Thesis, Lincoln University, Lincoln, New Zealand
- Mills, A., Moot, D. J. and McKenzie, B. A. 2006. Cocksfoot pasture production in relation to environmental variables. *Proceedings of the New Zealand Grassland Association*, **68**, 89-94.
- Mills, A., Smith, M. and Moot, D. J. 2008a. Sheep liveweight production from lucerne cocksfoot or ryegrass based pastures. *In*: M. Unkovich. (Ed.). "Global Issues. Paddock Action". Proceedings of the 14th Australian Agronomy Conference 2008, 21-25 September 2008, Adelaide, South Australia.
- Mills, A., Smith, M. C., Lucas, R. J. and Moot, D. J. 2008b. Dryland pasture yields and botanical composition over 5 years under sheep grazing in Canterbury. *Proceedings of the New Zealand Grassland Association*, **70**, 37-44.
- Milne, G. D. 2011. Can pasture persistence be improved through the use of non-ryegrass species. *In*: Pasture Persistence Symposium, 10-11 May 2011, Hamilton. New Zealand Grassland Association: Dunedin. p 157-162.
- Minchin, R., Fletcher, A. L., Gillespie, R., George, M., Meenken, E. D., Shorter, S. and Brown, H. E. 2011. Yield and quality of milling wheat in response to water deficit and sowing date on a shallow soil. *Agronomy New Zealand*, **41**, 49-58.
- Monks, D. P. 2009. The vegetative and reproductive development of balansa clover. Ph.D. Thesis, Lincoln University, Lincoln, New Zealand
- Monks, D. P., SadatAsilan, K. and Moot, D. J. 2009. Cardinal temperatures and thermal time requirements for germination of annual and perennial temperate pasture species. *Agronomy New Zealand*, **39**, 95-109.
- Monteith, J. L. 1977. Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London - B.*, **281**, 277-294.
- Monteith, J. L. 1972. Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology*, **9**, 747-766.
- Monteith, J. L. 1986. How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Society of London*, **A**, 245-258.
- Moot, D. J. 2012. An overview of dryland legume research in New Zealand. *Crop and Pasture Science*, **63**, 726-733.
- Moot, D. J., Brown, H. E., Pollock, K. and Mills, A. 2008. Yield and water use of temperate pastures in summer dry environments. *Proceedings of the New Zealand Grassland Association*, **70**, 51-57.
- Moot, D. J., Brown, H. E., Teixeira, E. I. and Pollock, K. M. 2003. Crop growth and development affect seasonal priorities for lucerne management. *In*: D. J. Moot, (ed). Legumes for Dryland Pastures. Lincoln University, New Zealand: New Zealand Grassland Association: Christchurch, 201-208
- Moot, D. J., Mills, A. and Pollock, K. M. 2010. Natural resources for Canterbury agriculture. *Proceedings of the New Zealand Grassland Association*, **72**, IX-XVIII.

- Moot, D. J., Pollock, K. M. and Lewis, B. 2012. Plant population, yield and water use of lucerne sown in autumn at four sowing rates. *Proceedings of the New Zealand Grassland Association*, **74**, 97-102.
- Moot, D. J., Robertson, M. J. and Pollock, K. M. 2001. Validation of the APSIM-Lucerne model for phenological development in a cool-temperate climate, Hobart. p 1-5.
- Moot, D. J., Scoot, W. R., Roy, A. M. and Nicholls, A. C. 2000. Base temperature and thermal time requirements for germination and emergence of temperate pasture species. *New Zealand Journal of Agricultural Research*, **43**, 15-25.
- Moran, S. M., Pinter, P. J., Clothier, B. E. and Allen, S. G. 1989. Effect of Water Stress on the Canopy Architecture and Spectral Indices of Irrigated Alfalfa. *Remote Sensing of Environment*, **29**, 251-261.
- Morton, J. and Roberts, A. 1999. Fertilizer use on New Zealand sheep and beef farms. Auckland: New Zealand Fertiliser Manufacturer's Association. 36 pp.
- Musgrave, D. J. 1977. An evaluation of various legumes at high altitude. *Proceedings of the New Zealand Grassland Association*, **38**, 126-132.
- Nicol, A. M. and Brookes, I. M. 2007. The metabolisable energy requirements of grazing livestock. In: P. V. Rattray, I. M. Brookes and A. M. Nicol, (eds). Pasture and Supplements for grazing animals. New Zealand Society of Animal Production, Hamilton, New Zealand, 151-172
- O'Connor, K. F. 1970. Influence of grazing management factors on herbage and animal production from lucerne pastures. *Proceedings of the New Zealand Grassland Association*, **32**, 108-116.
- Palmer, T. P. 1982. Weeds in lucerne, why are they there, what harm do they do. In: R. B. Wynn-Williams, (ed). Lucerne for the 80's. Agronomy Society of New Zealand: Palmerston North, 33-35
- Palmer, T. P. and Wynn-Williams, R. B. 1976. Relationships between density and yield of lucerne. *New Zealand Journal of Experimental Agriculture*, **3**, 71-77.
- Passioura, J. B. 1983. Roots and drought resistance. *Agricultural Water Management*, **7**, 265-280.
- Passioura, J. B. 1991. Soil Structure and Plant Growth. *Australian Journal of Soil Research*, **29**.
- Passioura, J. B. 2006. Increasing crop productivity when water is scarce - from breeding to field management. *Agricultural Water Management*, **80**, 176-196.
- Pearson, C. J. and Hunt, L. A. 1972. Effects of temperature on primary growth of alfalfa. *Canadian Journal of Plant Science*, **52**, 1007-1015.
- Penman, H. L. 1971. Irrigation at Woburn - VII. *Report for the Rothamsted Experimental Station 1970, Part 2*, 147-170.
- Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London, A*, **194**, 120-145.
- Peri, P. L. 2002. Leaf and canopy photosynthesis models for cocksfoot (*Dactylis glomerata* L.) grown in a silvopastoral system. Ph.D. Thesis, Lincoln University, Lincoln, New Zealand. 317 pp.
- Purves, R. G. and Wynn-Williams, R. B. 1989. Lucerne - a fresh look. *Agronomy Society of New Zealand*, **19**, 95-102.
- Rattray, P. V., Thompson, K. F., Hawker, H. and Summer, R. M. W. 1987. Pastures for sheep production. In: A. M. Nicol, (ed). Feeding livestock on pasture: New Zealand Society of Animal Production, Occasional Publication No. 10: Christchurch, New Zealand, 89-104

- Rawnsley, R. P., Chapman, D. F., Jacobs, J. L., Garcia, S. C., Callow, M. N., Edwards, G. R. and Pembleton, K. P. 2013. Complementary forages - integration at a whole-farm level. *Animal Production Science*, **53**, 976-987.
- Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research*, **8**, 1204-1213.
- Ritchie, J. T., Muchow, R. C. and Bellamy, J. A. 1991. Specifications of the ideal model for predicting crop yields, Wallingford, U.K. CAB International. p 97-122.
- Robertson, M. J., Carberry, P. S., Huth, N. I., Turpin, J. E., Probert, M. E., Poulton, P. L., Bell, M. J., Wright, G. C., Yeates, S. J. and Brinsmead, R. B. 2002. Simulation of growth and development of diverse legumes species in APSIM. *Australian Journal of Agricultural Research*, **53**, 429-446.
- Robertson, M. J., Fukai, S., Ludlow, M. M. and Hammer, G. L. 1993a. Water extraction by grain sorghum in a sub-humid environment. I. Analysis of the water extraction pattern. *Field Crops Research*, **33(1-2)**, 99-112.
- Robertson, M. J., Fukai, S., Ludlow, M. M. and Hammer, G. L. 1993b. Water extraction by grain sorghum in a sub-humid environment. II. Extraction in relation to root growth. *Field Crops Research*, **33**, 99-112.
- Salinger, J. 2003. Climate reality - actual and expected. In: D. J. Moot, (ed). Legumes for Dryland Pastures. Lincoln University, New Zealand: New Zealand Grassland Association: Christchurch, 13-18
- Semenov, M. A., Martre, P. and Jamieson, P. D. 2009. Quantifying effects of simple wheat traits on yield in water-limited environments using a modelling approach. *Agricultural and Forest Meteorology*, **149**, 1095-1104.
- Sheaffer, C. C., Tanner, C. B. and Kirkham, M. B. 1988. Alfalfa water relations and irrigation. In: A. A. Hanson, D. K. Barnes and R. R. J. Hill, (eds). Alfalfa and alfalfa improvement: American Society of Agronomy: Madison, WI, 373-409
- Sims, R. 1975. Lucerne Establishment: Precision versus conventional sowing methods. *Proceedings of the New Zealand Grassland Association*, **36**, 163-171.
- Sinclair, T. R. and Horie, T. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. *Crop Science*, **29**, 90-98.
- Sinclair, T. R. and Muchow, R. C. 1999. Radiation use efficiency. *Advances in Agronomy*, **65**, 215-265.
- Singh, P., Monteith, J. L., Lee, K. K., Rego, T. J. and Wani, S. P. 1998. Response to fertiliser nitrogen and water of post-rainy season sorghum on a Vertisol. 2. Biomass and water extraction. *Journal of Agricultural Science, U.K.*, **131**, 429-438.
- Speedy, A. 2012. The implications of spring grazing management on animal liveweight gain, yield and root reserves of lucerne (*Medicago sativa* L.). B.Ag.Sc. (Hons) Dissertation, Lincoln University, Lincoln, New Zealand
- Stocker, N. R. 2011. The effect of spring grazing management on yield, animal liveweight gain and root reserves of lucerne (*Medicago sativa* L.). A dissertation submitted in partial fulfillment of the requirement for the Degree of Bachelor of Agricultural Science with Honours at Lincoln University, New Zealand.
- Tanner, C. B. and Sinclair, T. R. 1983. Efficient water use in crop production: research or re-search? In: H. M. Taylor, W. R. Jordan and T. R. Sinclair, (eds). Limitations to efficient water use in crop production. Madison, U.S.A., January 25: American Society of Agronomy

- Teixeira, E. I. 2006. Understanding growth and development of lucerne crops (*Medicago sativa* L.) with contrasting levels of perennial reserves. Ph.D. Thesis, Lincoln University, Canterbury, New Zealand. 274 pp.
- Teixeira, E. I., Brown, H. E., Moot, D. J. and Meenken, E. D. 2011. Growth and phenological development patterns differ between seedling and regrowth lucerne crops (*Medicago sativa* L.). *European Journal of Agronomy*, **35**, 103-111.
- Teixeira, E. I., Moot, D. J. and Brown, H. E. 2008. Defoliation frequency and season affected radiation use efficiency and dry matter partitioning to roots of lucerne (*Medicago sativa* L.) crops. *European Journal of Agronomy*, **28**, 103-111.
- Teixeira, E. I., Moot, D. J. and Brown, H. E. 2009. Modelling seasonality of dry matter partitioning and root maintenance respiration in lucerne (*Medicago sativa* L.) crops. *Crop and Pasture Science*, **60**, 778-784.
- Teixeira, E. I., Moot, D. J., Brown, H. E. and Fletcher, A. L. 2007a. The dynamics of lucerne (*Medicago sativa* L.) yield components in response to defoliation frequency. *European Journal of Agronomy*, **26**, 394-400.
- Teixeira, E. I., Moot, D. J. and Mickelbart, M. V. 2007b. Seasonal patterns of root C and N reserves of lucerne crops (*Medicago sativa* L.) grown in a temperate climate were affected by defoliation regime. *European Journal of Agronomy*, **26**, 10-20.
- Teixeira, E. I., Moot, D. J., Pollock, K. J. and Brown, H. E. 2007c. How does defoliation management affect yield, canopy forming processes and light interception in lucerne (*Medicago sativa* L.) crops? *European Journal of Agronomy*, **27**, 154-164.
- Tesar, M. B. and Triplett, G. B. 1960. Improvements in methods of establishing alfalfa. *In: Proceedings of the 8th International Grassland Congress*, 1960.
- Thiebeau, P., Beaudoin, N., Justes, E., Allirand, J. and Lemaire, G. 2011. Radiation use efficiency and shoot:root dry matter partitioning in seedling growths and regrowth crops of lucerne (*Medicago sativa* L.) after spring and autumn sowings. *European Journal of Agronomy*, **35**, 255-268.
- Thornley, J. H. M. and Johnson, I. R. 2000. Plant and crop modelling: a mathematical approach to plant and crop physiology. (2nd ed.). New Jersey, U.S.A: The Blackburn Press
- Tonmukayakul, N., Moot, D. J. and Mills, A. 2009. Spring water use efficiency of six dryland pastures in Canterbury. *Agronomy New Zealand*, **39**, 81-94.
- Tozer, K. N., Bourdot, G. W. and Edwards, G. R. 2011. What factors lead to poor pasture persistence and weed ingress? *In: Pasture Persistence Symposium*, 10-11 May 2011, Hamilton. New Zealand Grassland Association: Dunedin. p 129-138.
- Triplett, G. B. and Tesar, M. B. 1960. Effect of compaction, depth of planting, and soil moisture tension on seedling emergence of alfalfa. *Agronomy Journal*, **52**, 681-684.
- Ulyatt, M. 1978. Aspects of the feeding value of pastures. *Proceedings of the Agronomy Society of New Zealand*, **8**, 119-122.
- Unger, P. W. and Stewart, B. A. 1983. Soil management for efficient water use: an overview. *In: H. M. Taylor, W. R. Jordan and T. R. Sinclair, (eds). Limitations to efficient water use in crop production*. Madison, U.S.A., January 25: American Society of Agronomy, 419-460
- Varella, A. C. 2002. Lucerne crop responses to continuous and intermittent light under artificial and agroforestry regimes. PhD Thesis. Ph.D. Thesis, Lincoln University, Lincoln. 268 pp.

- Vartha, E. W. 1973. Performance of lucerne-grass pastures on Wakanui silt loam. *New Zealand Journal of Experimental Agriculture*, **1**, 29-34.
- Waghorn, G. C., Burke, J. L. and Kolver, E. S. 2007. Principles of feeding value. *In*: P. V. Rattray, I. M. Brookes and A. M. Nicol, (eds). *Pasture and Supplements for grazing animals*. New Zealand Society of Animal Production, Hamilton, New Zealand, 35-59
- Watt, M., Silk, W. K. and Passioura, J. B. 2006. Rates of Root and Organism Growth, Soil Conditions, and Temporal and Spatial Development of the Rhizosphere. *Annals of Botany*, **97**, 839-855.
- Watt, M. S., Bloomberg, M. and Finch-Savage, W. E. 2011. Development of a hydrothermal time model that accurately characterises how thermoinhibition regulates seed germination. *Plant, Cell and Environment*, **34**, 870-876.
- Webb, T. H. 2000. Quantifying variability of soil physical properties within soil series to address modern land-use issues on the Canterbury Plains, New Zealand. *Australian Journal of Soil Research*, **38**, 1115-1129.
- Webb, T. H. 2003. Identification of functional horizons to predict physical properties for soils from alluvium in Canterbury, New Zealand. *Australian Journal of Soil Research*, **41**, 1005-1019.
- White, J. G. H. 1982. Lucerne grazing management for the 80's. *In*: R. B. Wynn-Williams, (ed). *Lucerne for the 80's*. Agronomy Society of New Zealand: Palmerston North, 111-114
- White, J. G. H. 1999. New Zealand pasture and crop science (pp. 1-10). *In*: J. G. H. White and J. Hodgson, (eds). *Farmlands of New Zealand*. Auckland, New Zealand: Oxford University Press
- Whitfield, D. M., Wright, G. C., Gyles, O. A. and Taylor, A. J. 1986. Growth of lucerne (*Medicago sativa* L.) in response to frequency of irrigation and gypsum application on a heavy clay soil. *Irrigation Science*, **7**, 37-52.
- Wigley, K. 2011. Lucerne (*Medicago sativa* L.) establishment after inoculation with different carriers of *Ensifer meliloti* on five sowing dates. B.Ag.Sc. (Hons) Dissertation, Lincoln University, Lincoln, New Zealand
- Wynn-Williams, R. B. 1982. Lucerne establishment - conventional. *In*: R. B. Wynn-Williams, (ed). *Lucerne for the 80's*. Agronomy Society of New Zealand: Palmerston North, 11-19

Acknowledgments

I would like to thank everyone who has made contributions, not only to my Ph.D. study but to my entire time at Lincoln. It has been a great journey and has created amazing opportunities.

Firstly I would like to thank my supervisor, Prof. Derrick Moot. You provided an excellent framework for my research which allowed me to follow my own path. But, offered exceptional guidance, support and learning opportunities along the way. Your inability to settle for mediocrity was a tough pill to swallow at times, but I know I am a better researcher and person for it!

To, my associate supervisor Prof. Bruce McKenzie, Dr. Hamish Brown and Dr. Edmar Teixeira for your direction, guidance and discussions helping me to explain my data. Special thanks to Dr. Anna Mills for help with statistics and many other things.

To the staff at the Field Service Centre. Dave Jack and Dan Dash for all your support with the field trials. Don Heffer for making what seemed like endless numbers of neutron probe access tubes. Malcolm Smith for all your work with the grazing experiments. Colin and Lorraine Pettigrew, farm managers at Ashley Dene, nothing was ever a problem and your enthusiasm for farming is an inspiration.

To Mariana, thanks for the love and support and I look forward to the future together.

To my colleagues who I was fortunate to share my time with during these studies.

I would like to gratefully acknowledge the financial support from the William Machin Memorial Trust.

Finally, I would like to thank my family, Mum and Dad, and my brothers for their love and support. Thank you for the endless encouragement which has allowed me take this amazing journey.