Lincoln University Digital Thesis

Understanding yield and water use of dryland forage crops in New Zealand

A thesis

submitted for a degree

of

Doctor of Philosophy

at

Lincoln University

New Zealand

by

Hamish E. Brown

Disclaimer

The data presented in this thesis were collected by me from April 2000. Prior to this data were collected by other workers but analysed by me for this thesis.

Abstract of a thesis submitted for a degree of Doctor of Philosophy

by

Hamish E. Brown

Understanding yield and water use of dryland forage crops in New Zealand

Lucerne (*Medicago sativa* L.) was found to be a more productive dryland forage option than chicory (*Cichorium intybus* L.) or red clover (*Trifolium pratense* L.). This was concluded from superior annual dryland yields of 20 t DM/ha from lucerne compared with 14–16 t DM/ha for chicory and red clover. This yield advantage was achieved by higher growth rates during both cool spring/autumn periods and dry summer periods. Lucerne was also the most persistent species maintaining a botanical composition of 94% six seasons after establishment, compared with 65% for chicory and 0% for red clover. All three species had similar herbage quality (25% crude protein, 11.5 MJ ME/kg DM) and grazing stock consumed 30% more protein and energy from lucerne than chicory or red clover crops.

The superior lucerne production during dry periods was due to increased water extraction up to 2.8 m depth, compared with ~1.9 m for chicory and red clover. All three crops displayed a top-down perennial water extraction pattern with an extraction front velocity of ~15 mm/day. Depletion of available water capacity in each layer of the soil profile was exponential following the arrival of the extraction front.

A detailed examination of lucerne physiology was conducted to understand seasonal variation, and the effects of water shortages on forage yield. Total DM production under non-water and non-temperature limiting conditions was related to total intercepted radiation. The total radiation use efficiency (RUE) was found to be 1.6 g/MJ. However, there was a seasonal change in DM partitioning between shoot and perennial organs (roots and crowns) and its influence on forage yield was quantified by

converting total RUE to shoot RUE. The shoot RUE was 1.3 g/MJ in September, gradually decreased to a constant 1.0 g/MJ from mid-December late-January and then abruptly decreased to 0.6 g/MJ in March/April. Temperature also influenced shoot production and this was quantified by multiplying RUE by a linear factor that declined from unity at a mean regrowth cycle air temperature of 18 °C to zero at 0 °C.

Seasonal changes in radiation interception were quantified by studying the influence of temperature and photoperiod (Pp) on the components of leaf area index (LAI) expansion. Specifically, main-stem node appearance was linear in response to Tt and the phyllochron was 37±7 °Cd for from August–January. However, phyllochron increased to 60 °Cd when the Pp on the day 150 °Cd before the first node decreased to 16 h (24 January). Continued decrease in Pp gave a 5.6 °Cd/h Pp reduction in phyllochron returning, it to 37±7 °Cd at a Pp of 13.5 h (15 March). There was a poor relationship between main-stem node appearance and LAI expansion, suggesting branching and leaf expansion have different seasonal responses to environment.

Water shortages were quantified by crop transpiration (E_T) relative to the crops E_T demand. Crop E_T was calculated from water balance by removing evaporation losses from the soil and outer canopy. Crop E_T demand (EP_T) was calculated from Penman evapotranspiration potential (EP) multiplied by crop cover and a calibration coefficient (0.86), determined by regressing the E_T of irrigated crops against EP. The RUE and LAI of dryland crops was expressed as a fraction of irrigated crops ($f_{D/I}$) to quantify the effects of water stress. The LAI expansion of lucerne was the most sensitive process with $f_{D/I}$ of 1.0 at an E_T/EP_T of 0.97 decreasing to 0.1 at an E_T/EP_T of 0.22. There was a 1:1 relationship between the $f_{D/I}$ of RUE and E_T/EP_T.

It is concluded that the improved understanding of lucerne environmental responses presented in this thesis must be considered when examining yield variability of lucerne.

Key words: *Cichorium intybus,* chicory, evaporation, leaf area index, lucerne, *Medicago sativa*, photoperiod, phyllochron, radiation interception, radiation use efficiency, red clover, temperature, transpiration, *Trifolium pratense,* water stress.

Table of Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

Abbreviation	Description	Units
a.i	active ingredient	
APSIM	Agricultural Production system SIMulator	
AWC	Available Water Capacity	mm
C_i/C_a	internal [CO_2]/atmospheric [CO_2]	dimensionless
CP	Crude Protein	g/g
CS	Canopy Storage coefficient (for precipitation)	mm/m^2 LAI
CV	Coefficient of Variation	%
DM	Dry Matter	kg/ha
DUL	Drained Upper Limit	mm
EFV	Extraction front velocity	mm/d
E_C	canopy Evaporation	mm
E_S	soil Evaporation	mm
E_T	transpiration	mm
E_{T_eff}	transpiration efficiency	kg DM/ha/mm
EP	Penman Potential Evapotranspiration	mm
EP_C	Potential canopy Evaporation	mm
EP_S	Potential soil Evaporation	mm
EP_T	Potential transpiration	mm
$f_{D/I}$	Dryland value/Irrigated value	dimensionless
GAI	Green Area Index	dimensionless
g_m	mesophyll conductance	m/s
g_s	stomatal conductance	m/s
H_a	alternative Hypothesis	
H_o	null Hypothesis	
IP_{R+I}	Intercepted Precipitation (Rainfall + Irrigation)	mm
-kl	extraction rate constant	/d
LAI	Leaf Area Index	dimensionless
LGR	Linear Growth Rate	kg DM/ha/d
LL	Lower Limit	mm^3/mm^3
LSD	Least Significant Difference	

Abbreviation	Description	Units
ME	Metabolisable Energy	MJ/kg
MSWD	Maximum Soil Water Deficit	mm
P	Probability	
PAR	Photosynthetically Active Radiation	$MJ/m^2/d$
PAWC	Plant Available Water Content	mm
P_g	gross Photosynthesis	$\mu g\ CO_2/s$
P_n	Net Photosynthesis	$\mu g\ CO_2/s$
Pp	Photoperiod	h
PSWD	Potential Soil Water Deficit	mm
P_{R+I}	Precipitation (Rainfall + Irrigation)	mm
θ	volumetric water content	mm^3/mm^3
R	intercepted Radiation	$MJ/m^2/d$
R_o	incident Radiation	$MJ/m^2/d$
R/R_o	fractional radiation interception	dimensionless
RUE	Radiation Use Efficiency	g DM/MJ
RUE_{opt}	Radiation Use Efficiency at optimal temperature	g DM/MJ
R^2	Coefficient of determination	
SEM	Standard Error of the Mean	
SWC	Soil Water Content	mm
SWD	Soil Water Deficit	mm
SWP	Soil Water Profile	mm
t_c	extraction start time within an individual layer	date
T_b	base Temperature	°C
T_m	maximum Temperature	°C
T_o	optimum Temperature	°C
Tt	Thermal time	°Cd
UL	Upper Limit	mm^3/mm^3
VPD	Vapour Pressure Deficit	kPa
WU	Water Use	mm
WUE	Water Use Efficiency	kg DM/ha/mm
Y	Yield	kg DM/ha

1   Introduction

1.1   Agricultural production under water limited conditions

Globally, water supply is the factor most limiting to crop/pasture production (Smil, 2000). Water shortages are common in many arid and semi-arid areas of the world, where annual evaporation (including transpiration) exceeds annual precipitation (rainfall, snow, irrigation). The extent of shortages is greatest in dry sub/tropical areas where evaporation is greatest (Bailey, 1979). Agricultural systems in these areas have evolved different strategies to produce grain and stock from a limited water supply (Hall *et al.*, 1979). However, seasonal precipitation is often variable and drought caused by below average precipitation reduces crop/pasture production below normal levels for a region (McWilliam, 1989).

Much of the worlds "developing" population is in semi-arid areas and the rapid growth of these populations highlights the importance of increasing agricultural production in water limited (dryland) environments (Smil, 2000). Drought is the single most important factor threatening the food security of people in developing countries (McWilliam, 1989) and improved dryland production will reduce the impact of such events. In addition, long distance transport of agricultural products means global food security can be improved by increasing dryland production in developed and developing countries. An increase in agricultural production in dryland environments is dependant on increasing crop/pasture production with a limited water supply and this may be viewed as a more efficient utilisation of precipitation (Taylor *et al.*, 1983).

Although water is essential for crop production the majority of water is not conserved in yield but lost from the landscape during the growth of crops/pasture (Kramer and Boyer, 1995). Water may be used by crop transpiration or lost from the system by the evaporation or drainage of precipitation from the soil reservoir (Ritchie, 1983). The scope for increasing dryland production is through increased efficiency of yield production with limited transpiration or by reducing evaporation/drainage losses to increase the water available to the crop/pasture (Taylor *et al.*, 1983). There are a number of strategies by which these factors may potentially be altered to increase

dryland production and many of the potential options are related to crop/pasture specific factors (Austin, 1989).

To understand which strategies are most suitable to different situations it is necessary to explain how water shortages influence yield and how this varies for different crop/environment/management situations (Muchow and Bellamy, 1991). Simulation modelling has emerged as a way of doing this because it enables the prediction of different crop yields in response to different management and environmental conditions (Boote *et al.*, 1996; Thornley and Johnson, 2000). However, to produce a model capable of accurate scenario prediction requires detailed understanding and quantified relationships of crop responses to environmental conditions.

1.2   The formation of yield

The study of yield formation in relation to the environment is called crop physiology (Hay and Walker, 1989). Yield formation is the result of a primary radiation input and a number of environmentally sensitive processes:

Equation 1.1 $\text{Yield} = R_o * R/R_o * RUE * H$

Yield for forage crops is the amount of shoot dry matter (DM) consumed (harvested) by grazing animals, R_o is the quantity of incident solar radiation, R/R_o is the fraction of radiation that the crop intercepts, RUE is the efficiency with which the crop uses intercepted radiation to produce DM, and H is the fraction of total DM that is partitioned to the harvested fraction of the crop/pasture (Hay and Walker, 1989). The factors R/R_o, RUE and H are a function of crop and environmental interactions.

1.2.1   **Environmental influences on yield**

The influence of environment on yield of a specific crop can be broken into a hierarchy of four levels (de Wit, 1986). The first level is the potential yield for that crop in a region, which is determined by local solar radiation (R_o) and temperature influences on R/R_o and RUE (Equation 1.1). Solar radiation and temperature are correlated so yield

potential changes with latitude and season (Monteith, 1972). The second level relates to the impact of water limitations, which can reduce R/R_o and RUE below the level one potential (Jamieson, 1999). Levels three and four are set by mineral availability/toxicity and these are a result of the soil conditions in which a crop is grown (Fageria *et al.*, 1997). It is the combination of all four levels of limitation that contribute to site and season specific yield of any crop or pasture.

1.2.2 **Water limitations to yield**

Water for crop growth and function is extracted from the soil by roots. In the absence of precipitation the soil dries and the ability of the crops roots to extract water declines (Passioura, 1983). Prolonged dry periods mean water supply becomes less than the crops water demand and growth/yield is restricted (Monteith, 1986). Further drying of the soil in the continued absence of substantial precipitation will further reduce water supply. The influence of reduced water supply on crop yield is displayed in the linear relationships, which are frequently reported between crop/pasture water use and yield in water-limited situations. An example of such relationship was given by Heichel (1983) who showed lucerne yields increased from 3 t DM/ha with 200 mm of transpiration to 11 t DM/ha with 700 mm of transpiration. This is a general relationship and incorporates a number of plant responses (Jamieson, 1999; Pugnaire, 1999), but it is useful in highlighting the influence of water on crop yield.

1.3 Dryland sheep production in New Zealand

1.3.1 **Climate and farming system**

New Zealand has a temperate climate (White, 1999), characterised by a low evaporation and reduced likelihood of water shortages affecting pasture growth compared with tropical and Mediterranean climates. However, the east coast of New Zealand is in the rain shadow of the central mountain ranges and the predominant westerly weather systems. Thus, from Gisborne to North Otago, inland Central Otago and the McKenzie Basin have a sub-humid climate (400–800 mm rainfall) with dry periods restricting pasture production during late spring, summer and autumn months (White, 1999). For example, Lincoln (Canterbury) has an evenly distributed annual rainfall (long-term) of

60 mm per month, but potential evaporation exceeds this from September–April and reaches a peak of 150 mm per month in December/January. Pasture production in these regions is generally greatest during the spring, declines due to water stress during the dry summer, increases with autumn rainfall and decreases with decreased temperature in winter (Radcliffe and Baars, 1987). However rainfall is unreliable and annual dryland pasture production may vary by 70% from the long-term mean.

Specialist sheep breeding systems occur in dryland east coast areas, where lambs are born outside in late winter and grown on spring pasture in the field. Surplus stock are sold in late spring/early summer so only the breeding stock are carried through the dry summer period. Breeding stock are generally mated on fresh autumn pasture growth and wintered on pasture or green-feed crops carried over from the autumn. Alternatively, stock can be wintered on pasture conserved from a spring surplus or purchased supplementary feed. These are generally intensive (high pasture utilisation) systems, running 8–16 stock units per hectare. Therefore, reductions in pasture production due to rainfall variability from year to year impacts on the productivity of stock and the farm business (Young, 1989). For instance a dry spring will reduce pasture available to lambs, reducing their sale weights (Rattray et al., 1987) and value. A very dry summer/autumn will reduce the body weight of ewes, reducing conception rates and the number of lambs born in the following spring.

1.3.2 Potential to improve New Zealand dryland pasture production

The typical New Zealand pasture consists of a binary mixture of ryegrass and white clover, which is tolerant of a wide range of management (Kemp et al., 1999). This combination is well suited to high rainfall areas and irrigated farms where the dairy industry is based. However, both species have shallow roots, which limits their access to soil water and production quickly declines during dry periods (Hoglund and White, 1985). Drought resistant species can be used to increase late spring, summer and autumn production in dryland farming systems but their successful integration generally requires different management to ryegrass/white clover pastures (Moloney and Milne, 1993; Purves and Wynn-Williams, 1989). Lucerne is the most common pasture alternative used as a specialist dryland forage for either grazing or feed conservation

(Wynn-Williams, 1982). However, chicory and red clover are two other tap-rooted perennials that have recently been advocated for dryland regions (Keoghan, 1991; Paton and Fraser, 1992).

A useful forage species must enable rapid animal growth. A feature of chicory, lucerne and red clover is their high quality forage, which supports higher stock growth than ryegrass/white clover during dry conditions (Burke *et al.*, 2002). However, a negative aspect of these forages is low cool-season production (Hay and Ryan, 1989; Li *et al.*, 1997b; Wynn-Williams, 1982). This limits the area of dryland forages that may be grown on a farm, as there must be a balance with areas of cool-season active pastures for winter and early spring grazing. Another negative aspect of these species is poor persistence.

Thus, the ideal dryland forage species for this region would produce high yields of high quality forage to enable maximum stock production during dry periods. To maximise the area of forage that can be used the ideal forage must also have minimal impacts on other aspects of the farming system. Therefore, it will also have the highest cool season productivity for later winter and early spring grazing and be persistent to reduce the requirement for pasture renewal.

1.4 Aim, objectives and thesis structure

The primary aim of the research presented in this thesis was to identify a high quality forage species that could be used to increase production in dryland grazing systems of the east coast of New Zealand. To do this, three forage species were grown under irrigated and dryland conditions and the most successful species selected. Success was determined by a combination of annual yield and its seasonal distribution, herbage quality and utilisation by grazing stock. Measurements were also made to help explain dryland yield differences. The secondary aim was to explain how water shortages affected forage yield and a detailed examination of this was carried out on the selected species. This analysis initially examined the influence of environmental factors on growth and development under irrigated conditions to explain non-water limited forage yield potential. Water shortages were then quantified and related to yield forming processes to explain the mechanism by which water stress reduced forage yields below potential.

The structure of the thesis is displayed in Figure 1.1 to demonstrate how the aims of this thesis were met. Following the introduction, the review of literature (Chapter 2) focuses on the processes involved in the formation of forage yield, how this is influenced by water shortages and the potential to increase dryland production in New Zealand. This is followed by a materials and methods section (Chapter 3), which describes the three experiments from which data were collected including measurement procedures and calculations common to two or more results chapters. Research was split into five results chapters each with a specific objective contributing toward the aim of the thesis. Specific objectives of each results chapter were:

Chapter 4. To select chicory, lucerne or red clover as a suitable tap rooted species for use in dryland grazing systems. This was done by comparing the DM yields, herbage utilisation, quality and stand persistence (over six growth seasons) of these species under dryland conditions at Lincoln University. The three species were also compared under irrigated conditions to determine their yield potential and the relative effects of water shortages.

Chapter 5. To explain yield differences between chicory, lucerne and red clover under conditions of water shortage. This was done by comparing the influence of water extraction patterns on seasonal water supply and the efficiency with which water supply was used to produce yield.

The following three objectives (chapters) all relate to the secondary aim to explain how the limited water supply influences the yield of the selected crop. This begins by explaining yield formation under non-water limited conditions.

Chapter 6. To quantify the relationship between solar radiation and shoot DM production of the selected species. Shoot DM was related to intercepted solar radiation by calculating radiation use efficiency (RUE) under irrigated conditions. Seasonal changes in shoot RUE were assessed and total DM production was also related to intercepted radiation using RUE. The influence of temperature on total RUE and DM partitioning on shoot RUE where also analysed.

Chapter 7. To quantify the influence of environment on the seasonal patterns of leaf area index expansion. This was done by studying the dynamics of the components of leaf area index in relation to temperature and photoperiod under irrigated conditions.

Chapter 8. To quantify the effect of water shortage on forage yield. Water shortage was quantified as water supply (described in Chapter 5) relative to crop water demand and yield forming processes were quantified under dryland conditions and expressed relative to irrigated values (described in Chapters 6 and 7) to demonstrate how this shortage affects crop yield.

Finally, Chapter 9 is a general discussion, which includes how the environment-yield response relationships may be used by crop physiologists and crop modellers to produce reliable simulations of forage yield. This includes recommendations of how farmers might use the selected forage species to increase dryland production.

Chapter 1 | General Introduction

Chapter 2 | Review of literature

Chapter 3

Results

Objectives

Select a forage crop for increasing dryland production

Chapter 4

Expt 1 — Agronomic performance of three dryland forage species

Explain species yield differences in dryland conditions

Chapter 5

Expts 1 & 2 — Comparison of water extraction patterns and water use efficiency

Chapter 6

Expts 1, 2 & 3 — Radiation use efficiency and partitioning influences on forage yields

Quantify environmental influences on yield potential

Chapter 7

Expts 1 & 2 — Leaf area index development for radiation interception

Quantify the effects of water shortage on yield

Chapter 8

Expts 1 & 2 — Water shortage influences on radiation use efficiency and leaf area index

Materials and Methods

Chapter 9 | General Discussion
Interpretations and recommendations from results

Figure 1.1 Flow diagram of thesis structure.

2   Review of literature

This chapter reviews the literature on the potential to increase dryland production and the three deep-rooted forage species that may be used to do this. It then goes on to review the concepts of environmental influences on forage yield to determine possible methods to explain how water shortages affect perennial forage crop yield.

2.1   Potential to increase dryland production

Water limited yield (Y) is proportional to transpiration (E_T) (Equation 2.1) so the potential to increase production is through changing the relationship between Y and E_T or by increasing E_T. Transpiration is a function of precipitation (P_{R+I}) and soil water extraction (SWE) during the duration of the crop (Equation 2.1). Thus, there is potential to increase E_T by increasing SWE. Agricultural landscapes are also subject to water losses through evaporation of P_{R+I} from the canopy of the crop (E_C) or the soil (E_S) or from drainage (D) of water below maximum root extraction depth in the soil profile. Soil water storage (SWS) is not a loss of water from a farm system but is a carry over of water from the current crop so also reduces E_T and yield.

Equation 2.1 $$Y \propto E_T = (P_{R+I} + SWE) - (SWS + E_C + E_S + D)$$

The outcome of Equation 2.1 may be summarised by a water use efficiency (WUE) when considering yield produced per mm of P_{R+I} received (Stanhill, 1986) and an increase in dryland production (independent of P_{R+I} variability) will give an increased WUE. Equation 2.1 demonstrates where there is potential to increase WUE but field research or simulation work is required to give an indication of appropriate strategies for specific situations. Therefore, an understanding of water losses and factors that contribute to the relationship between Y and E_T is required.

2.1.1   Components of water use efficiency

2.1.1.1   *Soil evaporation* (E_S)

Soil evaporation can range from 14–75% of P_{R+I} depending on the P_{R+I} distribution and crop cover (Asseng *et al.*, 2001). The E_S from a crop is also dependant on potential evapotranspiration (EP), and involves diffusion of water vapour through the soil medium, which is dependant on soil wetness (Ritchie, 1972). The potential E_S is reduced by the presence of a crop canopy, which intercepts solar radiation (reducing latent heat), and decreases vapour pressure deficit (VPD) and wind speed at the soil surface. Soil evaporation becomes un-important in annual crops when full cover is established (Jamieson *et al.*, 1995a). However, forage crops are repeatedly defoliated and may experience periods of 10–20 d of incomplete ground cover a number of times in a growth season. Soil evaporation may represent an important proportion of P_{R+I} in such situations and there is potential to reduce it through practices that increase crop ground cover.

Soil evaporation is difficult to measure directly and a number of methods of calculating it have been developed (Yunusa *et al.*, 1993). Ritchie (1972) was among the first to publish explicit algorithms for calculating E_S. Within the Ritchie model, E_S following precipitation is predicted in two phases; Phase 1 (E_S1) is energy limited and accounts for the first 9 mm of rainfall on a Canterbury silt loam (Jamieson *et al.*, 1995a). Phase 2 (E_S2) is diffusion limited and decreases as a function of time as the soil dries. This calculation has been widely used in crop water balance studies (Jamieson *et al.*, 1998c; Probert *et al.*, 1998b) and a number of improvements made. For instance Littleboy *et al.* (1992) suggested that evaporation of small rainfall events is limited by energy, rather than diffusion and should be removed as E_S1 rather than the slower E_S2. Boesten and Stroosnijder (1986) demonstrated E_S2 could be calculated more accurately as a function of EP in a cool climate. The Ritchie calculations fail to account for soil drying by crop roots which decreases E_S and may cause E_S overestimates (Eastham and Gregory, 2000). The research in this thesis looks at alternative calculations that may improve the predictions of evaporation from perennial forage crops.

2.1.1.2 Canopy evaporation (E_C)

Canopy evaporation is the evaporation of P_{R+I} that a crop canopy intercepts. Few studies of crop hydrology consider E_C, but Leuning *et al.* (1994) showed E_C from a wheat crop in New South Wales, Australia accounted for 33% of in-crop precipitation. The amount of E_C from a single rainfall event is dependent on the amount of precipitation the crop canopy intercepts (PI), and this has a physical upper limit described by the product of a canopy storage (CS) coefficient (mm/m^2 GAI) and green area index (GAI). Leuning *et al.* (1994) measured a CS value of 0.55 mm for wheat. The rate of E_C following a rainfall event is driven by EP and will potentially reduce E_T because it takes latent energy and reduces the VPD of air that would otherwise be used for E_T. Because E_C increases with crop cover, management practices that aim to reduce E_S through increasing cover will increase E_C and may not increase E_T or yield.

2.1.1.3 Drainage

Drainage is the percolation of water below the maximum depth to which it may be extracted by crop roots (Ritchie, 1981). Drainage occurs following P_{R+I} when the soil is at drained upper limit (DUL). Thus, potential to reduce drainage may occur through greater crop water extraction so the soil has a larger capacity to absorb P_{R+I}.

2.1.1.4 Transpiration efficiency

Crop yield may be increased with no increase in E_T if the efficiency with which the crop transpires is increased (Tanner and Sinclair, 1983). The link between RUE and transpiration efficiency (E_T_eff) is discussed in Section 2.5.1.3. It follows that any activity that increases RUE of a crop will increase the dryland production. This may be through crop selection or fertiliser management as nutrient deficiencies reduce RUE (Fageria *et al.*, 1997). Also timing production to cool periods may increase E_T_eff due to the lower VPD (Section 2.5.1.3).

2.1.1.5   *Water extraction*

Increased crop water extraction increases WUE (when considered in terms of P_{R+I} received) and this may be a direct result of reduced water loss from the soil, which increases water available for extraction. The other alternative for increased water extraction is through crop factors, which increase the amount of water the crop can extract from the soil demonstrated by a reduced lower limit (LL) or greater extraction depth. Extraction depth is a factor that may be manipulated by using deep-rooted crops. The following section reviews the agronomic aspects of three deep-rooted forage crop options for increasing dryland production in New Zealand.

2.1.2   **Lucerne**

2.1.2.1   *History*

Globally, lucerne (*Medicago sativa* L.) is the most widely used of all forage legumes (Frame *et al.*, 1998a) and has been cultivated for forage since recorded history began (Michaud *et al.*, 1988). The potential of lucerne to give greater dryland production than typical ryegrass/white clover pastures is well recognised (Iversen, 1967), and lucerne has been widely promoted and used as a dryland forage in east coast areas of New Zealand (Iversen, 1967; Wynn-Williams, 1982). However, lucerne has often failed to meet its potential in New Zealand (Langer, 1990) and a steady decline in its use since 1976 has been associated with the adverse effects of pests, diseases and poor grazing management (Purves and Wynn-Williams, 1989).

2.1.2.2   *Production and persistence*

Lucerne is capable of producing 28 t DM/ha/y under irrigated conditions on rich soils at Lincoln University (Hoglund *et al.*, 1974) and annual yields in excess of 20 t DM/ha are common when water was non-limiting (Douglas, 1986). Lucerne yields decrease with reduced rainfall and annual yields of 3 t DM/ha were reported in Central Otago where summer drought limited growth to the spring (Brash, 1985). However, lucerne yield is less sensitive to reduced rainfall than ryegrass/white clover pasture and the relative advantage of lucerne increases from 25% to 105% as annual rainfall decreases from 700 to 300 mm (Douglas, 1986). Lucerne production shows a distinct seasonal pattern with

maximum growth rates up to 185 kg DM/ha/d in December and January decreasing to negligible amounts during June and July (Baars *et al.*, 1990). Factors, which cause rapid stand thinning include poor persistence including incorrect defoliation management and pest/disease burdens (Purves and Wynn-Williams, 1989). Correctly managed lucerne and resistant cultivars should provide a 6–10 year stand life.

2.1.2.3 *Animal production*

Lucerne is a quality feed, high in crude protein and digestibility (Burke *et al.*, 2002; Jagusch, 1982) enabling high stock growth rates. Ulyatt (1978) summarised a number of live weight gain (LWG) studies showing lamb LWG was 70% greater on lucerne than ryegrass. The leaves and upper stems of lucerne contain the highest quality material and lower stems have a high proportion of indigestible lignin (Waghorn and Barry, 1987). As lucerne matures the proportion of stem increases and the overall quality of the forage decreases (Fletcher, 1976). However, stock will selectively graze leaf and soft stem fractions first (White and Cosgrove, 1990) and it is possible to maintain high stock production on mature lucerne by moving stock on to a different paddock once they have eaten the highest quality fraction of the forage.

2.1.3 **Chicory**

2.1.3.1 *History*

Traditionally, chicory (*Cichorium intybus* L.) has been used as a leaf vegetable, coffee substitute, energy crop or source of alcohol and was no more than a roadside weed to most farmers (Hare *et al.*, 1987). A few English farmers have advocated chicory as a high yielding, drought resistant pasture species (Rumball, 1986). A selection program in New Zealand resulted in 'Puna' chicory, the first registered forage chicory cultivar, selected for high leaf density and growth vigour (Rumball, 1986).

2.1.3.2 *Production and persistence*

Chicory is a perennial herb with prostrate leaves arranged in a low rosette (Rumball, 1986). Strong reproductive growth during summer and spring gives growth rates of up

to 180 kg DM/ha/d and production potential of 15–18 t DM/ha (Matthews *et al.*, 1990). In ideal conditions chicory has yielded up to 25 t DM/ha from December through to May, but a large proportion of this growth was low digestibility stem (Clark *et al.*, 1990). Defoliation prior to primary stem elongation stimulates development of smaller secondary shoots (Li *et al.*, 1997c; 1998) and severe defoliation (Li *et al.*, 1994) at 4 week intervals (Clark *et al.*, 1990) reduces stem production.

Chicory has a long thick taproot and has been shown to grow faster than ryegrass, prairie grass and tall fescue under dryland conditions in North Otago (Paton, 1992). Chicory has a prominent crown that can be damaged by grazing, especially when soils are wet. The crown is susceptible to attack by disease complexes particularly *Sclerotina* spp. (Moloney and Milne, 1993). These two factors and the inability of chicory to re-seed or vegetativley propagate itself cause continual stand thinning and poor persistence (Li *et al.*, 1997c).

2.1.3.3 *Animal production*

Chicory is a high quality forage (Barry, 1998) able to support higher LWG than grass based pastures. For example Komolong *et al.* (1992) showed lambs weaned onto chicory grew faster (335 g/head/d) than lambs weaned onto cocksfoot (200 g/head/d). Reasons for this include: efficient utilisation of consumed energy and protein within the rumen (Komolong *et al.*, 1992), faster rumen passage allowing greater intake (Kusmartono *et al.*, 1996), higher concentrations of minerals (Crush and Evans, 1990) and lower internal parasite levels (Knight *et al.*, 1996; Moss and Vlassoff, 1993) in stock grazing chicory.

2.1.4 **Red clover**

2.1.4.1 *History*

Red clover (*Trifolium pratense* L.) is a perennial legume that grows from a central crown at the top of a taproot (Bowley *et al.*, 1984). Easy establishment and rapid growth have seen it become widely cultivated and developed into a wide range of regional races in Europe (Taylor and Quesenberry, 1996). Its erect growth and high

feed quality make it ideal for hay/silage cropping, and its ability to fix nitrogen saw it replace fallow periods in many cropping rotations (Frame *et al.*, 1998b). Red clover has not been widely utilised as a dryland forage in New Zealand in spite of its deep tap root and similar morphology and growth pattern to lucerne.

2.1.4.2   *Production and persistence*

Sheath *et al.* (1977) and Allen *et al.* (1976) both showed red clover yield of ~13 t DM/ha under irrigated conditions and ~5 t DM/ha under dryland conditions (560 mm rainfall) in the Waitaki Valley. These values were ~20% and 40% lower than lucerne under irrigated and dryland conditions (respectively) and are consistent with other reports of 12 t DM/ha yield potential under moist conditions (Anderson, 1973; Hay and Ryan, 1989). Red clover production is seasonal with ~45% of its annual production during the summer and <5% during the winter (Hay and Ryan, 1983). Red clover is intolerant of hard grazing and usually fails to persist for longer than three years under normal grazing (Hickey and Harris, 1989) due to poor resistance to a wide range of root diseases (Skipp and Christensen, 1990). Red clover can reseed if grazing is sufficiently lax to allow seed set.

2.1.4.3   *Animal production*

Red clover is also a quality forage with high digestibility and protein levels (Waghorn and Barry, 1987) capable of sustaining high LWG (Burke *et al.*, 2002). For instance Niezen *et al.* (1993) showed red deer calves grew 430 g/head/d grazing red clover compared with 330 g/d grazing ryegrass/white clover.

2.2   Environmental influences on forage yield

Part of this thesis was to explain the influence of water shortages on forage yield. To do this it is first necessary to understand how other environmental factors (temperature and solar radiation) influence yield potential (Section 1.2) and then explain how water shortages affect these relationships. Lucerne is the forage crop most extensively studied and turned out to be the most productive of the three species compared in this thesis so the remainder of this review concentrates on lucerne.

2.2.1   Crop yield

Most yield forming processes are common to all plants, but specific aspects of each process may differ between species and cultivar. Plant processes are strongly influenced by environment and different genotypes may have differing environmental responses (Boote et al., 1994). For the major annual crops of wheat, rice, maize and potatoes extensive research has occurred to understand yield forming processes (Hay and Walker, 1989). The underlying principles from such studies can be used to investigate the environmental responses of other species. For perennial forages, there are additional challenges in dealing with perennial organs (e.g. roots and crown structures) that interact with the shoot and influence forage yields during the growth season. The issue of how to deal with the perennial aspects of forage crop physiology is an important part of this thesis.

The yield of any crop is generally described in basic terms by Equation 1.1 which integrates the influence of environment (R_o, temperature, water supply) on processes contributing to DM production (R/R_o, and RUE) and its partitioning (H) to yield over the duration of the crop (Ritchie, 1991). However, crop processes and environmental factors vary within the growth cycle of a crop/pasture and timing of limitations may therefore have different effects on yield. Potential yield and yield reductions below potential are a result of dynamic changes in crop/pasture growth and development processes. Growth processes are summarised in Equation 1.1 by the expression of R_o*R/R_o*RUE which results in DM production. Development processes control the duration of growth phases and crop/pasture DM partitioning, which contribute to R/R_o and H. To understand how yield forming factors change over the duration of a

crop/pasture cycle it is necessary to study growth and development processes in response to environment.

2.2.2 Growth

The growth of a crop is defined as the net increase in DM as a result of the crop fixing atmospheric CO_2 to produce carbohydrate (Fosket, 1994). Some of this carbohydrate is used for plant function, which causes the release of CO_2 and a loss in plant mass (Hay and Walker, 1989). The overall growth of a crop can be described by:

Equation 2.2 $$\text{Growth} = P_g - R$$

Where P_g is gross CO_2 fixation by the Calvin cycle and R is respiration, which represents the amount of CO_2 released by the plant as it lives.

2.2.2.1 *Gross photosynthesis*

Photosynthesis occurs in the leaves of a plant and is driven by photons of radiation, which are used to split water molecules and release protons (H^+) and electrons (e^-). The protons are used in the phosphorylation of ADP to ATP and the electrons are used to reduce $NADP^+$ to NADPH (Hopkins, 1999). Collectively the production of ATP and NADPH are called light reactions and the products are used in Calvin cycle reactions to reduce CO_2 to carbohydrate. In lucerne, P_g ranges from 0.12–2.38 g CO_2 per metre of leaf area per second (Heichel *et al.*, 1988).

Potential growth is set by R_o (Section 1.2), which influences the concentration of photons falling on leaves, and controls the production of ATP and NADPH and subsequent CO_2 reduction. The response of lucerne leaves to photosynthetically active radiation (PAR) is linear at first with P_g increasing at ~0.016 g CO_2/J between 0 and 100 W PAR/m^2 (Varella, 2002). However, the capacity of the Calvin cycle to use the ATP and NADPH supplied by light reactions has an upper limit and the response to radiation becomes non-linear above 100 W/m^2 and reaches a maximum of 2 g CO_2/m^2/s at 400 W PAR/m^2 (Varella, 2002).

Potential growth is also determined by temperature, which limits P_g through affects on the capacity and efficiency of Calvin cycle reactions. Calvin cycle reactions are catalysed by enzymes so reaction rates increase with temperature up to an optimum and then decrease at super-optimal temperatures (Hopkins, 1999). The Calvin cycle is also subject to an inefficiency called photorespiration as a result of oxidation of a Calvin cycle intermediate (RuBP) rather than reduction. The Rubisco that catalyses this part of the cycle has an affinity for both O_2 and CO_2 and its affinity toward CO_2 is reduced three fold with a temperature increase from 15–35 °C with no change in its affinity toward O_2 (Hay and Walker, 1989). As a result P_g increases with temperature up to an optimum then decreases at supra-optimal temperatures (Acock, 1991). For example, Peri *et al.* (2002) showed P_g of cocksfoot leaves showed a linear increase from 10–18 °C, no change from 18–23 °C and a linear decrease above 23 °C.

Growth is reduced below potential by water shortages because P_g is decreased. Photosynthesis is a diffuse process dependant on the concentration of CO_2 surrounding the Calvin cycle (Hay and Walker, 1989). The diffusion of CO_2 is controlled by concentration gradients and stomatal conductance. Atmospheric CO_2 can be considered constant, but stomatal conductance decreases during water stress. As stomata close CO_2 exchange is restricted and subsequently P_g decreases. This was demonstrated by Antolin and Sanchez-Diaz (1993), who reported a decrease in mid-day leaf water potential of lucerne (demonstrates water stress) from −1.5 to −3.5 MPa gave an 80% decrease in stomatal conductance and a decrease in P_g from 1.0–0.13 g $CO_2/m^2/s$. Similarly, Irigoyen *et al.* (1992) measured a decrease in P_g from 0.66–0.13 g $CO_2/m^2/s$ as leaf water potential decreased from −1.4 to −3.1 MPa.

2.2.2.2 Respiration

Changes in respiration also affect growth (Equation 2.2). Respiration involves the oxidation of carbohydrate in the mitochondria to produce ATP and substrates necessary for plant function (Opik, 1980). Respiration has two parts; maintenance respiration is the energy required for a plants basal metabolism and increases with plant mass. Growth respiration is the energy requirement of carrying out photosynthesis and converting P_g into plant structure and increases in proportion to P_g (Hay and Walker, 1989). Heichel *et al.* (1988) reported lucerne respiration ranged from 0.04–0.19 mg $CO_2/m^2/s$. Respiration was lowest in older leaves at low temperature and highest in young leaves (growing rapidly) at high temperatures.

2.2.2.3 Photosynthesis and growth

The influence of temperature, solar radiation, and water supply on crop growth are displayed by a crop's net CO_2 exchange (Equation 2.2). The net photosynthesis (P_n) of individual leaves can be multiplied up to the canopy level to explain the canopy P_n and subsequent growth rates (Acock, 1991; Peri *et al.*, 2002; Varella, 2002). Net photosynthesis from a canopy is dependant on the photosynthetic capacity of the crop, respiration, and leaf angle (Varella, 2002). The influence of radiation on net canopy photosynthesis was displayed by Asseng and Hsiao (2000) who measured a near linear increase in the CO_2 assimilation of a lucerne crop up to 2 g $CO_2/m^2/s$ at 325 W PAR/m^2.

The influence of other environmental factors on lucerne growth were demonstrated by Kendall *et al.* (1994) who measured an increase in growth rates as temperature increased from 16–28 °C and a decrease beyond 28 °C. The same author showed lucerne growth rates decreased as water supply declined below adequate levels. Growth rates also change with regrowth stage and Baars *et al.* (1990) demonstrated a distinct sigmoidal DM accumulation with lucerne growth reaching a ceiling yield ~2 months after regrowth began. This demonstrates that growth rate by itself will not fully explain yield. The duration and changes in growth and DM partitioning over that duration are also important and these are related to development processes.

2.2.3 Development

Development has two aspects (Ritchie, 1991); morphological development is the change in crop dimensions which influences growth potential through effects on R/R_o. Phenological development is the change in the crops maturity through its growth/reproduction cycle. This relates to changes in RUE and H during the growth cycle, and controls the duration of growth. Both development processes respond to environmental factors with temperature and photoperiod the most important (Hodges, 1991a). These responses are controlled by plant substances which vary in concentration in response to environmental stimulus (Fosket, 1994; Hay and Kirby, 1991). Control substances involved in development processes include auxins, gibberellins, cytokinins, and ethylene (Arteca, 1996). However, the exact role of control substances is not well understood (Hay and Kirby, 1991) so development is usually related directly to environmental variables.

2.2.3.1 *Phenology*

Phenological development describes the changes in crop ontogeny (age) through vegetative and reproductive stages and is related to events on the apex (Jamieson *et al.*, 1998a). Changes in growth (Section 2.2.2.3) and partitioning priority (Section 2.3.2) are related to the changes in phenological stage (maturity) of the crop (Kiniry *et al.*, 1991). For perennial forages, such as lucerne, phenological development involves the transition from basic vegetative growth to floral initiation and flowering (Angus *et al.*, 1981; Major *et al.*, 1991). For lucerne, the progression through the ontogeny of a regrowth cycle is accompanied by a change in the priority of DM partitioning initially to the shoots and then to perennial organs (Fick *et al.*, 1988).

In most instances forage crops are defoliated at or prior to flowering so seed growth and ripening phases are less important. Kalu and Fick (1981) provided a scale to subdivide the vegetative development phase of lucerne into early, mid and late phases (based on stem height) to increase the aggregation of development stages in a regrowth cycle. However, stem length is affected by growth rates and development processes (Hesketh *et al.*, 1991; Petit *et al.*, 1992). Sanderson *et al.* (1994) reported different relationships between vegetative development and temperature for spring, summer and autumn,

which indicate this method is not an appropriate way of representing crop development. An alternative way of representing vegetative development is by the number of vegetative organs. This is a function of development and is less influenced by growth factors (Boote *et al.*, 1998).

2.2.3.2   *Morphology*

Morphological development describes the change in dimension or number of crop organs such as leaves and roots (Fitter and Hay, 2002a). This controls the crops interface with the environment, which affects processes such as radiation interception (Section 2.4) and water extraction (Section 2.5), which in turn affect growth (Section 2.2.2). The change in crop morphology involves the appearance, expansion and duration of organs.

The duration of plant organs begins with initiation at the apex and ends with its senescence (Ritchie, 1991). Development of shoots incorporates the appearance of nodes and internodes, which are associated with leaves and stems. Main-stem node appearance is often represented by the appearance of fully expanded leaves (Kiniry *et al.*, 1991), which is a fixed point between the beginning and end of a leaf organ. This point can be compared with previous leaves to establish a rate of development that is preceded by the initiation of leaves (primordia) on the apex, the development of primordia into leaves (leaf tip appearance) and the duration to full expansion.

The rate of primordium initiation is a temperature dependant constant (Hay and Kirby, 1991) and leaf tip/fully expanded leaf appearance may proceed at slower rates (Hay and Kemp, 1992) and unexpanded primordia can accumulate on the apex. Leaves expand consecutively so the rate of their appearance is dependent on the duration of expansion. Crops can control this duration and subsequently control leaf appearance rates (Hay and Kirby, 1991). For example Jamieson *et al.* (1995b) showed wheat leaf appearance rate decreased when the crop changed from the vegetative to the reproductive phase. Photoperiod can affect the rate of leaf appearance (Kiniry *et al.*, 1991). The rate of leaf appearance is usually set at one or two points within the crop growth cycle and is also affected by temperature (Section 2.2.3.3). Senescence proceeds at a slower rate than

leaf expansion (Hay and Kemp, 1992) and it is this difference that allows leaf area to accumulate.

2.2.3.3 Thermal time

Development processes proceed faster at warmer temperatures. For example, McKenzie and Hill (1989) showed an exponential decrease in the time for lentils to reach flowering as temperature increased from 8–16 °C. This influence of temperature on development processes is usually presented in relation to thermal time (Tt in °Cd), which standardises daily development rate for varying temperature regimes (Fitter and Hay, 2002b; Hodges, 1991b). The calculation of Tt is often based on three cardinal temperatures; a base (T_b) below which no development occurs (Tt = 0), an optimum temperature (T_o) where daily development reaches a maximum and a maximum temperature (T_m) above which development stops (Tt = 0). The relationship between Tt accumulation and temperature is termed the temperature threshold and usually consists of a linear increase to the T_o and linear decrease to T_m. However, Bonhomme (2000a) cautioned that Tt accumulation becomes non-linear at lower temperatures. Non-linearity is less important in warm climates, but Wilson et al. (1995) demonstrated that the use of a broken stick, which accounts for the non-linearity of the temperature threshold at lower temperatures, improved the description of sweet corn development in Canterbury.

Fick et al. (1988) have presented a temperature threshold for lucerne with a T_b of 5 °C, a T_o of 30 °C and a T_m of 40 °C. This threshold has been used to explain a number of development processes of lucerne (Bootsma, 1984; Robertson et al., 2002). However, differing processes, such as primordia initiation, leaf expansion, branching and floral induction have different temperature thresholds (Boote et al., 1998; Hay and Kemp, 1992; Kiniry et al., 1991). Sharratt et al. (1989) demonstrated that T_b for lucerne time to flowering changed from 3.5 °C in the spring to 7.5 °C in the summer and 10 °C in the autumn in Minnesota. They suggested this was due to non-linearity in the temperature threshold. Further evidence of a non-linear temperature threshold can be taken from germination response to temperature (Fitter and Hay, 2002b). Moot et al. (2000) demonstrated a T_b close to 0 °C for germination and emergence of four different lucerne

cultivars and Masiunas and Carpenter (1984) demonstrated lucerne radical expansion had a T_m of 40 °C, T_o of 30 °C, a linear decline from 30–17 °C and a reduced rate of decline from 17–0 °C. Moot *et al.* (2001) used a similar threshold to describe node appearance of lucerne in Canterbury and demonstrated an improvement compared with the threshold presented by Fick *et al.* (1988). Correct estimations of development are important for simulating yield and the influence of thermal time on lucerne development will be studied in this thesis.

2.2.3.4 *Growth interactions with development*

The appearance and expansion of new organs may be controlled by development processes but there is also a substrate requirement to produce and expand new organs. Therefore, carbohydrate supply may limit the expression of development and yield potential at some times. The appearance of some organs is only reduced by growth under severe limitations (Kiniry *et al.*, 1991) and this reduction can still be viewed as a development process if the internal concentration of carbohydrate is acting as a control substance. However the expansion of organs has a greater requirement for carbohydrate (Penning de Vries *et al.*, 1989) and is more limited by growth restrictions.

Leaf expansion is the best example to explore the interaction of growth and development on crop morphology. A single cell has an upper size limit (Fosket, 1994) so cell division is necessary for an increase in the size of leaves. However, cell division alone only increases the number of cells and won't give an increase in the size of an organ unless it is accompanied by cell expansion. If we assume assimilate supply is adequate for absolute expression of leaf size then size will be determined by cell number and the maximum cell size (Christian, 1977) which can be considered development. Cell division in lucerne leaves ceases at the time of leaf tip appearance (Koehler, 1973) so the potential size of a leaf is set at this point. Development also controls the duration of expansion (Section 2.2.3.1), which affects the possibility of these cells reaching their maximum size. The rate of cell expansion during this duration is the other factor that controls whether cells reach their potential size.

Cell expansion was expressed by Kutschera (1992) as;

Equation 2.3 Expansion = ϕ(P-Y)

Where ϕ (mm^2/Pa/d) represents the rheological properties of leaf epidermis, P is epidermal cell turgor (Pa) and Y is the minimum turgor allowing cell expansion. Equation 2.3 demonstrates the association between leaf water potential and leaf expansion and indicates ϕ will control leaf expansion in non-water limited conditions. The ϕ is controlled by the activity of enzymes involved in the breaking down and reforming of the cell wall. These enzymes are controlled by temperature and plant signals, and in this context leaf expansion could be considered development (Tardieu *et al.*, 1999). However, there are a number of references that show intensity of radiation, concentration of CO_2 and mineral nutrition also affect leaf size (Hay and Walker, 1989; Penning de Vries *et al.*, 1989; Tardieu *et al.*, 1999). This is due to the substrate requirement for cell expansion (Thornley and Johnson, 2000), which may limit the rate of leaf expansion below the potential that development sets and influence crop yield potential. Indeed, some authors consider leaf expansion to be entirely dependant on growth process (Penning de Vries *et al.*, 1989). The seasonal pattern of assimilate partitioning (Section 2.3.2.2) can influence shoot growth and the possibility of this influencing development is an issue that needs to be considered with perennial forages.

2.2.4 **Simulation modelling**

2.2.4.1 *Integrating physiological processes*

Much of the understanding about physiological processes has been integrated into crop simulation models. They provide a mechanism for incorporating a number of complex/interacting components that contribute to eventual yield (Thornley and Johnson, 2000). The complexity, generality and success of simulation models for explaining crop yield is highly variable (Kiniry *et al.*, 1991). Simulation models have been widely used to predict crop yield and environmental impact results (Matthews and Stephens, 2002) despite poor reviews of past modelling success (Seligman, 1990). Modelling procedures have developed substantially since these reports and the

incorporation of large amounts of published and measured data has resulted in robust models for extensively researched crops such as wheat (Asseng *et al.*, 1998; Jamieson *et al.*, 1998b).

2.2.4.2   *Simulation models for explaining environmental yield response*

Simulation models may provide a mechanistic framework for understanding and explaining yields and interpreting experimental results (Boote *et al.*, 1996). Thus, the aim of explaining how water shortages affected forage yield can be aided using the theoretical framework of a simulation model. Environmental response mechanisms to explain yield may be taken from a number of different models. Discrepancies between assumed and measured relationships highlight issues of the crops physiology that require further understanding to be accurately simulated. Most simulation models use some form of hierarchy where potential yield is predicted from radiation and temperature and then reduced by lower order limitations. Therefore, to explain the influence of water stress on yield a logical start point is first to explain how growth and development processes that determine potential yield.

2.2.4.3   *Lucerne simulation models*

Lucerne is the forage species that has been most extensively studied (Hanson *et al.*, 1988) and there was a substantial amount of work in the development of simulation models in the 1970's and early 1980's (Fick *et al.*, 1988). However, this pursuit seemed to stop during late 1980's and early 1990's and this may have been due to limited success of lucerne models. A renewed interest in simulation modelling of lucerne has occurred in Australia since the late 1990's (Latta *et al.*, 2002; Lyons and Latta, 2003) where lucerne has been included into cropping systems to reduce saline leaching (Dunin *et al.*, 2001) and improve the nitrogen status of the soil for the following crop (Latta *et al.*, 2001).

As a result of this interest, a lucerne module was developed for APSIM farm system simulator (McCown *et al.*, 1996) to simulate the impact of including lucerne in crop rotations (Probert *et al.*, 1998a). The APSIM-lucerne model is based on physiological

principles (Robertson *et al.*, 2002), but fails to account for some of the perennial aspects of lucerne growth. It displayed reasonable accuracy in the area where it was developed (Probert *et al.*, 1998c) but lacks robustness as indicated by reduced accuracy in different environments (Chen *et al.*, 2003; Moot *et al.*, 2001; Shafiq Zahid *et al.*, 2003). The poor results of APSIM-lucerne in cooler environments has been attributed to perennial aspects of the crop that are not an issue with annual crops. It is important to address these issues to improve the understanding of perennial forage crop physiology and specific issues related to this are dealt with throughout this thesis.

2.3 Dry matter production and partitioning

2.3.1 Intercepted radiation and dry matter production

The influence of radiation on DM production can be described using a detailed canopy photosynthesis/respiration model to predict net CO_2 gain (Section 2.2.2.3). Other models use a generalised relationship of a linear increase in DM accumulation with increased radiation interception (Sinclair and Muchow, 1999). This is a gross simplification of canopy CO_2 exchange factors but gives a good relationship over a long period when other factors are not limiting growth (Monteith, 1977). The slope of this relationship describes the DM production potential of a crop and is called the radiation use efficiency (RUE).

2.3.1.1 *Radiation use efficiency*

Radiation use efficiency is widely used in crop physiology to explain or predict the DM production of a crop over a period of weeks or months (Sinclair and Muchow, 1999). The RUE is dependant on P_n and differs between crops accordingly (Monteith, 1977). For example, the highest RUE values ~1.8 g DM/MJ (total radiation) are reported for C_4 crops which have the highest photosynthetic capacity, compared with ~1.4 g DM/MJ for C_3 crops (Sinclair and Muchow, 1999). Leguminous crops have the lowest RUE values (~1.0 g DM/MJ) because they use energy to fix nitrogen and their mass has a higher energy content (Sinclair and Horie, 1989).

Caution must be taken in the use of RUE values because they are often not well defined (Norman and Arkebauer, 1991). Radiation may be defined as total solar radiation intercepted, PAR intercepted or absorbed PAR (Bonhomme, 2000b). This thesis presents RUE values in total intercepted radiation. Dry matter values used in RUE calculations usually exclude root production with the assumption the root production/respiration is a small and constant fraction of total production (Sinclair and Muchow, 1999). The production of roots is more important in perennials because they can make up a greater fraction of total DM production and respiration losses from roots can be substantial (Norman and Arkebauer, 1991). The fraction of DM that RUE represents is particularly important in lucerne because the amount of production partitioned to the roots changes with season (Section 2.3.2.2). The influence of root production on shoot yield will be studied in this thesis.

Lucerne is a leguminous C_3 crop but has an assimilation capacity similar to C_4 crops under favourable conditions (Asseng and Hsiao, 2000; Loomis and Connor, 1992). Khaiti and Lemaire (1992) are the only authors to include lucerne roots in calculations of RUE and presented a constant value of 1.15 g DM/MJ over three growth cycles in France. Varella (2002) has reported a reduction in shoot RUE from 0.65 g/MJ in January to 0.45 g/MJ in April in Canterbury, New Zealand and Avice *et al.* (1997a) reported shoot RUE values of 0.7–0.9 in a temperate region of France. Higher shoot RUE values have also been reported with Yunusa *et al.* (1995) reporting a value of 1.15 g/MJ in Canterbury, New Zealand, and Robertson *et al.* (2002) reported a value of 1.0 g/MJ in Queensland, Australia.

2.3.1.2   Temperature influences on RUE

Radiation use efficiency and radiation interception by a plant give potential production. Temperature may reduce potential growth by reducing net assimilation (Section 2.2.2.1) and subsequently RUE (Sands, 1996). There is little information on the effect of temperature on lucerne RUE and Robertson *et al.* (2002) assumed RUE was not affected by temperature between mean daily temperatures of 10 and 25 °C based on the RUE response of wheat (van Keulen and Seligman, 1987). Temperature is likely to

limit production in the temperate climate at Lincoln University and therefore the influence of temperature on production will be considered in this thesis.

2.3.2   Dry matter partitioning

Potential forage yield is also dependent on the partitioning of DM production to shoot and perennial organs (Hay and Walker, 1989). A lucerne plant is able to produce new shoots following defoliation or winter dormancy. The assimilates necessary to produce new shoots are predominantly carbohydrate and nitrogen compounds (Ta et al., 1990). These are stored within the taproot, crown and lateral roots (perennial organs) of the lucerne plant (Avice et al., 1996a) as starch and vegetative storage proteins (Avice et al., 1997b; Avice et al., 1996b). Remobilisation of assimilates creates issues for explaining yield potential because shoot production is not limited to R_o*RUE (Equation 1.1). The influence of perennial DM dynamics upon shoot yield will be studied in this thesis because it has important influences on potential production.

2.3.2.1   Dry matter partitioning within a regrowth cycle

Lucerne displays a distinct pattern of DM accumulation during a regrowth cycle, which is related to changes in partitioning as the regrowth cycle progress through its development (Heichel et al., 1988). Immediately after defoliation the DM of perennial organs declines (Lemaire et al., 1992) due to a loss of carbon and nitrogen compounds. For example Avice et al. (1996a) showed 34% of labelled N in perennial organs at defoliation was remobilised into regrowth shoots. This remobilisation is necessary for the formation of the photosynthetic mechanism and the re-establishment of the autonomy of shoots. Defoliation substantially reduces nitrogen fixation (Kim et al., 1993). Uptake of soil nitrogen is minimal after defoliation (Kim et al., 1991; Ta et al., 1990) because the transpiration stream will be small so N must come from reserves. The remobilisation of nitrogen continues until the N fixation capacity of the crop is restored between 10 and 21 d after defoliation (Kim et al., 1991; Ta et al., 1990) and this represents about 40 kg N/ha each regrowth period in a productive lucerne stand (Lemaire et al., 1992).

Half the total root carbohydrate may be lost following defoliation (Gramshaw *et al.*, 1993) but only 25% of this is retained in the shoots, the remainder is lost via respiration (Ta *et al.*, 1990). Some authors conclude nitrogen is a more important substrate than carbohydrate in the perenniality of lucerne (Avice *et al.*, 1997b; Ourry *et al.*, 1994) but the respiration loss from perennial organs represent the cost of remobilising and re-incorporating N into shoots. This loss also represents the maintenance of the root, which removes the carbohydrate demand from the shoots allowing all fixed carbohydrate to be retained for shoot growth at early stages of regrowth. Carbohydrate loss from the root continues until shoot production is sufficient for export of carbohydrate (Heichel *et al.*, 1988) and this may be 10–20 d after defoliation (Gramshaw *et al.*, 1993; Ta *et al.*, 1990).

Once the lucerne crop has established autonomous shoots the perennial organs switch from being an assimilate source to a sink (Kim *et al.*, 1991). The time of change is related to the development stage of the crop (Heichel *et al.*, 1988) and at this point nitrogen compounds and carbohydrate are partitioned to the perennial organs to replenish reserves for the following regrowth cycle. The amount of replenishment is dependant on the time of defoliation with more reserves accumulated at later stages of maturity (Avice *et al.*, 1997a).

2.3.2.2 *Seasonal pattern of dry matter partitioning*

The storage and remobilisation of assimilates is necessary to maintain the lucerne plant during winter dormancy and initiate regrowth in the spring (Cunningham and Volenec, 1998; Hendershot and Volenec, 1992; Justes *et al.*, 2002). Winter dormancy is often a long period and the crop requires high solute concentrations to enable frost tolerance (Cunningham and Volenec, 1998; Li *et al.*, 1996). For example, Cunningham and Volenec (1998) showed soluble sugars and protein accumulated in the root in autumn, remained high during winter and then declined following the onset of spring growth. Starch levels continually declined during the winter indicating the plant was consuming soluble sugars for respiration and metabolising starch reserves to maintain soluble sugar levels for frost protection of perennial organs. Perennial assimilate reserves for over-wintering are accumulated in the autumn (Khaiti and Lemaire, 1992). The rate of spring

regrowth is strongly influenced by the amount of nitrogen stored in the roots during autumn and management that affects autumn assimilate storage will also affect spring growth rates (Dhont *et al.*, 2003; Justes *et al.*, 2002).

The seasonal change in partitioning is probably related to changes in photoperiod and Noquet *et al.* (2001) showed 40% of total N uptake was partitioned to perennial organs under an 8 hour photoperiod compared with 30% under a 16 hour photoperiod. Asparagus is another perennial crop that replenishes root reserves in the autumn for winter dormancy. Woolley *et al.* (2002) have shown an abrupt increase in asparagus root growth when photoperiod decreases below 14 hours. Al-Hamdani and Todd (1990) showed temperature did not have a substantial effect on partitioning of labelled carbon in lucerne.

2.3.2.3   *The influence of partitioning on shoot production*

The influence of partitioning behaviour on shoot production was displayed by Khaiti and Lemaire (1992) who measured a constant RUE of 1.15 g/MJ. However, they also measured a decrease in shoot RUE from 0.9 g/MJ in summer to 0.55 g/MJ in the autumn when the crop partitioned more DM to the perennial organs. The effect is also evident within regrowth periods where a longer defoliation period enables faster regrowth because more assimilate was stored in the roots and is available for regrowing shoots (Avice *et al.*, 1997a).

2.3.2.4   *Partitioning within the shoot fraction*

Partitioning of DM between stem and leaf fractions may affect yield of forage crops because stock favour the leaf fraction of the crop (White and Cosgrove, 1990) and stems may not be utilised (Thomson, 1977). The stem fraction affects forage quality because stems become thicker and their digestibility and nitrogen content decline as the crop develops (Fletcher, 1976; Smith, 1970; Thom, 1978). The amount of shoot DM that stem represents also increases as the crop progresses through development stages (Fletcher, 1976; Thom, 1978).

2.4   Radiation interception

The next process explaining potential yield is the amount of radiation the crop intercepts described by incident radiation (R_o) and the fraction of this the crop intercepts (R/R_o). The function of radiation interception is carried out by leaves and is influenced by the architecture of the canopy.

2.4.1   A canopy of leaves

2.4.1.1   Canopy architecture and radiation interception

The two most important attributes of canopy architecture in relation to radiation interception are: 1. the area of leaves in a canopy (Brown and Blaser, 1968) described by the leaf area index (LAI, m^2 leaves/m^2 land) and, 2. the angle of leaves relative to incoming radiation (Trenbath and Angus, 1975). A number of other architectural factors, such as leaf arrangement (Nouvellon *et al.*, 2000), thickness, shape and surface properties (Hay and Walker, 1989), also affect the relationship. The influence of canopy architecture on R/R_o can be described by its exponential relationship with LAI, quantified by the extinction coefficient (Hay and Walker, 1989).

Equation 2.4 $R/R_o = 1-\exp(-k*LAI)$

Where the extinction coefficient (k) represents the influence of all other aspects of canopy architecture and is most sensitive to leaf angle (Kubota *et al.*, 1994; Trenbath and Angus, 1975). The extinction coefficient is also dependant on solar elevation and changes accordingly during the day (Warren Wilson, 1965). In practice k may be integrated over the range of solar elevations encountered during the day (Thornley and Johnson, 2000) and assumed to be conservative to calculate daily R/R_o from LAI data. Robertson *et al.* (2002) presented a daily integrated k of 0.8 for lucerne, Whitfield *et al.* (1986) presented a value of 0.84 and Goose et al. (1982); cited by Avice *et al.* (1997a) presented a value of 0.88. Therefore, it is possible to explain dynamics of R/R_o and production potential by explaining changes in LAI.

The value of the extinction coefficient and the exponential relationship between R/R_o and LAI has important implications on the influence of errors in LAI (measurement or simulation) on R/R_o calculations. With an extinction coefficient of 0.8 a 20% error in LAI will cause a 13% error in R/R_o at a LAI of 1.0, an 8.3% error at a LAI of 2.0, a 5.0% error at a LAI of 3.0 and a 0.9% error at a LAI of 6.0 (Jamieson *et al.*, 1998c). This displays the decreasing importance of accurately explaining changes in LAI as it increases and differences in LAI > 3.0 will be of little consequence to R/R_o and subsequent dry matter production.

2.4.1.2   *Expansion of LAI*

A number of methods have been proposed for explaining the expansion of LAI and subsequent radiation interception. One of the simplest is the prediction of LAI in relation to Tt (Ritchie, 1991), based on the assumption that development has a greater control over leaf appearance and expansion than growth (Section 2.2.3.3). The opposite approach is to predict LAI as a function of the amount of carbohydrates that a crop partitions to leaf tissue. An example of this was displayed (implicitly) in the SIMED lucerne model (Holt *et al.*, 1975) where R/R_o was calculated from leaf mass assuming a constant specific leaf area (SLA). Barnes *et al.* (1969) showed SLA and leaf area of lucerne were under separate controls and the failure of SIMED to endure in the literature indicates this approach was unsuccessful.

In practice LAI expansion is a function of growth and development processes and a robust simulation needs to account for the effect of each of these processes on the components of LAI expansion. A framework to do this was presented by Porter (1984), who broke LAI formation into separate components of leaf appearance, tillering and leaf expansion which are driven by development processes (Tt). A growth limitation on leaf expansion can be incorporated to account for the effects of growth (Porter, 1993). Validation of this approach was given by Porter *et al.* (1993) who made a direct comparison of AFRCWHEAT2 (developed in England), CERES-wheat (USA) and SWHEAT (the Netherlands) with observations collected in New Zealand. The latter two models predict LAI based on growth of leaf mass and did not perform as well as the approach used in AFRCWHEAT2. Expansion of perennial LAI differs to annuals

because of the possible influences of assimilate storage/remobilisation. The quantification of LAI expansion is also complicated in a temperate environment because of the large seasonal changes in environment. This thesis studies some of these issues by aiming to quantify the environmental response of lucerne LAI expansion.

2.4.2 Components of leaf area index

The static LAI ($m^2 m^{-2}$) of lucerne has the components of mean leaf size (m^2), number of leaves per main-stem (n) and stem population (m^{-2}). Stem population may be considered constant within a single regrowth cycle so the change in LAI (ΔLAI) can be represented by Equation 2.5;

Equation 2.5 $$\Delta LAI = [(L_A * S_A) - (L_S * S_S)] * \text{stem population}$$

Where the product of leaf appearance per stem (L_A, n main-stem^{-1}) and the mean size of new leaves (S_A, m^2) minus the product of leaf senescence per stem (L_S, n main-stem^{-1}) and the mean size of senesced leaves (S_S, m^2) is multiplied by stem population (m^{-2}) to give ΔLAI ($m^2 m^{-2}$). The primary unit of L_A is main-stem node appearance and branching then gives rise to secondary nodes that contribute to increased L_A.

2.4.2.1 Stem population

Main-stem population dictates the number of primary leaf producing units per unit area (Thornley and Johnson, 2000). For annual crops this is a function of seeding density (and germination/survival). Stem population is also considered a constant in lucerne (Robertson et al., 2002) because decreased plant density can be compensated by increasing stem number per plant (Gosse et al., 1988; Volenec et al., 1987). However, the ability of increasing plant size to compensate for reduced plant number is limited and stem population dynamics need to be considered for long-term simulations when poor management reduce plant populations (Douglas, 1986).

2.4.2.2 Main-stem node appearance

Main-stem node development is the primary driver of leaf appearance because it controls the rate of main-stem leaf appearance and the appearance of axial buds from which branch nodes and leaves may occur (Kiniry et al., 1991). Main-stem nodes appear in response to accumulated Tt (Kiniry et al., 1991) and the amount of Tt needed to produce a single main-stem node is called the phyllochron. There is little information on the direct relationship between node appearance and Tt for lucerne but Patterson (1993) and Pearson and Hunt (1972a; 1972b) all demonstrated a linear relationship between leaf number and mean growing temperature. Robertson et al. (2002) reanalysed some of these results to calculate a phyllochron of 35 °Cd per leaf.

Moot et al. (2001) suggested the phyllochron of lucerne is also affected by photoperiod. Day-length effects are often apparent in the vegetative phase (Major, 1980) and this affects main-stem node appearance in a number of crops (Kiniry et al., 1991). Sanderson et al. (1994) has shown the rate of morphological development demonstrates a different relationship with Tt in spring, summer and autumn possibly due to photoperiod effects. The effect of day-length on leaf appearance has been most studied in wheat where phyllochron decreases as day-length increases and the response appears to be induced at the time of emergence (Hay, 1999). Baker et al. (1980) suggested that day-length response was induced by rate of change of photoperiod. Node appearance has also been correlated with absolute photoperiod (Masle et al., 1989). Jamieson et al. (1995b) argued that leaf appearance is insensitive to photoperiod and apparent day-length responses are due to systematic seasonal errors in the use of air (as opposed to apex tissue) temperature for the calculation of Tt.

Growth limitations only affect main-stem node appearance under severe restrictions (Fletcher et al., 2003; Hodges, 1991b). However, only a few species have been investigated in detail and it is possible growth has a greater effect on leaf appearance rates in some species. For example Truong and Duthion (1993) demonstrated an increase in node appearance rate of peas in relation to growth rates.

With an understanding of how environmental factors affect main-stem node appearance it will be possible to simulate this variable. It is possible to simulate LAI as a function

of node appearance (Boote *et al.*, 1998; Pengelly *et al.*, 1999; Sinclair, 1984) but this procedure assumes branching and leaf size will be a constant function of main-stem nodes.

2.4.2.3 *Branching*

A plant is able to increase leaf number above that of main-stem leaves by producing branches or tillers (Hesketh *et al.*, 1991). Each main-stem node contains an auxiliary meristem which has potential to produce leaves in the same way as the apical meristem (Teuber and Brick, 1988). The expression of branching can be considered a development process (Hesketh *et al.*, 1991) and described as a direct function of Tt accumulation (Porter, 1984). Similarly, branching can be expressed through the relationship between main-stem node number and total node number (Hammer *et al.*, 1995). Fitting a linear regression to total node number as function of main-stem node number gives a description of when branching begins and how many branched leaves occur per main-stem node (Ranganathan *et al.*, 2001; Robertson *et al.*, 2002). Branching is also partly controlled by growth limitations and Penning de Vries *et al.* (1989) assumes tillering is a function of carbohydrate supply in rice. In practice both factors need to be accounted for (Hesketh *et al.*, 1991).

Between 17 and 27% of lucerne shoot DM is made up by branches (Evans and Peaden, 1984) and Maruyama and Fukunaga (1991) have shown a linear increase in number of lucerne branches with increased temperature. Juan *et al.* (1993) has shown the relative expression (% of total leaves) of branching is not affected by temperature indicating it shows the same response to temperature as main-stem node appearance. Juan *et al.* (1993) and Carlson (1965) both showed expression of branching was greater under short photoperiods in controlled environment chambers. Reduced stem density may encourage greater branching (Robertson *et al.*, 2002) but, Evans and Peaden (1984) reported weak correlations between lucerne stem density and branching.

2.4.2.4   Senescence

Senescence is the conclusion to the development of any plant organ (Fitter and Hay, 2002a) and needs to be quantified to enable net leaf appearance and LAI dynamics to be estimated. Senescence is primarily due to age and has been presented as a linear function of Tt for a number of crops (Carberry and Muchow, 1992; Chapman *et al.*, 1993; Hay and Kemp, 1992; Muchow and Carberry, 1990; Ranganathan *et al.*, 2001). However, senescence is also accelerated by mutual shading by the overlying canopy and stresses such as drought (Irigoyen *et al.*, 1992) and frost (Robertson *et al.*, 2002).

2.4.2.5   Leaf size

The final factor contributing to LAI is the size of leaves that are present in the canopy. The ultimate size of a leaf is dependant on the rate and duration of its expansion (Hay and Walker, 1989). Field and Hunt (1974) showed days to full leaf expansion was related to the rate of leaf appearance rate, indicating the duration of expansion is temperature dependant. Also, Wolf and Blaser (1971) showed leaf area expansion rate is constant when expressed in proportion to fully expanded size over a range of temperatures indicating lucerne leaf size is a result of expansion rate rather than duration. The rate of expansion is dependant on temperature and growth restrictions (Section 2.2.3). Robertson *et al.* (2002) provided a useful framework for integrating growth and development effects on leaf size by defining a genetic potential size for leaves at each nodal position and assuming leaves reach this size unless growth was insufficient to meet carbon demand for leaf expansion, set by a minimum leaf thickness. The genetic size potential of leaves is not well justified as it is represented by leaf size in optimal conditions, rather than cell number, which sets the maximum (Section 2.2.3.4). It is possible limited carbohydrate supply from the small leaf area gives the small leaf size recorded at early stages of regrowth (Brown and Tanner, 1983; Robertson *et al.*, 2002). A further improvement may be to incorporate a mechanistic leaf growth model such as that presented by Thornley (1998), to explain the expansion of leaves as they appear.

2.5   The influence of water shortages on yield

The influence of water shortages on forage yield can be explained by the influence of water stress on RUE or R/R_o. Water stress reduces yield below potential and these yield forming factors are affected differently at various degrees of water shortage. Therefore it is necessary to determine the extent of water shortage and this can be represented by crop/pasture water demand relative to supply (Jamieson, 1999).

2.5.1   Water demand

Crop water demand is a function of passive water loss by evaporation from moist mesophyll surfaces and diffusion of water through stomata in a process called transpiration (E_T). Transpiration demand can be measured as the E_T of a well-watered crop and this demand is a combination of atmospheric and crop factors (Meinke *et al.*, 2002).

2.5.1.1   *Atmospheric demand (physical)*

Evaporation from any surface is driven by solar radiation that provides the latent energy (λ) for vaporisation and requires a sink in the form of atmospheric saturation vapour pressure deficit (VPD). Evaporation is also dependant on atmospheric turbulence, which facilitates the replacement of wet air close to evaporating surfaces with dry air from higher layers (Hatfield, 1990). Turbulence is related to wind run (u) and the effects of u, VPD and λ on evaporation are explicitly described by the potential evapotranspiration (EP) equation, formulated by Penman (1948). The concept of EP is firmly entrenched in hydrology and is considered a good representation of E_T demand of a well-watered crop fully covering the ground (Heine, 1976).

2.5.1.2   *Crop demand*

The actual E_T of a crop may differ from the EP if canopy cover is incomplete. For example Carter and Sheaffer (1983a) showed an exponential increase in E_T of irrigated lucerne (as a fraction EP) from 0.6 with a LAI of 1.0 to an asymptote of 1.2 with a LAI of 4.0. This effect can be accounted for by multiplying EP by crop cover (French and

Legg, 1979). There may also be differences between EP and E_T demand due to crop specific resistances or site specific discrepancies in the calculation of EP. These can be accounted for by calibrating the product of EP and R/R_o against E_T measured from a fully irrigated crop (Doorenbos and Pruitt, 1977). This thesis will attempt to calibrate local EP to represent the E_T demand of lucerne.

2.5.1.3 *Physiological transpiration demand*

An alternative calculation of E_T demand was proposed by Monteith (1986) based on concepts of plant physiology. This approach calculates E_T demand from potential DM production and E_T_eff adjusted for daylight averaged VPD. This assumes that E_T_eff decreases linearly with increased VPD and is independent of all other factors. This method of calculating water demand has been adopted by some simulation models because it requires fewer data inputs than calculations based on physical atmospheric measurements (Meinke *et al.*, 2002).

Traditionally the product of VPD and E_T_eff is considered a constant with the assumption that an increase in VPD causes a linear increase in E_T with no effect on photosynthesis (Tanner and Sinclair, 1983). This also assumes the gradient for CO_2 diffusion from the atmosphere into the leaf (internal [CO_2]/atmosphere [CO_2] = C_i/C_a) is a crop specific constant (Monteith, 1988). Wilson (1985) demonstrated a linear relationship between wheat DM and the product of E_T/VPD, but the relationship was for cumulative data which tends to de-emphasise errors. Recent studies (e.g. Zhang and Nobel, 1996) show $E_T\_eff*VPD$ is not constant for a species and studies that use $E_T\_eff*VPD$ to predict E_T demand (Section 2.5.1.3) may be erroneous.

One possible error in this constancy of $E_T\_eff*VPD$ is the representation of VPD which is assumed to be at air temperature in the absence of leaf temperature data (Jamieson, 1999). However, leaf temperature may be either higher or lower than the air depending on crop water status and energy balance relations, so the value of VPD may be incorrect.

The relationship between C_i/C_a and E_T_eff is well established (Farquhar *et al.*, 1989; Monteith, 1988; 1993) and used to explain differences in E_T_eff between species and genotypes (e.g. Ray *et al.*, 1998; Virgona and Farquhar, 1996). It is also possible the C_i/C_a will change over time for an individual species and this will cause variability in E_T_eff. The assumption that C_i/C_a is constant was based on single leaf measurements in laboratory conditions (Monteith, 1988). Rawson *et al.* (1977) have also shown that single leaf photosynthesis is constant but E_T increases linearly with increased VPD. However, they also showed that when whole plants were subjected to the same treatments the increase in VPD decreased assimilation and $E_T\_eff*VPD$ decreased. Changes in C_i/C_a are due to changes in C_i (assuming constant C_a) and can be represented by Equation 2.6 (Jarvis and Morison, 1981):

Equation 2.6 $\qquad\qquad C_i = C_a g_s / (g_s + g_m)$

Where g_s is stomatal conductance and g_m is mesophyll conductance. A crops C_i (and C_i/C_a) will remain constant if g_s and g_m change in a constant proportion (g_s/g_m is constant), which is often not the case. For instance Stockle and Kiniry (1990) showed g_s decreased in response to an increase in VPD which decreases C_i/C_a (Zhang and Nobel, 1996) and increases $E_T\_eff*VPD$.

The g_m is a function of the photosynthetic capacity of the leaves (Hay and Walker, 1989) and it will increase in proportion to g_s if leaf photosynthesis is below saturation (Jones, 1998). However, beyond saturation any increase in g_s will give a greater increase in E_T than photosynthesis and $E_T\_eff*VPD$ will decrease. For instance numerous authors (Ashok *et al.*, 1999; Jamieson *et al.*, 1998b; Johnson and Tieszen, 1993; Lu *et al.*, 1996) have shown E_T_eff increased with a decrease in g_s. A number of authors have also reported a linear relationships between g_s and photosynthesis (Evans and von Caemmerer, 1996; Peri *et al.*, 2002; Whitfield, 1990) indicating the effect of g_s on E_T_eff is dependant on the crop/environment combination in which measurements are conducted.

Environmental factors also affect the photosynthetic capacity of a leaf. For example Peri *et al.* (2002) showed temperature and nitrogen levels induced variation in

assimilation of a cocksfoot pasture that could not be explained by variation in g_s. Nitrogen affects E_T_eff through its influence on g_m and this was shown by Caviglia and Sadras (2001) who reported an increase in E_T_eff with increased levels of nitrogen fertiliser in wheat. This paper and Sadras *et al.* (1991) also draw attention to the implicit link between RUE and E_T_eff that is not commonly mentioned in literature. The effects of temperature on E_T_eff were demonstrated at an early stage by Arkley (1963); cited by Tanner and Sinclair (1983) who showed Y vs E_T*VPD fitted groups of lines corresponding to different mean temperatures. Other examples that relate the effects of temperature on g_m to ET_eff are rare. However, it is possible E_T_eff is influenced by temperature and not a stable value for the calculation of E_T demand. This thesis will assess the suitability of E_T_eff as a predictor of E_T demand.

2.5.2   Water supply

A crop/pastures E_T demand is met with a supply of water that the root system extracts from the soil which has two components; 1) extraction of in-growth season precipitation from the upper layers of the soil, and 2) extraction of water stored at depth in the profile during substantial precipitation or periods of low EP. The influence of precipitation on E_T is well recognised with numerous presentations of increased E_T with higher precipitation (Sheaffer *et al.*, 1988). The influence of soil water extraction is a function of crop root characteristics (depth, density) and soil conditions (Passioura, 1983). Potential soil water extraction declines as the soil dries so the extent of water shortage on any day will be dependant on soil, crop and atmospheric factors.

2.5.2.1   *The soil as a water reservoir*

Potential crop water extraction is set by the available water capacity (AWC) of the soil it is growing in. This is determined by the depth of the soil, the drained upper limit (DUL) and the permanent wilting point (PWP) within that profile (Scotter, 1977). The DUL and PWP are a function of soil pore size distribution and can be determined by taking soil cores to the laboratory and measuring the soil water content at certain soil water potentials (Scotter, 1977). Alternatively, AWC can be estimated from correlations between soil texture and pore properties (Watt and Brugham, 1992). Webb

et al. (2000) have reported physical properties of Wakanui silt loam soil around Lincoln University and presented an AWC of 0.22 mm^3/mm^3 for top soil and 0.17 mm^3/mm^3 for sub-soils. However, laboratory analysed AWC uses a small core to imply the hydraulic character of a deep soil profile (Ritchie, 1981).

In the field textural layering can impede drainage causing water to 'perch' in overlying layers above DUL. Clothier *et al.* (1977) found the hydraulic conductivity of a course layer dropped faster than a fine overlying layer which stopped drainage from the fine layer at a water content 31% higher than DUL in a soil with the coarse layer absent. Similarly, Reid *et al.* (1984) reported water content in a sand layer underlain by a low conductivity fine silt layer stabilised at values much higher than laboratory determined DUL on a Templeton silt loam. Also Webb (1989) reported a stable water content 60–80% higher than laboratory determined DUL for a Wakanui silt loam. Although these soils are not drained to DUL, perched water is available for plant extraction and must be considered. Hence DUL should ideally be considered for the entire profile and determined in the field (Ritchie, 1981).

2.5.2.2   *Soils of New Zealand*

Cultivatable soils in New Zealand are predominantly volcanic ashes in the North island and alluvial or loessial deposits in the South Island (McLaren and Cameron, 1990). For instance, the Canterbury Plains is 4.6 million hectares of broad alluvial fans, terraces and flood plains deposited by rivers flowing from the Southern Alps (Kear *et al.*, 1967). Almost 83% of the plains are shallow stony soils such as the Lismore and Eyre series. There are smaller areas of soils with deep layers of fine materials (0.9–3.5 m) over lying gravels (Cox, 1978).

A characteristic of alluvial/loessial soils is their high degree of lateral and vertical textural variability. For example Karageorgis *et al.* (1984) showed two Wakanui silt loam profiles from either side of a 0.8 m wide pit differed in the depth, thickness and distribution of textural layers. Similarly, Reid *et al.* (1984) reported the variation in texture of a Templeton silt loam to be as great over 1.0 m as it was over the length of a field. This results in variability in soil physical properties such as AWC (Webb *et al.*,

2000) and hydraulic conductivity (Di and Kemp, 1989). For instance, an Eyre stony soil is excessively well drained and holds only 50 mm of available water compared with an imperfectly drained Wakanui soil that holds 190 mm for every metre of fine material (Watt and Brugham, 1992). Soil type has a corresponding influence on yield (Hayman, 1985) with annual dryland lucerne yields decreasing from 12.0 t DM/ha on a Wakanui silt loam (with > 1.5 m fine material) to 6.5 t DM/ha on an Eyre stony soil.

2.5.2.3 Water extraction by crop roots

The actual amount of a soils AWC that a crop is able to extract is dependant on the crops root characteristics (Jamieson and Ewert, 1999) and is described by the plant available water capacity (PAWC). This also uses DUL as the upper limit but has a lower limit (LL), which may be higher than the PWP depending on root characteristics (Ritchie, 1981). The PAWC can be represented for a crop/soil combination by measuring profile DUL prior to sowing a crop and LL when the crop becomes very dry (Hochman *et al.*, 2001b). Potential to increase water supply may occur through a greater extraction depth or a reduced LL in the depth of extraction. The PAWC takes no account of the pattern of water extraction from the time of DUL to the LL. The dynamic influence of water shortages on forage yield is dependant on the daily pattern of water extraction.

A methodology to describe this was presented by Monteith (1986). An extraction front velocity (EFV) can be used to describe the progress of water extraction downward through the soil. Water extraction is described in individual profile layers by an exponential decline in PAWC (Passioura, 1983) once the extraction front reaches that depth. The rate of extraction is described by an extraction rate constant (-kl), which is made up of two factors; k is a soil dependant diffusion constant (cm^2/day) and l is root length density (cm/cm^3). Differences in EFV and -kl influence the daily water supply and the rate at which PAWC is exhausted. This methodology has been validated for a number of annual crops in varying climates and soils (Meinke *et al.*, 1993; Robertson *et al.*, 1993b; Singh *et al.*, 1998; Thomas *et al.*, 1995) including seedling lucerne (Dardanelli *et al.*, 1997), where the downward progress of the extraction front can be explained by primary root growth (Bland and Dugas, 1989; Robertson *et al.*, 1993c).

2.5.2.4   *Perennial water extraction*

Perennials such as lucerne also display a top down water extraction pattern following a dormant cool season (Sheaffer *et al.*, 1988), but the cause of this pattern has not been studied in detail. Water extraction by perennials can be from absorption through older suberised roots or from the growth of new primary (absorbing) roots (Kramer and Boyer, 1995). Sheaffer *et al.* (1988) has suggested the top down pattern is due to preferential extraction via the shortest path to the transpiring tops. However, a number of authors have presented constant water uptake over a re-wetted profile depth (Jodari-Karimi *et al.*, 1983; Kipnis *et al.*, 1989; Kohl and Kolar, 1976) indicating this is not the cause. The other possible cause is top down production of fine roots. The seasonal pattern of lucerne roots has not been studied over depth under continuous drying, but the life span of lucerne fine roots is 58–131 d (Goins and Russelle, 1996) and fine root losses increase during periods of dormancy (Jones, 1943; Luo *et al.*, 1995). New fine root production of lucerne is greatest in the spring (Pietola and Smucker, 1995). This thesis will attempt to quantify the extraction patterns of perennial forage species to explain its influence on water supply and subsequent water stress.

2.5.3   **Water stress**

2.5.3.1   *Defining water stress*

Water stress is defined as "the induction of cell turgor below a maximum potential" (Pugnaire, 1999) and this occurs when the roots are unable to supply water at the rate it is being transpired from the tops (Kramer and Boyer, 1995). The water stress status of a crop can be represented by measurements of leaf water potential (Ψ). For example Carter and Sheaffer (1983a) reported a constant Ψ of ~1.0 MPa for irrigated lucerne over a summer regrowth cycle when Ψ of dryland lucerne decreased from -1.0 to -4.0 MPa. However, using Ψ to represent stress is complicated because values are highly dependant on the conditions when the sample was taken (Brown and Tanner, 1981).

The decrease in Ψ is accompanied by reduced g_s (Ottman, 1999) and reduced E_T (Sharratt *et al.*, 1983). For example Irigoyen *et al.* (1992) showed E_T rates decreased

from 9.5–0.8 μmol $H_2O/m^2/s$ when in Ψ decreased from -1.4 to -3.1 MPa and Carter and Sheaffer (1983a) showed crop E_T decreased below EP when 60% of AWC had been extracted from the soil. This corresponded to the same point when midday Ψ decreased below -1.0 MPa. Therefore, representing crop E_T as a function of EP gives a representation of water stress integrated over a measurement period of changing environmental conditions. A number of authors have used crop E_T relative to its E_T demand to represent water stress (Jamieson *et al.*, 1998b; Robertson *et al.*, 2002; Sinclair *et al.*, 1987) and this approach will also be used in this thesis.

2.5.3.2   *Water stress effects on growth*

Stomata close during water stress (Ottman, 1999) and this reduces E_T (Carter and Sheaffer, 1983b) but also causes a reduction in CO_2 exchange. For example, Irigoyen *et al.* (1992) showed a reduction in lucerne CO_2 exchange from 14.9–3.1 μmol/m^2/s when water stress reduced g_s from 0.42–0.03 mol/m^2/s. Some of the reduced CO_2 exchange is due to stress effects on photosynthesis and Antolin and Sanchez-Diaz (1993) demonstrated a 70% reduction in Rubisco activity of lucerne leaves with a reduction in Ψ from −1.0 to −3.5 MPa. Transpiration demand follows a diurnal cycle and under mild water stress stomatal closure only occurs during the middle of the day (Ottman, 1999). As water stress increases the plant is unable to maintain cell turgor for a larger portion of the day so stomata remain closed longer and the effect on E_T and CO_2 assimilation becomes more pronounced (Rawson *et al.*, 1978).

The influence of water shortage on P_n causes a reduction in RUE. Singh and Sri Rama (1989) showed a decrease in RUE of chickpea from ~0.6 g/MJ with full water supply to ~0.45 g/MJ when water stress limited actual transpiration to 60% of potential. Similarly, Whitfield *et al.* (1986) showed lucerne RUE decreased from 1.1–0.75 g/MJ when irrigation frequency was decreased from 1 to 2 weeks. It is also possible to imply the influence of water shortages on crop growth by assuming water stress decreases growth through stomatal control so growth limitations will be equivalent to E_T reductions (Jamieson *et al.*, 1995a).

2.5.3.3 *Water stress effects on LAI expansion*

The reduction in cell turgor causes a reduction in cell expansion, which is also highly sensitive to water stress (Pugnaire, 1999). This was displayed in lucerne by Brown and Tanner (1983), who measured a 90% reduction in leaf and stem expansion rates as Ψ decreased from -0.8 to -2.5 MPa. This, accompanied by reduced growth to drive leaf expansion, reduces the LAI and subsequent R/R_o of the crop. An example of this was given by Jamieson *et al.* (1995a) who showed severe water shortages halved the maximum LAI achieved by barley relative to fully irrigated controls. The reduced R/R_o has two effects. Firstly, it reduces radiation interception, which reduces DM production (Section 2.2.2) and secondly it reduces crop E_T demand (Section 2.5.1), which slows the increase in water stress (Section 2.5.3.1). Water stress increases as a crop develops a greater leaf area and its E_T demand increases. This was displayed by Brown and Tanner (1983) who showed the leaf expansion rates of dryland lucerne decreased (relative to irrigated) as the crops LAI increased throughout a regrowth cycle.

2.6 Summary

- Dryland production may be increased by the extraction of more soil water from depth. Chicory, lucerne and red clover are three deep-rooted forage species, which have a reputation for producing large quantities of high quality forage in dryland conditions. However, there are few comparisons between the three species to show which is the most suitable for inclusion in dryland east coast farming systems.

- The formulation of strategies to increase dryland production in specific situations requires an understanding of growth and development factors that contribute to yield formation and the factors that determine the utilisation of limited precipitation. This understanding may be incorporated into a simulation model, which can be used as a tool to assess various strategies for improving dryland yield.

- Primarily forage yield is a result of radiation and temperature influences on net photosynthesis (radiation use efficiency) and the partitioning of dry matter between harvested and perennial crop fractions.

- Potential yield is also influenced by radiation interception. Radiation interception is a result of the crops leaf area index and the effect of environment upon this can be separated into the components of leaf appearance, expansion and senescence.

- Water shortages occur when the crops root system is unable to extract soil water at the rate it is required by the shoots and this can be quantified by crop transpiration relative to demand. The influence of water shortages on crop yield can be explained by relating net assimilation and leaf area index expansion to water stress.

3 Materials and Methods

In this chapter materials and methods are described including measurements and methods of analysis that were common to two or more results chapters. Additional methods specific to an individual chapter are described within the results chapter.

3.1 Site

3.1.1 Location

All three experiments were located on flat land in Iversen field adjacent to the Lincoln University field service centre (43 ° 38 'S, 172 ° 28 'E, 11 m a.m.s.l.). The three experiments were contained within two adjacent paddocks (Iversen 8 and 9) with the same topography and soil type.

3.1.2 Soil

The soil is a Wakanui silt loam (*Udic Ustochrept*, USDA Soil Taxonomy) with 1.8–3.5 m of fine textured material overlying gravels (Cox, 1978). Typically, Wakanui silt loams have 0.3 m of uniform top soil with a weakly developed granular structure underlain by layers of varying depth ranging from fine silt to loamy sand or sand in texture. Wakanui soils are imperfectly drained and display strong mottling below 0.7 m indicating periods of water logging (Watt and Brugham, 1992). The AWC (determined from pore size distribution) range from 120–180 mm/m (Watt and Brugham, 1992; Webb *et al.*, 2000). Saturated hydraulic conductivity of this soil is variable from 5000 mm/day through course textured layers to <1 mm/day in fine textured layers. Layers with a hydraulic conductivity of 1 mm/day are considered to impede drainage causing perching in overlying layers (Watt and Brugham, 1992).

3.1.3 Meteorological conditions

3.1.3.1 *Rainfall and evapotranspiration and irrigation*

The driest season was 1997/98 when rainfall of 466 mm and Penman potential evaporation (EP) of 1152 mm give a potential soil water deficit (PSWD; Section 3.4.2.3) of 786 mm (Table 3.1). The PSWD was also higher than the long-term mean (LTM) of 510 mm in the 2000/01 (583 mm) and 1998/99 (633 mm) seasons. Irrigation application ranged from 65 mm in $I8_{01/02}$ to 437 mm in $I8_{99/00}$. Details of exact dates and amounts of irrigation are presented in Appendix 1.

Table 3.1 Total seasonal and long-term mean (LTM) rainfall, Penman potential evapotranspiration (EP), irrigation and potential soil water deficit (PSWD) for six growing seasons (1 July–30 June) at Lincoln University, Canterbury, New Zealand.

Season	EP	Rainfall	PSWD	I8 irrigation	I9 irrigation
1996/97	974	679		80	-
1997/98	1152	466	786	381	-
1998/99	1057	707*	633	437	-
1999/00	949	844	380	80	-
2000/01	1048	587	583	281	323
2001/02	953	785	324	65	220
LTM	1050	665	510		

Note: Rainfall was measured at the experimental site and EP was calculated from data collected at Broadfields meteorological station 2 km North of the site. * includes 150 mm of irrigation applied to reduce soil water deficit of dryland crops in September 1998. Iversen 8 and Iversen 9 represent the fields Iversen 8 and Iversen 9 (respectively) where irrigation was applied.
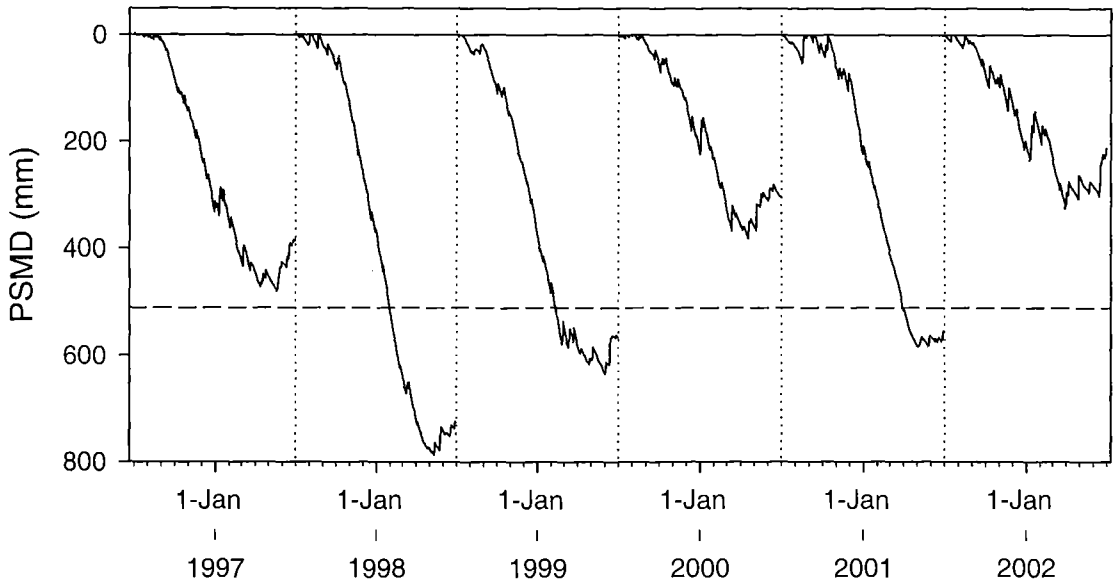
Figure 3.1 Seasonal pattern of potential soil water deficit (PSWD) calculated for six growth seasons at Lincoln University, Canterbury, New Zealand. ⋮ marks 30 June each year. --- marks the long-term mean of maximum PSWD (510 mm).

Note: Rainfall was measured at the experimental site and EP calculated were based on data collected at Broadfields meteorological station 2 km north of the site.

Total monthly EP followed a similar pattern in each season increasing from a low of 20–40 mm/month in July to reach a peak between 130 and 160 mm/month in December or January and declining to a minimum again in June (Figure 3.2). Daily EP ranged from 0.2 mm in the winter up to 8.0 mm on hot windy summer days. The PSMD generally began to increase in September but the timing and extent of PSMD (Figure 3.1) is dependant on rainfall distribution. Rainfall was variable but generally lower than EP from September through to March. Rainfall was 54% lower than the LTM from September–April in the 1997/98 season and 70% lower from December–April in the 2000/01 season. From 1 July 1996–30 June 2002 daily rainfall only exceeded 35 mm on 13 occasions and on average 250 d per annum experienced no rainfall.
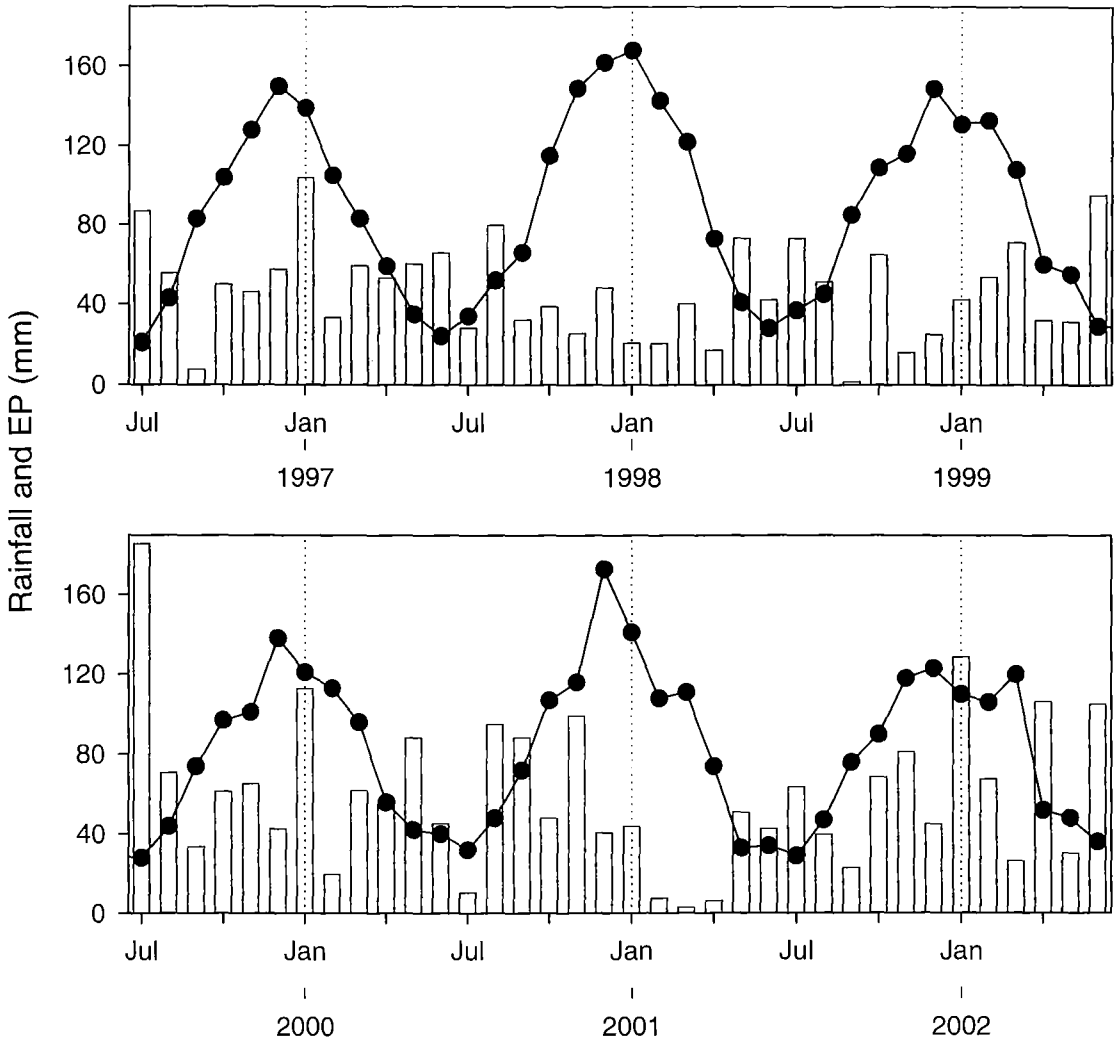
Figure 3.2 Monthly rainfall ( ) and Penman evapotranspiration potential (EP, −●−) from 1 July 1996–30 June 2002 at Lincoln University, Canterbury, New Zealand.

Note: Rainfall was measured at the experimental site and EP calculated were based on data collected at Broadfields meteorological station 2 km north of the site.

3.1.3.2   Temperature and solar radiation

The mean daily total solar radiation and daily air temperature followed a similar pattern each season (Figure 3.3). Total solar radiation cycled from a low of 5 MJ/m^2/day in mid winter (July) to a peak of about 24 MJ/m^2/day in December. The exception was the 2001/02 season where solar radiation only peaked at 19 MJ/m^2/day. On a daily basis,

total solar radiation varied from <1.0 MJ/m² on cloudy days during June and July, to >30 MJ/m² on clear sunny days in December and January. Mean daily temperature ranged from 5–7 °C in June/July to 16–20 °C in February. The diurnal temperature range was about 5 °C either side of the daily mean and temperature extremes over the 6 year period were 35 °C on 24 March 1998 and –5.7 °C on 9 July 2000.
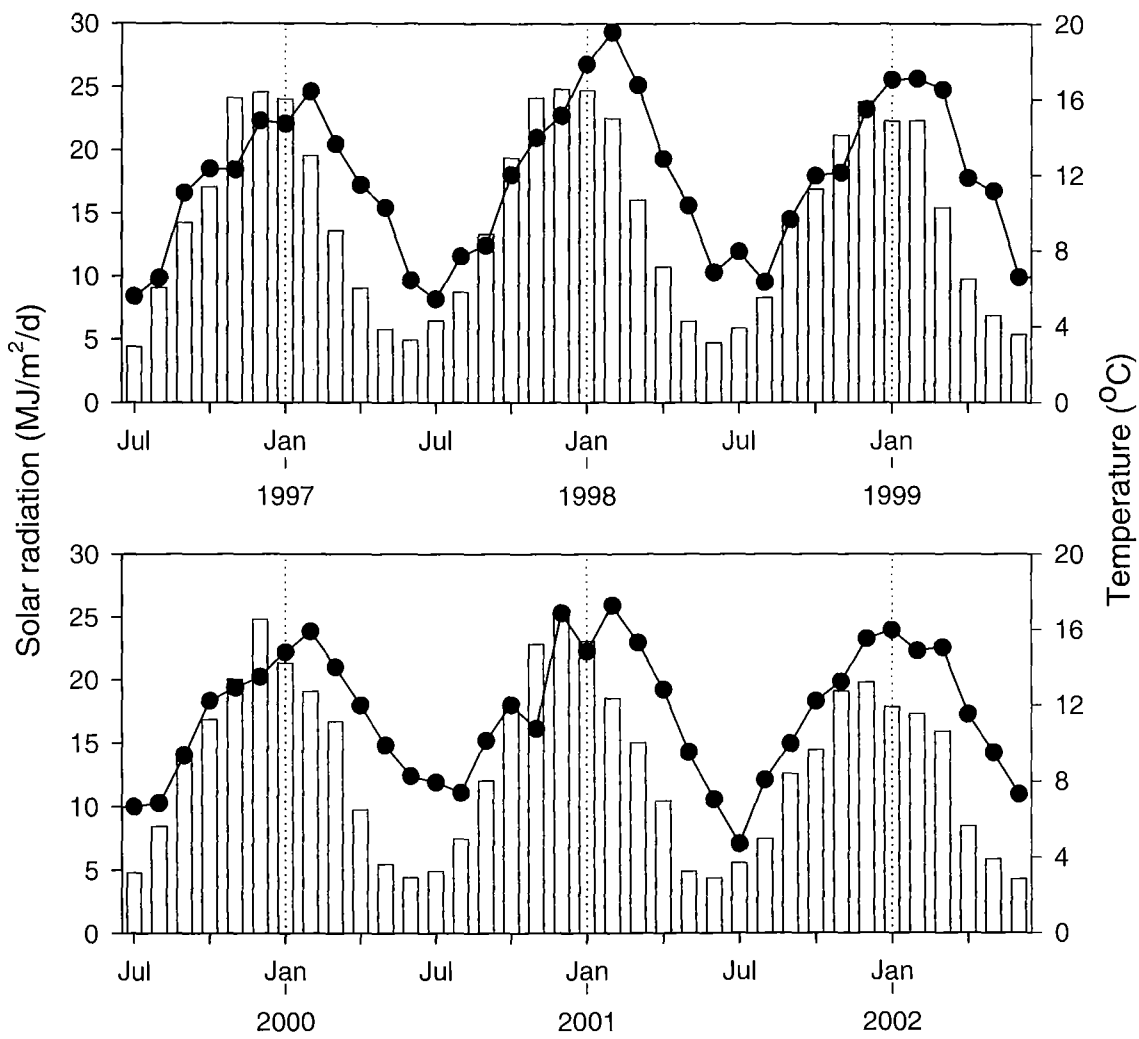
Figure 3.3 Mean daily solar radiation (☐) and mean daily air temperature (–●–) from 1 July 1996–30 June 2002. Data from Broadfields (2 km north of the site), Canterbury, New Zealand.

3.1.3.3   *Vapour pressure deficit and wind run*

Average monthly VPD ranged from 0.3 kPa in winter to 1.3 kPa (Figure 3.4) in the hot dry months of January and February in 1998. Daily values of VPD ranged from 0.1 kPa on the coldest days (<5 °C) to 2.5 kPa on exceptionally hot days (>28 °C). Wind run increased from around 200 km/d in the winter up to about 450 km/d in hot dry months (Figure 3.4). Daily wind run ranged from 14–1300 km/d.
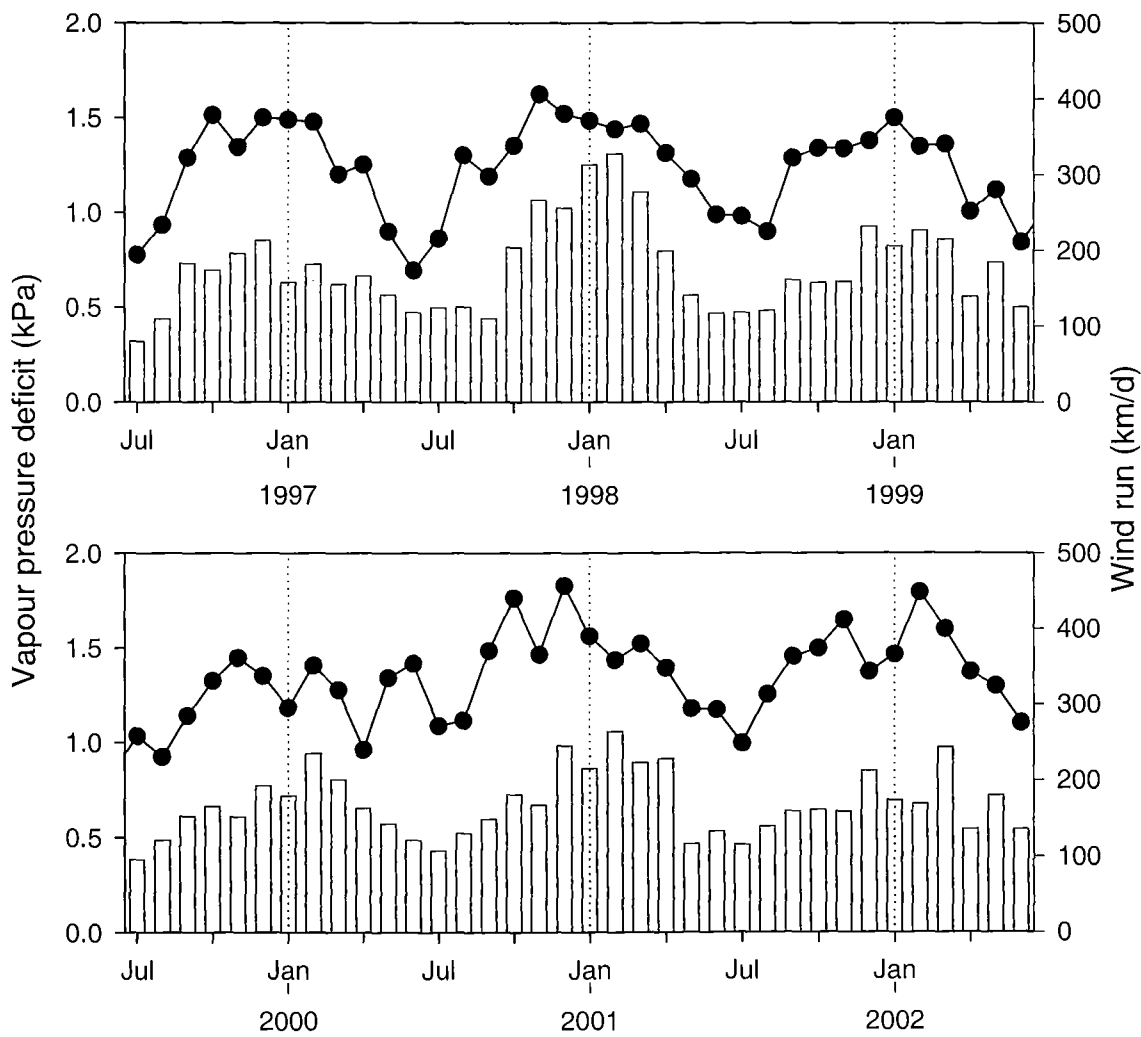
Figure 3.4 Mean daily vapour pressure deficit ( ) and mean daily wind run (–●–) from July 1996–June 2002 from Broadfields, Canterbury, New Zealand (2 km north of the experimental site).

3.2 Management

3.2.1 **Experiments**

The data presented in this thesis were collected for three experiments. Experiment 1 was a field experiment to compare the production of chicory, lucerne and red clover under dryland and irrigated conditions (Table 3.2). Detailed data on the physiology of lucerne yield was collected in Experiment 2 and data on the seasonal pattern of lucerne DM partitioning was collected from Experiment 3. Results from Experiment 3 are only used in Chapter 6 and specific materials and methods details are given in Section 6.2.2.

Experiments were conducted over a six year period (1 November 1996–30 June 2002) incorporating six annual growth seasons (Table 3.2). Each growth season was defined as 1 July–30 June incorporating two half years and are referred to by the two years in which they occurred. Each growth season was divided into a number of regrowth cycles which are referred to in their chronological order within the growth season and their exact timings are displayed in Appendix 2. Regrowth cycles were defined as the time from the finish of grazing until the start of the subsequent grazing.

Table 3.2 Summary of the three experiments conducted at Lincoln University, Canterbury, New Zealand.

	Experiment 1	Experiment 2	Experiment 3
Type	Field	Field	Column in field
Location	Iversen 8	Iversen 9	Iversen 9
Main-plot	± Irrigation	± Irrigation	short/long regrowth
Sub-plot	3 species	4 sowing dates	sequential destructive harvests
Duration	1 November 1996–30 June 2002	24 October 2000–30 June 2002	4 January 2001–30 September 2002
Species	lucerne chicory red clover	lucerne	lucerne

3.2.1.1   Nomenclature

Chapters 5, 6, 7 and 8 all use data from the duration of both Experiments 1 and 2. Observations are referred to in text by the field where the experiment was conducted and the season of measurement (Table 3.2). An acronym of field identification followed by a subscript of the growth season was used to represent each field-season combination and a specific symbol was used to represent each field-season combination when a number are presented on a single figure (Table 3.3).

Table 3.3 Description of acronyms and the symbols used in figures to represent each field-season-treatment combination.

Field	Growth season	Acronym	Sowing date treatment	Number of regrowths	Figure symbol
Iversen 8	1997/98	$I8_{97/98}$	-	6	◇
	1998/99	$I8_{98/99}$	-	7	⊕
	1999/00	$I8_{99/00}$	-	6	▽̵
	2000/01	$I8_{00/01}$	-	7	○
	2001/02	$I8_{01/02}$	-	6	▽
Iversen 9	2000/01	$I9_{00/01}$	1	3	□
			2	2	⊞
			3	2	△̟
			4	2	◈
	2001/02	$I9_{01/02}$	1	6	△

1.1.1 Establishment

1.1.1.1 Experiment 1

Experiment 1 was established in Block 8 of Iversen fields (Iversen 8) at Lincoln University (Plate 1). The experiment was established as a split-plot within a randomised complete block design. The main-plots were two irrigation levels (full and nil), replicated three times and each main-plot was separated by at least 11 m of white clover guard plots. The sub-plots (22 x 6.3 m) were the three forage species (chicory, lucerne and red clover).

Iversen 8 contained a potato experiment in the previous season. The paddock was sub-soiled on the 20 September 1996, then grubbed and roto-crumbled on the 10 October 1996 to control Californian thistle (*Cirsium arvense*) and volunteer potato. Plots were sown on 1 November 1996 with chicory ('Grassland Puna' at 3.5 kg/ha), lucerne ('Grasslands Kaituna' at 7 kg/ha) and red clover ('Grasslands Pawera' at 10 kg/ha) using an Øyjoord cone seeder. Seeds were lime coated and legumes were inoculated prior to sowing. Plant populations at the end of the establishment season were 200–250 plants/m^2 for lucerne and red clover, and 115 plants/m^2 for chicory.
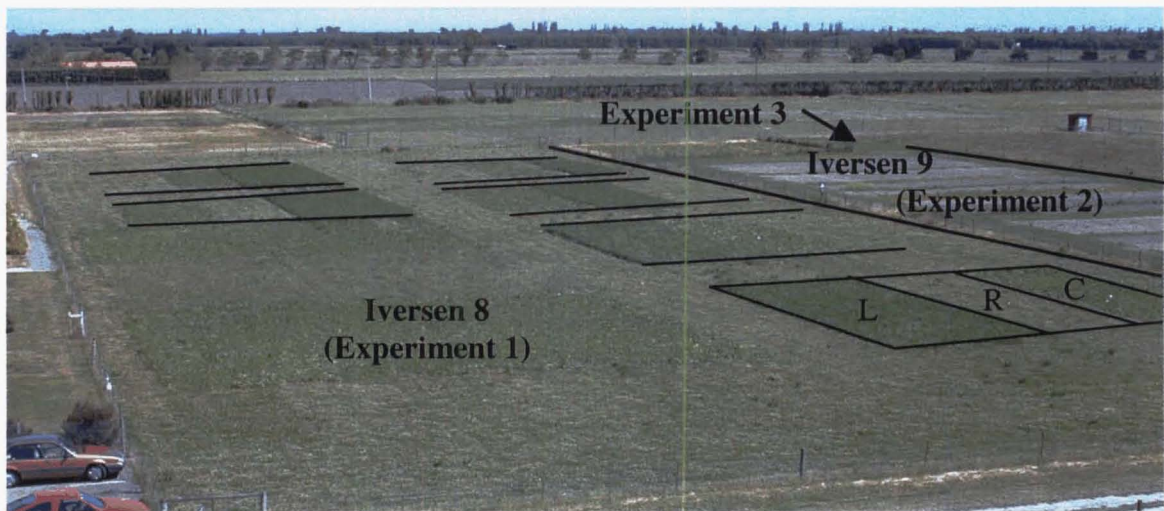
Plate 1 Aerial photograph of Iversen fields

3.2.2.2   Experiment 2

Experiment 2 was established in Block 9 (Plate 1) of Iversen field (Iversen 9) in October 2000 and consisted of a split-plot within a randomised complete block design. Main-plots (full and nil irrigation) were replicated three times and surrounded on all sides by at least 4.4 m of dryland lucerne. Sub-plots (4.4 x 10 m) were four sowing dates (24 October, 15 November, 5 December, 27 December) to provide seedling and regrowth crops at different stages of development throughout the season.

Iversen 9 contained a rape (*Brassica napus* s.s *oleifere*) experiment in the 1999/2000 season. This experiment was ploughed and sown into oats in April 2000. Oats were grazed with ewes and lambs and the paddock was ploughed on 10 September 2000, roto-crumbled twice on 12 and 14 September 2000 and roto-crumbled, harrowed and rolled on 9 October to prepare the seedbed for sowing. A 45 mm rainfall occurred on 11 October 2000 so the paddock was roto-crumbled, harrowed and rolled again on 16 and 20 October to re-prepare the seedbed. The first sowing date treatment and the remaining guard areas were sown on 24 October 2000 using an Øyjoord cone seeder. Inoculated 'Grasslands Kaituna' lucerne seed was sown to 20 mm depth at a rate of 10 kg/ha (coated) and germination tests showed seed was 93% viable. The paddock was harrowed following sowing to ensure good seed coverage. The following three sowing date treatments were sown in the same way on 15 November, 5 December and 27 December 2000.

3.2.3   Weed control

3.2.3.1   Experiment 1

Prior to sowing, sites were sprayed with treflan (Trifluralin; 0.8 kg a.i./ha) on 30 October 1996 to control *Poa sps*, fathen (*Chenopodium album* L.), wire weed (*Polygonum aviculare* L.) and chickweed (*Stellaria media* L). A post emergence spray of Preside (flumetsulum; 0.48 kg a.i./ha) was applied when chicory plants reached the four-leaf stage to control hedge mustard (*Sisymbrium officinale* L.), shepard's purse (*capsella bursa-pastoris* L.) and camomile (*Matricaria chamomilla* L.). Subsequently, crops were sprayed each winter (during July) with a mixture of Basagran (bentazone;

0.96 kg a.i./ha); to control chamomile, shepard's purse, chickweed and sow thistle (*Sonchus*); and Gallant (Haloxyfop; 0.125 kg/ha); to control meadow grass, brown top (*Agrostis tenuis* L.), ryegrass (*Lolium perenne* L.) and other grass weeds.

3.2.3.2 Experiment 2

This field had the same weed species as Iversen 8 as well as volunteer rape from the previous experiment. Treflan (0.8 kg a.i./ha) was applied on 16 October and incorporated by cultivation to give pre-emergence weed control. Areas for sowing dates 2–4 were pre emergent sprayed with glyphosate (1.0 l a.i./ha) on 18 November (Sowings 2-4), 8 December (Sowings 3 and 4) and 30 December 2000 (Sowing 4) to remove establishing weeds. Spinnaker (imazethapy 240 g a.i./ha) was applied to the first and second sowings once lucerne seedlings had produced three trifoliate leaves on 5 December and 30 December 2000 respectively. Sowings 3 and 4 were hand weeded in January to remove rape and camomile.

3.2.4 Defoliation

3.2.4.1 Experiment 1

The entire one hectare paddock was defoliated at the end of each regrowth cycle by grazing with sheep of mixed classes. In general, the first two spring regrowths were defoliated with about 120 ± 20 ewes with lambs at foot. Subsequent summer and autumn defoliations were with 120 ± 20 ewes or 70 ± 15 hoggets.

The timing of defoliation was a compromise between the ideal management for all three species. The first defoliation in spring aimed to minimise the risk of lodging in lucerne crops but allow chicory and red clover crops to maximise their linear growth phase. The second and third defoliations were a balance between maximising linear growth rates and prevention of primary flower stem formation in chicory crops. Subsequent defoliations occurred at a time when lucerne crops had visible flower buds and for one regrowth cycle between February–March, defoliation was delayed to allow 50% of lucerne stems to have open flowers. A final defoliation occurred once growth stopped

in May/June. This management criteria resulted in 6–7 defoliations per season. Details of the timing and duration of defoliations is shown in Appendix 2a.

3.2.4.2   *Experiment 2*

Defoliation management was as for Experiment 1 but timing of defoliations differed as detailed in Appendix 2b.

3.2.5   Irrigation and rain-sheltering

3.2.5.1   *Experiment 1*

All of Iversen 8 was irrigated to DUL (Section 3.4.3.3) on 22 October 1996 and irrigated once more in December to ensure even establishment. Irrigation treatments were imposed from the 1997/98 season onward. Irrigation requirements were calculated from a water balance (Section 3.4.3) with an aim of avoiding a soil profile water deficit in excess of 200 mm. Irrigation was applied using a travelling mini-boom irrigator at a rate of 10–20 mm per pass, needing 2–7 passes to apply the full amount of irrigation over a 4–7 d period. The amount of irrigation applied was measured with rain gauges placed in the path of the irrigator. Dryland crops were irrigated on one occasion at the beginning of the 1998/99 growth season when soil water measurements indicated the soil profile had not recharged to DUL during the winter. Dryland crops were not irrigated in subsequent years even if winter soil water recharge was incomplete. The amount and timing of irrigations are displayed in Appendix 1a.

3.2.5.2   *Experiment 2*

Irrigation treatments were applied to Iversen 9 during the establishment season in 2000/01 using a removable array of trickle irrigation lines A flow metre was used to measure application and water was applied at rates between 6–8 mm per hour.

Irrigation was applied in small (25–55 mm) regular amounts at the beginning of the 2000/01 season because the crop had removed little water from the soil so the capacity to absorb irrigation was low. Irrigation was justified by shallow root systems of the

establishing crop. In the 2000/01 season irrigation was applied in larger (70–80 mm) amounts following each defoliation. The timing and rate of irrigation application is presented in Appendix 1b.

Dryland plots in Iversen 9 received 70 mm of irrigation from 8–11 August 2001 to reduce the soil water deficit (SWD) from the previous season. Mobile rain-shelters were then used to eliminate rainfall during the 2001/02 season. These rain-shelters were 3 x 3 m steel structures covered with corrugated plastic (transmitted 50% of incident PAR). The shelters were 1 m high and angled toward a gutter at the North end. Water was removed from the gutter by a 15 m long hose and the south side of the shelters was covered with a sheet of corrugated plastic to block southerly rainfall. The shelters were kept off plots during fine weather and manually wheeled on at the beginning of rainfall events or in the evening if rain was expected overnight.

3.2.6 Fertility

3.2.6.1 Experiment 1

A soil test, on 19 Sep 1996, indicated pH and sulphur were below optimum levels (Table 3.4). To correct these deficiencies, 4 t/ha of lime was applied on 4 October 1996 and 150 kg/ha, sulphate of potash (0,0,40,7) and 250 kg/ha, super phosphate (0,9,0,12) were applied on 7 October 1996. A subsequent soil test (13 Aug 1997) showed fertility levels had risen to become optimal. Subsequent fertiliser applications were 200 kg/ha super phosphate on 29 May 1998, 260 kg/ha potasic super phosphate (0,6,15,14) on 2 November 1999, 250 kg/ha sulphur super phosphate (0,9,0,16) on 17 July 2000 and 200 kg/ha of super phosphate on 19 June 2001. These applications maintained fertility at optimal levels for the duration of the experiment (Table 3.4).

Table 3.4 Soil nutrient test results for Iversen 8 from 1996–2002 at Lincoln University, Canterbury, New Zealand.

Date		pH	Ca m.e/100g	K m.e/100g	P µg/ml	Mg m.e/100g	Na m.e/100g	S ppm
19 Sep 1996		*5.7*	*12*	*10*	*22*	*32*	*7*	*15*
13 Aug 1997		*6.6*	*13*	*13*	*19*	*32*	*8*	*15*
25 May 1999	Dry	6.8	12	23	24	25	10	9
	Irr	7	13	22	18	25	11	6
09 Jun 2000		*6.3*	*9*	*22*	*16*	*18*	*8*	*8*
09 May 2001	Dry	6.5	10	12	17	21	13	11
	Irr	6.2	9	18	20	20	10	10
27 May 2002	Dry	6	9	26	17	19	8	16
	Irr	6.5	10	12	14	7	8	7
Lower optima		5.8		5	20	8		10

Note: Samples from irrigated and dryland treatments were pooled on dates where test results are presented in bold italics. Soil tests were carried out using the Ministry of Agriculture and Fisheries Quick test (MAF QT). Lower optima for plant growth from Morton *et al.* (1994).

3.2.6.2   *Experiment 2*

A soil test was conducted on 13 September 2000 (prior to sowing) that showed a sulphur deficiency.

Table 3.5 Soil nutrient test results for Iversen 9 from 2000–2002 at Lincoln University, Canterbury, New Zealand.

Date		pH	Ca m.e/100g	K m.e/100g	P µg/ml	Mg m.e/100g	Na m.e/100g	S ppm
13 Sep 2000		*6.1*	*9*	*14*	*20*	*22*	*8*	*6*
18 May 2001	Dry	6.2	9	18	20	20	13	11
	Irr	6.5	10	12	17	21	10	10
Lower optima		5.8		5	20	8		10

Note: Samples from irrigated and dryland treatments were pooled on the date where test results are presented in italics. Soil tests were carried out using the Ministry of Agriculture and Fisheries Quick test (MAF QT). Lower optima for plant growth from Morton *et a.l* (1994).

3.3 Measurements

3.3.1 Meteorological conditions

Rainfall (mm) data was recorded on site. Solar radiation ($MJ/m^2/d$), wind speed (m/s), and air temperature were recorded at Broadfields meteorological station 2 km to the north of the site using standard National Institute of Water and Atmosphere equipment. Wind speed was measured at 6 m height and temperatures (wet and dry bulb) were recorded inside a Stevenson screen. Measurements were recorded at hourly intervals and calculated to daily values.

3.3.2 Dry matter

Dry matter (DM) measurements were taken from each plot by cutting a single 0.2 m quadrat above crown height (to avoid damaging the plants) with a set of hand shears. Plots were small and uniform so it was not necessary to take multiple cuts per plot. To avoid re-cutting previously sampled areas in any year plots were divided into six sections and cuts taken from a different section in each regrowth cycle. All DM samples were dried in a forced air oven (65–70 °C) to constant weight.

3.3.3 Stem number

Stem number was measured in lucerne plots by counting the number of stems present in each quadrat harvested for DM measurements (Section 3.3.1).

3.3.4 Soil water content

A single 50 mm hole was augured in the centre of each plot in Iversen 8 (18 plots, Section 3.2.2.1) during July 1997 for the installation of 47 mm (diameter) aluminium neutron probe access tubes. Access tubes were installed in the first sowing date treatment in Iversen 9 (6 plots, Section 0) on 27 October 2000. All access tubes were installed to 2.3 m depth where saturated sand collapsed the side of the holes, preventing further auguring. A set of stainless steel TDR rods (0.2 m length) were installed within 0.2 m of the neutron probe access tubes at the time of installation.

The volumetric soil water content (θ, in mm^3/mm^3) was measured in 22 layers throughout the profile of each plot. The top layer (0–0.2 m) was measured with a time domain reflectometer (Trace system, Soil Moisture Equipment, Santa Barbara, California, USA) which integrates its measurements over the entire depth. The other 21 layers (0.1 m layers from 0.2–2.3 m) were measured at their mid depth with a neutron probe (Troxler Electronic Industries Inc, Research Triangle Park, North Carolina, USA).

The neutron probe was calibrated against water content, measured gravimetrically, on a Templeton silt loam near Lincoln University (range = 0.07–0.37 mm^3/mm^3, R^2 = 0.99). This soil has the same parent material as a Wakanui silt loam and differs only in texture and depth to gravels (Cox, 1978).

3.3.5   Fractional radiation interception

3.3.5.1   Tube Solarimeter

Fractional radiation interception (R/R_o) was measured directly in $I8_{00/01}$ using tube solarimeters, one above canopy reference and one below the canopy in each of the six lucerne plots. These solarimeters were permanently mounted in square aluminium tubes with the sensor area of the solarimeter parallel with the top of the mounting channel. The mounted solarimeters were set inside a larger section of aluminium channel which was installed below ground level so the top of the solarimeter was flush with the soil surface. The aluminium channels were situated East-West (perpendicular to the drill rows).

Solarimeters were all wired into a data logger that recorded at 15 minute intervals for regrowth cycles 2–6 in $I8_{00/01}$. All solarimeters were placed level and side by side with the reference solarimeter during each grazing period and data from this period was used to calculate calibration coefficients for individual solarimeters (relative to the reference) for the subsequent regrowth cycle.

3.3.5.2   Canopy analyser

Radiation interception was also measured with a LI-COR LAI-2000 canopy analyser (Lincoln, Nebraska, USA; Welles and Cohen, 1996) in $I8_{00/01}$, $I9_{00/01}$ and $I9_{01/02}$.

One above canopy reference and five below canopy measurements were taken per replicate during stable overcast or twilight conditions as recommended by LI-COR. Measurement positions were selected at random and the LAI-2000 was used without a lens cap so measurements considered all surrounding foliage.

3.4   Calculations

3.4.1   Day-light hours and photoperiod

3.4.1.1   Day-light hours

Some measurements were summed or averaged for day-light periods. This was done by calculating the solar zenith angle (z) at the time of each measurement and excluding measurements if z>90 ° (i.e. when the sun was above the horizon). The z was calculated from latitude (43° 38' S) and longitude (172° 28' E) coordinates using the equation presented by Monteith and Unsworth (1990).

3.4.1.2   Photoperiod

Daily photoperiod (Pp) for each day was also determined from longitude and latitude coordinates using the method presented by Good speed (1975). This calculates the time (hours) for the centre of the sun to move from 6° below the eastern horizon to 6° below the western horizon and therefore includes twilight.

3.4.2   Meteorological variables

3.4.2.1   Vapour pressure deficit (VPD)

Vapour pressure deficit (kPa) was taken as the difference between vapour pressure (e) and saturated vapour pressure (e^o) at air temperature calculated using wet and dry bulb

temperatures (Section 3.3.1). Formulation of VPD calculations was taken from Jenson *et al.* (1990):

Equation 3.1 $\quad\quad\quad\quad\quad$ $\text{VPD} = e^{\text{o}} - e$

e^{o} (kPa) was calculated as:

Equation 3.2 $\quad\quad\quad\quad$ $e^{\text{o}} = 0.611 * \exp[(17.27 * T)/(T + 237.3)]$

Where T is temperature (°C). e was calculated from wet and dry bulb temperatures (T_{wet} and T_{dry}) using the psychomotor equation:

Equation 3.3 $\quad\quad\quad\quad$ $e = e^{o}_{\text{wet}} - [\gamma(T_{\text{dry}} - T_{\text{wet}})]$

Where $e^{\text{o}}_{\text{wet}}$ is the saturation vapour pressure calculated from wet bulb temperature, ($T_{\text{dry}}-T_{\text{wet}}$) is termed wet bulb depression, and γ is the psychometric parameter (kPa/°C) calculated as:

Equation 3.4 $\quad\quad\quad\quad$ $\gamma = [(C_{\text{p}} * P)/(0.622 * \lambda)]$

Where C_{p} is the specific heat of moist air at constant pressure (1.013 kJ/kg), P is atmospheric pressure (assumed constant at 101.1 kpa, calculated for 17 m a.m.s.l) and λ is the latent heat of vaporisation (kJ/kg) given by:

Equation 3.5 $\quad\quad\quad\quad$ $\lambda = 2501 - 2.361 * T_{\text{dry}}$

VPD was calculated hourly and averaged over daylight hours (Section 3.4.1).

3.4.2.2 *Potential Evapotranspiration (EP)*

Mean daily EP was calculated for the duration of the experiment (1 July 1997–20 June 2002) from hourly weather data from Broadfields meteorological station using Penman evapotranspiration potential (EP) as formulated by French and Legg (1979):

3.4.2.3   Potential soil water deficit

Potential soil water deficit (PSWD) was calculated throughout each season using the formulation presented by French and Legg (1979):

Equation 3.6 $PSWD = PSWD_{i-1} + EP - rainfall$

Where $PSWD_{i-1}$ is the PSWD on the previous day, PSWD was set to zero at the start of each season (1 July) and was not allowed to exceed zero (i.e. field capacity).

3.4.3   Soil water

3.4.3.1   Soil water profile

The amount of water in the soil was termed the soil water profile (SWP in mm of water to 2.3 m depth) and was calculated using Equation 3.7.

Equation 3.7 $SWP = \sum_{bot}^{top} \theta * d$

Where θ is the volumetric water content of individual soil layers (Section 3.3.4), d is the depth (mm) of the layer, top is the 0–0.2 m layer and bot is the 2.2–2.3 m layer.

3.4.3.2   Soil water deficit (SWD)

The SWD represented the difference between DUL and the SWP interpolated from measurements at 7–14 d intervals for the duration of the experiment. Daily changes in SWD were calculated using Equation 3.8.

Equation 3.8 $SWD = SWD_i + WU_{daily} - P_{R+I}$

Where, SWD_i is the previous days SWD and daily water use (WU_{daily}) is described in Equation 3.10, and P_{R+I} is daily precipitation, where the subscripts $_{R+I}$ represents irrigation and rainfall. The maximum soil water deficit (MSWD) for each growth season was calculated from this data.

3.4.3.3   Drained upper limit

The DUL for Iversen 8 was not determined when the paddock was fallow (prior to establishment). Given that the experiment is still running there has been no other opportunity to apply saturating treatments. Also, it was not possible to use SWP after full recharge during the experiment because on the few times complete recharge occurred crops were actively growing and extracting water so a stable θ was not achieved. Thus, an alternative method was used.

The soil profile above 1.0 m depth was always fully rewetted at the end of each winter and DUL could be determined from late July–early August when plant water uptake was minimal. The θ in each soil layer was determined 5 d after the last rainfall event to allow for drainage. This was done on five occasions, at the start of each season and the average of these values was used as the DUL in the top 1.0 m. Below 1.0 m rewetting was less reliable but plant water uptake was also less and there were periods when θ remained stable. Thus, for each soil layer below 1.0 m, θ was observed over the duration of the experiment and DUL was taken as the stable θ following complete recharge.

3.4.3.4   Water use

The water use (WU) was calculated for each period between measurements using a soil water balance;

Equation 3.9 $WU = P_{R+I} - (SWP_e - SWP_s)$

Where, SWP_s and SWP_e represent the actual measurements of profile soil water (Section 3.4.3.1) at the start and end of the period, respectively. P_{R+I} is the sum of rainfall and irrigation over the measurement period. This equation assumes that drainage, up-flow, lateral soil water movement and runoff are zero.

Then daily WU within each measurement period was calculated using Equation 3.10.

Equation 3.10 $\qquad$ $\text{WU}_{\text{daily}} = (\text{WU/EP}) * \text{EP}_{\text{daily}}$

Where, WU and EP are the calculated water use (Equation 3.9) and Penman potential evapotranspiration for the corresponding period and EP_{daily} is EP on the day of calculation.

3.4.4 Fractional radiation interception

3.4.4.1 *Calculations from solarimeter data*

The output of individual solarimeters relative to the reference was stable throughout the experiment and only minor changes were required to the calibration coefficients (Section 3.3.5) for each regrowth period. Voltage outputs of individual solarimeters were summed for daylight periods (Section 3.4.1.1) and divided by the reference voltage sum to give daily R/R_o for each plot.

3.4.4.2 *Canopy Analyser*

The software in the LAI-2000 uses radiation interception for all five zenith angles (Section 3.3.5.2) to give an integrated value for daily R/R_o.

3.4.4.3 *Extrapolation of R/R_o from DM measurements*

Radiation interception was extrapolated from the relationship between accumulated DM and R/R_o (Figure 3.5a) for periods when radiation interception measurement were not taken. This relationship was described by a broken stick function, which was fitted to dryland treatments in $I8_{00/01}$ and irrigated treatments from the first sowing date in $I9_{01/02}$. This showed R/R_o increased from zero to 0.55 with 600 kg DM/ha cover and then became constant at 0.96 beyond 2500 kg/ha (Figure 3.5a). Irrigated treatments in $I8_{00/01}$ were excluded from the fitted relationship because of weed invasion (Section 4.3.1.2). Dryland treatments in $I9_{01/02}$ deviated from this relationship due to a reduction in stem number in severely droughted treatments. This effect is displayed in Figure 3.5b where the mean R/R_o measured for each regrowth cycle was in agreement with the relationship fitted in Figure 3.5a for the first four regrowth cycles of the season. However, R/R_o was

10% and 200% greater than the expected values in the fifth and sixth regrowth cycles respectively. The R/R_o values were corrected for these two rotations by a factor of 0.9 and 0.4 for regrowth cycles 5 and 6 (respectively) to account for this error.
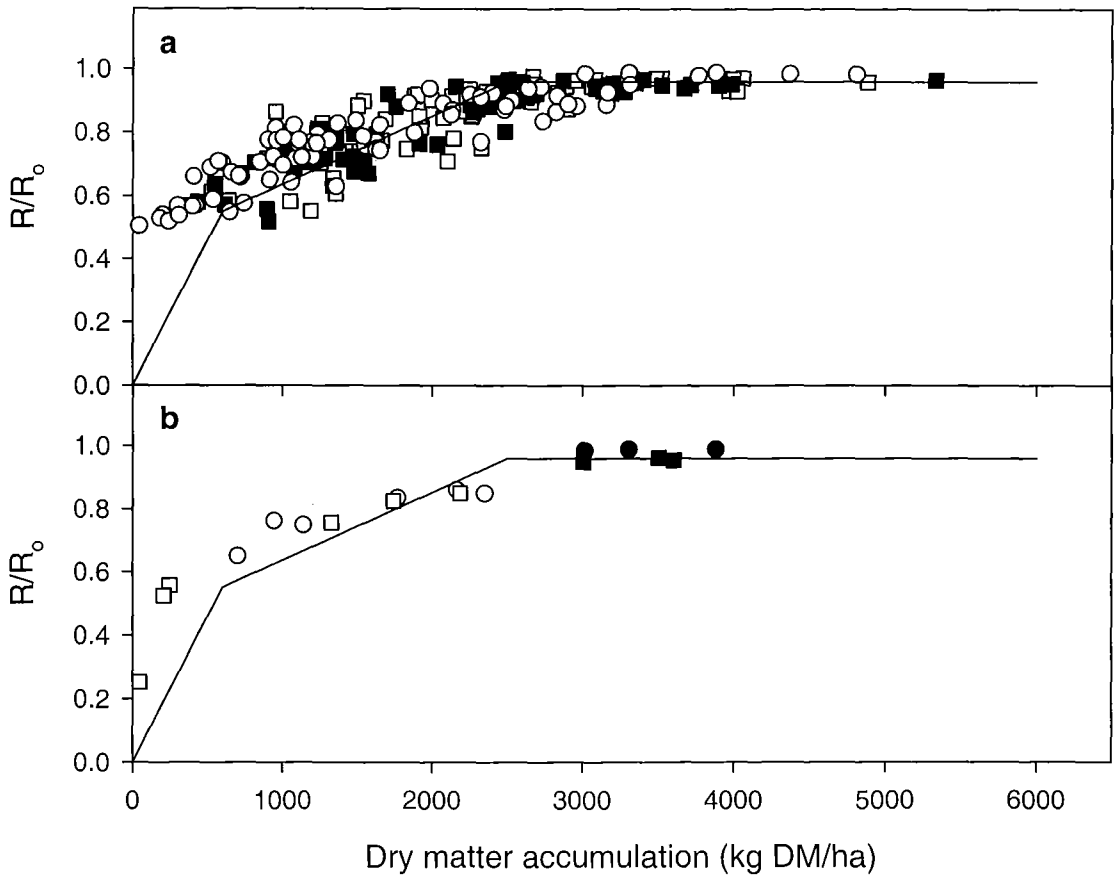
Figure 3.5 Fractional radiation interception (R/R_o) in relation to dry matter accumulation a) means from individual measurement dates in $I8_{00/01}$ (dryland =) and $I9_{01/02}$ (irrigated = ■ and dryland = O). b) Values from individual replicates at defoliation of each regrowth cycle (1=O, 2=□, 3=●, 4=■, 5= , 6=) in the dryland treatments of $I9_{01/02}$.

Note: fitted regression (————) is of the form y = 0.96–((0.96-0.0002*(DM+2500-600))*(DM<2500))–((0.96-.009*(DM+600))*(DM<600)). $R_2 = 0.75$.

3.4.5 Leaf area index

3.4.5.1 Green area index

The software in the LAI-2000 calculates green area index (GAI) by inversion of radiation transfer models assuming leaf foliage is randomly distributed (Welles and Norman, 1991).

3.4.5.2 Leaf area index

Leaf area index (LAI) was calculated from GAI (Section 3.4.5.1) by a calibration exercise which is described in Appendix 3. Briefly, the LAI-2000 gave a good estimation of GAI > 2.0 (n = 10, a=0, b=1, R^2 = 0.95) but GAI values were transformed [(GAI+1.3)/1.65] to account for an underestimation at GAI < 2.0. The adjusted GAI was then multiplied by 0.86 to convert to LAI based on a regression of LAI against GAI (n = 13, a = 0, b = 0.86, R^2 = 0.99).

3.5 Statistics

3.5.1 Treatment mean separation

All statistical analyses were carried out using Systat (v9.01).

3.5.1.1 Analysis of variance

Analysis of variance (ANOVA) was used to partition observed variation between treatment effects and errors. Different ANOVA's were used depending on experimental design and the number of factors being considered. Both Experiments 1 and 2 were split plot experiments (main and sub-plots represent different factors) and repeated measurements within a treatment (seasons or regrowth cycles for instance) were considered repeated measures and also treated as sub-plots or sub-sub-plots. Some analyses only required comparison of the levels of a single factor within another treatment. For example much of the data analysed from Experiment 2 uses only the first sowing date treatment and compares irrigation treatments within this level. A single factor ANOVA was used in this instance. ANOVA gives error means square

values for main-plots (E$_A$), sub-plots (E$_{AB}$) and sub-sub-plots (E$_{ABC}$) and a test (for each individual factor and factor combination) of the hypothesis "variation within that combination is random".

3.5.1.2   *Fishers least significant difference*

Fisher's least significant difference (LSD) was used to ascertain the extent of difference between different levels of a factor when ANOVA gave a $P<0.05$. Degrees of freedom were taken from midway between the sub-plot and sub-sub-plots for a split-split-plot analysis, and midway between main-plot and sub-plot error degrees of freedom for a split-plot analysis (Little and Jackson, 1978).

3.5.2   Regression

The focus of this thesis was to determine relationships involved in the formation of crop yield. This involved the relating of a yield forming variable to a continuous crop or environmental variable which is done by regression. The variable to be explained was called the dependent or y variable (because it is always plotted against the y-axis) and the variable it is related to is termed the independent or x variable (x-axis). All regressions were carried out using a model/loss fitting procedure, which runs iterations with different coefficients (from a specified start point) to reach coefficient values that give the best fit (least loss) of the relationship.

3.5.2.1   *Broken stick regression*

Broken stick regressions were fitted using the Gauss Newton method (Draper and Smith, 1998). This involved the specification of a regression model that included the inflection point as a parameter. This enabled the best fit for the inflection point to be determined in an iterative process along with the other model parameters.

4 Yield, persistence and quality of chicory, lucerne and red clover

4.1 Introduction

On dryland east coast farms typical ryegrass/white clover pastures provide high yields of quality feed when water is adequate in spring, but DM production declines during the summer (Hoglund and White, 1985). One possibility to increase dryland production is through increased soil water extraction from deep-rooted forage species such as chicory (*Cichorium intybus* L.), lucerne (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.). These species have all been reported to produce higher quality herbage and greater DM yield than ryegrass/white clover pastures in dryland conditions (Section 2.1.1.2).

The suitability of these three forages for increasing dryland production is dependent on them supporting greater stock live weight gain/maintenance year round. One contributing factor is yield and the potential advantage of these forage species will be greatest on soils that enable them to extract water from deep in the soil profile. Increased stock production also requires equal or greater quality than a lower producing alternative. To be acceptable to farmers, forages must also be persistent, able to respond to any seasonal precipitation and have minimal impact on cool season production (Section 1.3.2). Despite frequent use of all three species in dryland conditions, direct comparisons of their yield distribution, quality and persistence are unknown.

Thus, the objective of this chapter was to select chicory, lucerne or red clover as a suitable tap rooted species for use in dryland grazing systems. This will be achieved by comparing the annual and seasonal DM yield, herbage quality and forage utilisation under dryland and irrigated conditions. Irrigated crops allow the yield potential of this environment to be assessed. Dryland crops indicate the potential yield of these crops during periods of water deficit. In addition, species persistence in both irrigation regimes can be examined through changes in botanical composition over time.

4.2 Materials and Methods

This chapter reports the agronomic findings of Experiment 1 (I8), for all six growth seasons (Section 3.2.1).

4.2.1.1 *Dry matter measurements*

Dry matter (DM) yields were measured at the end of every regrowth cycle (within the 24 hour period prior to grazing). Measurements were also taken at 7–10 d intervals for 22 of the 33 regrowth cycles. Residual cuts were taken within 24 h of the removal of sheep. DM yield accumulation was assumed to stop at the start of grazing. The methodology of DM measurements was described in Section 3.3.1.

4.2.1.2 *Botanical composition*

Botanical composition was determined after weed invasion became significant in the third perennial growth season (1999/00) at the final harvest and on 1–2 occasions during regrowth cycles. Sub-samples of at least 50 g fresh weight were taken from DM cuts. These were separated into sown species and other (weeds) before being dried to constant weight.

4.2.1.3 *Nutritive analysis*

The nutritive value of dry matter was assessed at the time of defoliation for 12 regrowth cycles at various times throughout the five growth seasons. Dried samples from DM measurements were ground to pass through a 1 mm mesh in a Cyclotec 1093 sample mill. Nitrogen content was determined using the Kjeldahl method and multiplied by a factor of 6.25 to give values for crude protein. Metabolisable energy (ME) concentrations of samples were calculated from in-vitro organic matter digestibility.

4.2.1.4   Plant population

Plant population measurements for red clover and chicory were determined by counting total plant number in a 1 m^2 quadrant. Lucerne population was determined by stem population (Section 3.3.1).

4.2.1.5   Linear growth rates

Linear growth rates (LGR) were calculated by dividing DM accumulation (kg/ha) during the linear growth phase by the time of the phase (d). In most cases, the lack of true ceiling yield prevented the fitting of logistic growth curves. Thus, the start point for the linear growth period was taken as the first data point beyond 5% of the maximum DM and the end was the last data point or the data point beyond 95% of the maximum when a ceiling yield was displayed.

4.2.1.6   Stem fraction

Red clover stems were succulent at the time of harvest so were considered to be of equal nutritive value to the leaf. The stem fraction of chicory was determined by removing stem from DM samples (Section 3.3.1) and weighing stems separately.

For lucerne, DM samples were separated into short (<0.1 m), medium (<0.3 m) and long (>0.3 m) stems and representative numbers were taken from each height class to make up a sub-sample of 10–12 stems. Each sub-sample was then separated using the 'breaking-point method', where the top of each stem was bent round and pulled back down the length of the stem until it broke. Stem from above the breaking point and all lamina were considered palatable to stock and defined as the leaf fraction. It was assumed that the stem broke at the point to which lignification had occurred. Thus, any stem below this point was considered less palatable to stock and defined as the stem fraction.

4.2.1.7   Herbage utilisation

Herbage utilisation was calculated as the percentage difference between final DM cuts and post grazing cuts (of 0.2 m^2) taken the day sheep were removed.

4.2.1.8   Protein and energy consumption

The consumption of protein (t/ha) and energy (GJ ME/ha) by grazing stock was calculated to give an indication of the annual animal growth/maintenance potential of each treatment.

Equation 4.1

a) Protein consumption = $(DM_S * C_{PS} + DM_W * C_{PW}) - (DM_{tot} * (1 - HU) * C_{PR})$

b) Energy consumption = $(DM_S * C_{ES} + DM_W * C_{EW}) - (DM_{tot} * (1 - HU) * C_{ER})$

Where, DM_S is the annual dry matter yield of the sown species, DM_W is the annual dry matter yield of weeds, DM_{tot} is total annual dry matter yield and HU is annual herbage utilisation. For Equation 4.1 a) C_{PS} is the concentration of protein (g/g) of the sown species, C_{PW} is the concentration of protein in weeds and C_{PR} is the protein concentration in the post grazing residual. For Equation 4.1 b) C_P values are replaced with C_E values, which represent energy concentration (MJ ME/kg DM).

The first set of parentheses in each equation represents the total annual energy or protein yield and the second set of parentheses represents the annual residual protein and energy. The difference then represents the protein and energy consumed by grazing stock.

The DM_S, DM_W and HU values for each season were calculated using the mean botanical composition (Appendix 4) and utilisation (Appendix 5) values for that season. There was less data available for C_P (Appendix 6) and C_E (Appendix 7) values. However, there was no apparent systematic change in values over time so the mean of

all measurement dates was used for each species. The C_{PW} and C_{EW} were only analysed for chicory and assumed to be the same for the weed fractions of lucerne and red clover.

4.2.1.9   Statistics

Annual DM yields were analysed as a split-split-plot design with irrigation (dryland and full irrigation) as the main-plot, species (chicory, lucerne and red clover) as the sub-plot and perennial growth season (1997/98–2001/02) as the sub-sub-plot (repeated measure). Standard errors of the mean were calculated to compare species and irrigation effects both within and between seasons. The establishment season (1996/97) was not included in this analysis because irrigation treatments had not been imposed. Annual DM yield was also analysed within each growth season as a split-plot design to allow more sensitive comparison of species and irrigation means. In addition, DM yield was analysed for individual regrowth cycles within each season as a split-split-plot with irrigation as the main-plot, species as the sub-plots and regrowth cycle as the sub-sub-plot.

As herbage utilisation showed no irrigation effect, irrigation treatments were pooled and herbage utilisation was re-analysed as a split-plot with species as a main-plot and growth season as a sub-plot. Herbage utilisation was also analysed as a single factor ANOVA within each season.

The LGR was affected by temperature and rainfall so it was non-sensical to compare LGR within growth seasons where temperature and rainfall varied substantially (Section 3.1.3). Thus, the pattern of LGR was analysed over the growth season by assigning the LGR from each regrowth cycle to the month in which the mid point of that cycle occurred and displaying means and standard errors for each month. Data from the establishment season (1996/97) and regrowth cycles where sown species contributed less than 60% of total yield were excluded from this analysis. Mean LGR for spring (September–November) summer (December–February) and autumn (March–May) were calculated from the 1997/98 and 1998/99 seasons when all three species were pure and compared within each season as a single factor ANOVA. It was not practical to

calculate long-term monthly means for dryland crops due to the large seasonal variability in rainfall.

Energy and protein values were taken from pooled samples (all replicates combined), which were representative but did not allow statistical analysis. There were insufficient energy and protein concentration data to allow growth season variation to be analysed and there was no apparent irrigation effect. Thus, all energy and protein data were averaged over the six years of the experiment and standard errors presented for each species.

4.3 Results

4.3.1 Annual dry matter yield

4.3.1.1 Sown species yield

Red clover crops had the greatest ($P<0.001$) yield in the establishment growth season (1996/97) producing 12 t DM/ha compared with about 8.5 t DM/ha for chicory and lucerne (Figure 4.1). For the following five growth seasons there was an interaction ($P<0.001$) between irrigation, species and season because each treatment showed a differing decline in DM yield over the duration of Experiment 1.

Lucerne showed the greatest ($P<0.001$) yield under both irrigated (28 t DM/ha) and dryland (21 t DM/ha) conditions in the 1997/98 season. Lucerne yield was also greater than the other two species in the following four growth seasons. Irrigated lucerne yield ranged from 22 t DM/ha in 1997/98 to 10.3 t DM/ha in 2001/02. Dryland lucerne yield decreased from 21 to 16.7 t DM/ha over the same cycle. Chicory and red clover yield were similar in the 1997/98 and 1998/99 growth seasons (13–18 t DM/ha) but chicory yield decreased to 7.5 t DM/ha and red clover to 0 ($P<0.001$) in 2001/02 (Figure 4.1).

Irrigated lucerne, red clover and chicory crops yielded 7, 4 and 3 t DM/ha more ($P<0.001$) respectively than dryland crops in the 1997/98 season (Figure 4.1). Irrigation also increased sown species yield of chicory (3 t DM/ha) in the 1998/99 season but reduced ($P<0.001$) yields in lucerne (3.2 t DM/ha) and red clover (3.7 t DM/ha) crops in 1999/00 and irrigated crops produced less ($P<0.001$) lucerne (6.3 t DM/ha) in the 2001/02 season.
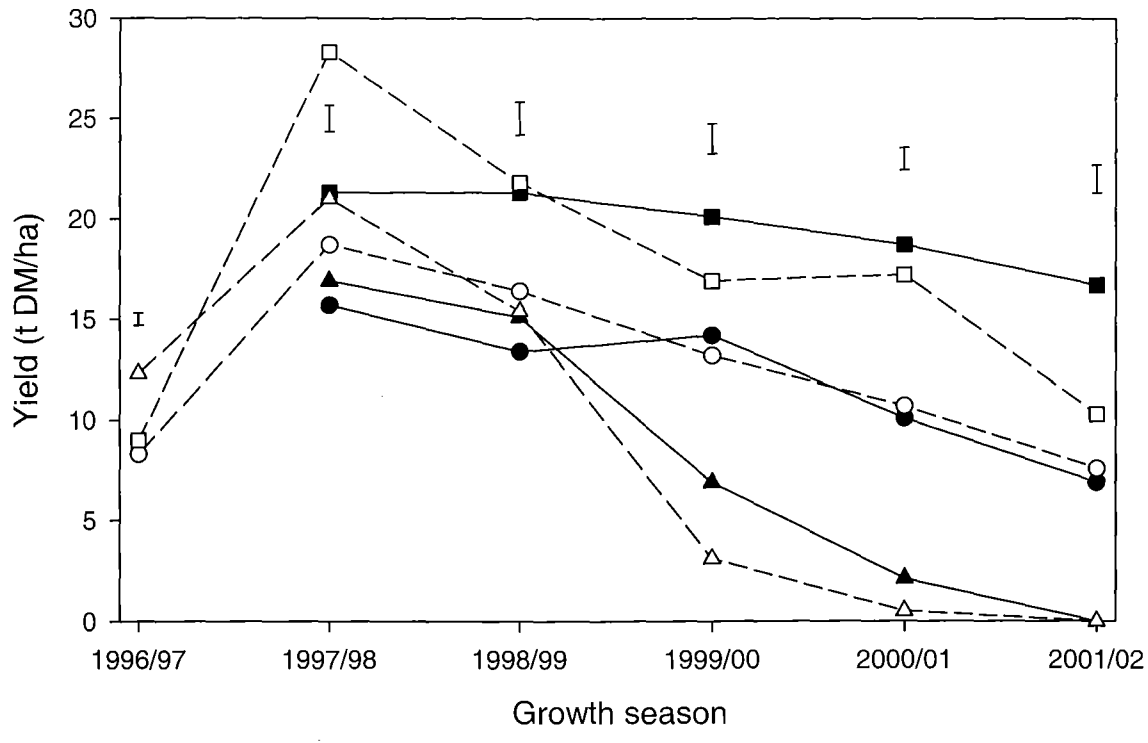
Figure 4.1 Total annual dry matter yield of dryland (closed) and irrigated (open) chicory (●○), lucerne (■□) and red clover (▲△) crops sown in November 1996 at Lincoln University, Canterbury, New Zealand.

Note: Bars represent one standard error of the mean for comparison of species means within and between irrigations treatments.

4.3.1.2   Botanical composition

All crops remained pure during 1996/97, 1997/98 and for the majority of the 1998/99 season. However, weed invasion was observed in red clover and chicory crops by the autumn of 1999. The sown species component of botanical composition then declined in each of the following seasons and was faster (P<0.001) in irrigated crops. Irrigated red clover showed the most rapid decrease (P<0.001) to 27% in 1999/00, 3% in 2000/01 and 0% in 2001/02 (Table 4.1). Similarly, dryland red clover declined to 54% in 1999/00, 17% in 2000/01 and was negligible in 2001/02. Chicory crops showed a slower decline with irrigated crops declining to 54% and dryland crops to 61% by 2001/02. Dryland lucerne crops showed the smallest decline, remaining 94% pure in the 2001/02 season. However, irrigated lucerne crops had declined to 65% of the botanical composition by the 2001/02 season (Table 4.1).

Table 4.1 Botanical composition (% sown species) of chicory, lucerne and red clover crops established on a Wakanui silt loam soil in November 1996 and grown under dryland (Dry) and irrigated (Irr) conditions for six seasons in Canterbury, New Zealand.

Species	Irrigation	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02
Chicory	Dry	100	100	100	88	83	61
	Irr	100	100	100	84	74	55
Lucerne	Dry	100	100	100	99	97	94
	Irr	100	100	100	93	85	65
Red clover	Dry	100	100	100	54	17	0
	Irr	100	100	100	27	3	0
SEM$_{AB}$		-	-	-	2.8	3.8	6.7
P$_{ABC}$	< 0.001						
SEM$_{ABC}$	4.24						

Note: Subscript A represents irrigation, B represents species and C represents growth season. Details of botanical composition for individual regrowth cycles is displayed in Appendix 4.

4.3.1.3 Plant population

Plant population declined from 115 plants/m² in chicory crops at the end of the establishment season (1996/97) to 20 and 30 plants/m² for irrigated and dryland crops respectively at the start of 2000/01 season. Similarly, red clover crops declined from 200–250 plants/m² in the 1996/97 season to 5 and 11 plants/m² in irrigated and dryland crops by 2000/01. Stem number for lucerne crops declined from 600 stems/m²and in 1998/99 season to 450 and 300 stems/m² for dryland and irrigated crops in 2001/02.

4.3.1.4 Total dry matter yield (sown species + weeds)

Total DM yield (Table 4.2) only differed from sown species yield (Figure 4.1) when weed invasion occurred from 1999/00 onwards. Lucerne crops had a higher (P<0.05) total DM yield (16.2–20.3 t DM/ha) than chicory (10.9–16.4 t DM/ha) and red clover (11.4–14.6 t DM/ha) from 1999/00–2001/02. Total yield in these seasons was lower (P<0.05) than sown species yield in 1997/98 and 1998/99.

Table 4.2 Annual dry matter yield (kg DM/ha) of chicory, lucerne and red clover crops grown under irrigated and dryland conditions from 1 July 1999–24 June 2002 in Canterbury, New Zealand. Values in parenthesis represent DM yield of sown species.

Species	Irrigation	1999/00		2000/01		2001/02	
Chicory	Dry	16.4	*(14.2)*	12.8	*(10.1)*	10.9	*(6.9)*
	Irr	15.7	*(13.2)*	14.6	*(10.7)*	13.6	*(7.6)*
Lucerne	Dry	20.3	*(20.1)*	19.3	*(18.7)*	17.5	*(16.7)*
	Irr	18.2	*(16.9)*	20.2	*(17.2)*	16.2	*(10.3)*
Red clover	Dry	11.7	*(6.9)*	11.0	*(2.1)*	11.5	*(0.0)*
	Irr	11.4	*(3.1)*	14.6	*(0.5)*	12.3	*(0.0)*
SEM$_{AB}$		1.04	*(1.00)*	1.05	*(0.85)*	1.11	*(1.06)*
P$_{ABC}$		< 0.05	*(< 0.001)*				
SEM$_{ABC}$		1.57	*(1.58)*				

Note: Subscript A represents irrigation, B represents species and C represents growth season. Details of total production for individual regrowth cycles is displayed in Appendix 8

4.3.2   Seasonal dry matter yield

4.3.2.1   *Dry matter accumulation of sown species*

The pattern of DM accumulation of sown species, throughout each regrowth cycle is displayed in Figure 4.2a from 1997/98–1998/99 and Figure 4.2b from 1999/00–2001/02. Values of DM yield and statistics for all regrowth cycles are presented in Appendix 9. The greater (P<0.05) yield of red clover in the establishment season (1996/97) came from 7.4 t DM/ha in the first seedling crop and 4.9 t DM/ha in the subsequent regrowth crop compared with 5.4 and 3.6 t DM/ha for lucerne and 4.2 and 4 t DM/ha for chicory.

In 1997/98 irrigated lucerne had higher (P<0.001) yields than chicory and red clover in spring and autumn (Figure 4.2a). In the spring, lucerne yielded 6 and 6.2 t DM/ha in the first and second regrowth cycles compared with 2.4 and 4.7 t DM/ha for irrigated chicory and 5.1 and 4.3 t DM/ha for irrigated red clover. In the autumn irrigated lucerne yielded 4 t DM/ha in the fifth regrowth cycle. In contrast, irrigated chicory yielded 1.6 t DM/ha and irrigated red clover yielded 1.2 t DM/ha. Yields were lowest (P<0.05) in the sixth regrowth cycle but lucerne still yielded 1.9 t DM/ha, which was greater (P<0.05) than chicory and red clover (1.6 t DM/ha). Yields of dryland treatments were the same as irrigated treatments in regrowth cycles 1 and 2 but declined below (P<0.001) irrigated yields in the four remaining regrowth cycles. Dryland lucerne yielded 10.3 t DM/ha during these four regrowth cycles, which was 3 t DM/ha greater (P<0.05) than DM production from chicory and red clover crops.

In 1998/99 irrigated lucerne also had greater (P<0.001) yields than chicory and red clover in spring and autumn (Figure 4.2a). Specifically, in the first regrowth cycle lucerne yielded 5.3 t DM/ha compared with about 2.5 t DM/ha for chicory and red clover. There were no differences in DM yield during the second, third and fourth regrowth cycles but irrigated lucerne yield in regrowth cycles 5, 6 and 7 totalled 8.1 t DM/ha, which was greater (P<0.001) than for chicory (5.4 t DM/ha) and red clover (3.9 t DM/ha). Dryland crops yielded less (P<0.05) than irrigated in regrowth cycles 4, 5 and 6 and lucerne yielded 7.3 t DM/ha during this cycle compared with 5.7 and 5 t DM/ha for red clover and chicory respectively.
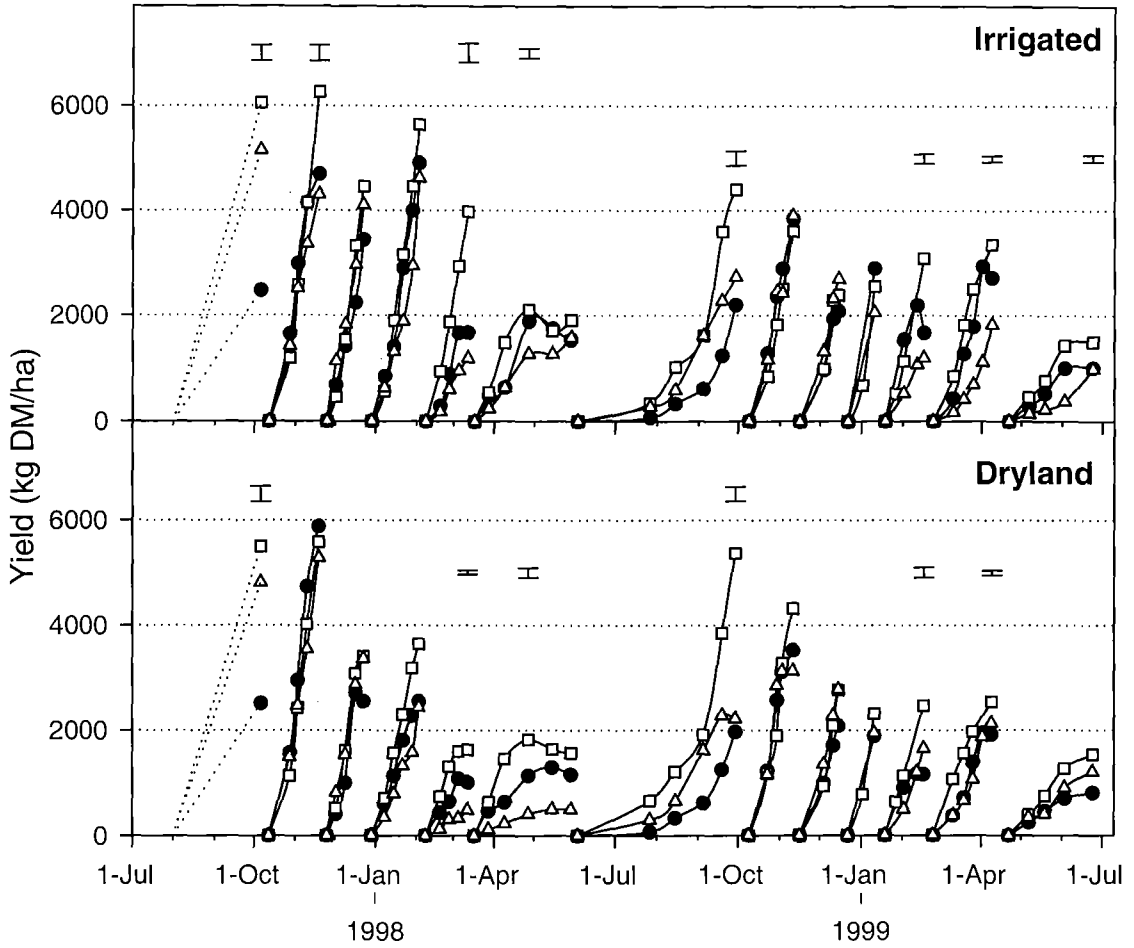
Figure 4.2a) Yield accumulation from 1 July 1997–24 June 1999 for chicory (●), lucerne (□) and red clover (△) crops sown in November 1996 on a Wakanui silt loam at Lincoln University, Canterbury, New Zealand.

Note: Bars represent one standard errors of the mean above the final point in each regrowth cycle where species yields were different (P<0.05). Dryland yields were different to irrigated in regrowth cycles 3, 4, 5 and 6 in 1997/98 and cycles 4, 5 and 6 in 1998/99 (Appendix 9).
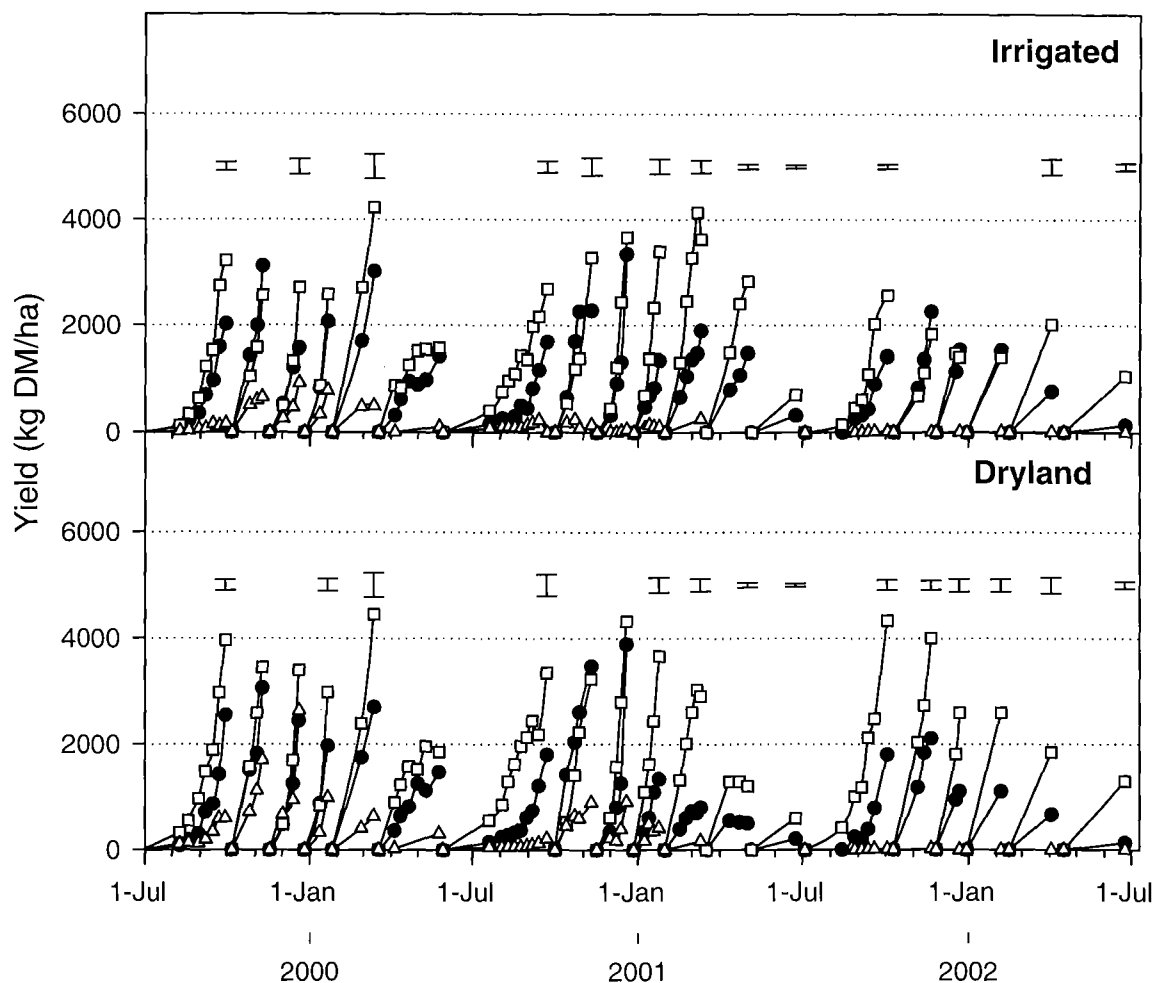
Figure 4.2b) Yield accumulation from 1 July 1999–30 June 2002 for chicory (●), lucerne (□) and red clover (△) crops sown in November 1996 on a Wakanui silt loam at Lincoln University, Canterbury, New Zealand.

Note: Bars represent one standard error of the mean above regrowth cycles where chicory yields were different (P<0.05) to lucerne (red clover was always less). Dryland yields were greater than irrigated in regrowth cycles 1–4 in 1999/00, cycles 1–3 in 2000/01, cycles 1–4 in 2001/02 and less than irrigated in regrowth cycle 5 in 2000/01 (Appendix 9).

In 1999/00 irrigated lucerne yielded 2.5–4 t DM/ha in all but the final regrowth cycle. In contrast chicory yielded 1.5–3 t DM/ha and red clover was lowest (P<0.05) at less than 1 t DM/ha per regrowth cycle (Figure 4.2b). Dryland yield differed (P<0.05) to irrigated in regrowth cycles 1–4, but in this season irrigated crops had lower yields than dryland. Specifically, dryland lucerne yield was about 1 t DM/ha greater (P<0.05) than

irrigated in each of these regrowth cycles. Dryland chicory yield showed a similar advantage in regrowth cycles 2 and 4 and dryland red clover showed an advantage in the second and third regrowth cycles.

In 2001/02 irrigated lucerne yield again ranged from 2.5–4.0 t DM/ha in all but the final regrowth cycle and was 1.0–2.0 t DM/ha greater (P<0.01) than irrigated chicory in all but the third regrowth cycle (Figure 4.2b). Dryland lucerne and chicory yield were greater (P<0.05) than irrigated in the regrowth cycles 1, 2 and 3 but irrigated crops yielded more (P<0.001) than dryland in the fifth regrowth cycle. Dryland red clover yielded 1.0 t DM/ha in regrowth cycles 2 and 3, but did not produce more than 500 kg DM/ha in any other regrowth cycles or at any time under irrigated conditions.

Irrigated lucerne yielded 2.5 t DM/ha in the first regrowth cycle of 2001/02 and yield ranged from 1.5–2.0 t DM/ha for the remainder of the season (Figure 4.2b). This was about 1.0 t DM/ha greater than chicory in regrowth cycle 1 (spring), 5 and 6 (autumn) and irrigated red clover yield was zero during this season. Dryland lucerne crops yielded 1.0–2.0 t DM/ha more than irrigated lucerne in regrowth cycles 1–4 but there was no difference between dryland and irrigated chicory yield during this time. Dryland red clover yield was also zero during this season.

4.3.2.2   Linear growth rate of irrigated crops

The long-term monthly mean LGR for irrigated crops is shown in Figure 4.3. This indicates that growth was nil from June–August (winter) because the mid point of regrowth cycles never occurred during this time. Field observations showed slow but not measurable growth, particularly for lucerne. The LGR of lucerne in spring, reached 30 kg DM/ha/d in September when irrigated chicory and red clover were growing at 17 kg DM/ha/d (P<0.001). However, the advantage of lucerne LGR diminished by the end of spring when all crops growing at about 70 kg DM/ha/d in November. The mean spring LGR from the 1997/98 and 1998/99 seasons (Table 4.3) was greater (P<0.01) for lucerne (75 kg DM/ha/d) than chicory and red clover (50 kg DM/ha/d).
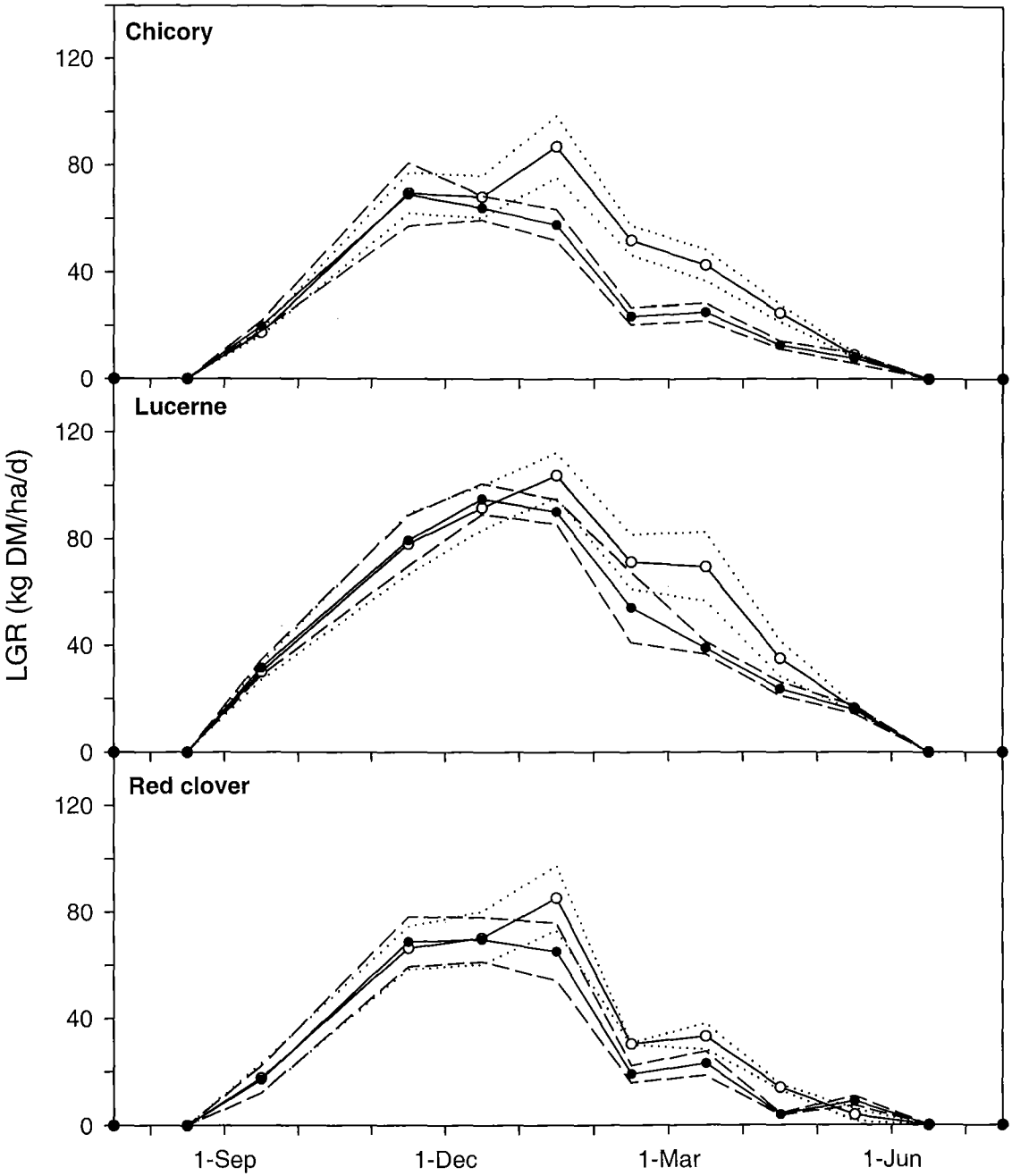
Figure 4.3 Long-term mean monthly linear growth rates of three forage species grown under dryland (—●—) and irrigated (—○—) conditions on a Wakanui silt loam soil from 1997–2002 in Canterbury, New Zealand. One standard error either side of the mean is represented by the dashed lines for dryland treatments and the shaded area for irrigated.

Note: Individual values for each regrowth cycle are displayed in Appendix 10. Regrowth cycles where sown species contributed less than 60% of total DM yield are excluded from means.

The mean monthly LGR of all three species reached a peak of about 90 kg DM/ha/d in January (Figure 4.3) and averaged 80 kg DM/ha/d for the summer months of the 1997/98 and 1998/99 seasons. However, all irrigated crops showed a substantial decrease in LGR in February with red clover, chicory and lucerne declining to 30, 50 and 70 kg DM/ha/d respectively. The LGR continued to decrease during the autumn season (Figure 4.3) when lucerne had a higher mean LGR (43 kg DM/ha/d) than chicory (29 kg DM/ha/d) or red clover (19 kg DM/ha/d).

Table 4.3 Mean linear growth rate (kg DM/ha/d) of three irrigated forage species during the spring (September–November), summer (December–February) and autumn (March–May) at Lincoln University, Canterbury, New Zealand.

	Spring	Summer	Autumn
Chicory	47	81	29
Lucerne	75	94	43
Red clover	52	71	19
P	< 0.01	ns	< 0.01
SEM	5.6	10.8	4.7

4.3.2.3   Linear growth rates of dryland crops

The long-term mean LGR of dryland crops became less (P<0.05) than irrigated crops in January and remained 10–30 kg DM/ha/d lower (P<0.05) until May. In the 1997/98 season crops were pure and a substantial dry period occurred (Figure 3.1) giving reduced dryland yields relative to irrigated regrowth crops in regrowth cycles 3–6 (Section 4.3.2.1).   There were no differences between species in cycle 3 (110 kg DM/ha/d) but the LGR of lucerne (90–20 kg DM/ha/d) was 30, 20 and 10 kg DM/ha/d greater (P<0.05) than red clover and chicory in regrowth cycles 4, 5 and 6 respectively (Figure 4.4).
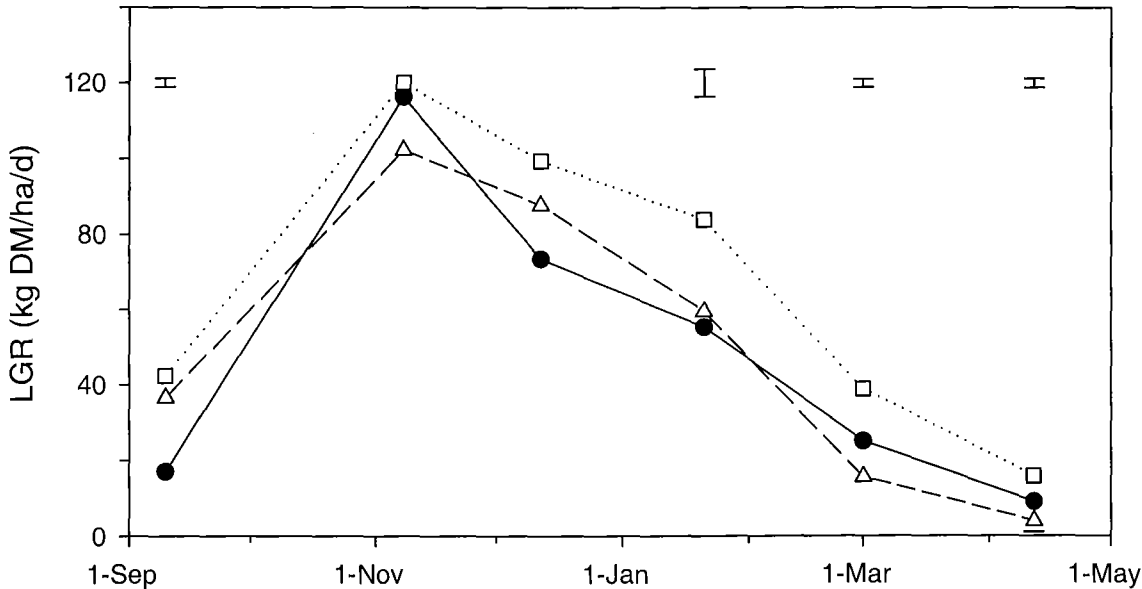
Figure 4.4 Linear growth rate (LGR) of dryland chicory (—●—), lucerne (··· ···) and red clover (-△-) from September 1997–May 1998 at Lincoln University, Canterbury, New Zealand. Bars represent one standard error and are displayed when species LGR were different (P<0.05).

4.3.3   Stem percentage

There was no systematic difference in the stem percentage between dryland and irrigated treatments so results were pooled for further analysis. The data for individual regrowth cycles within each growth season are given in Appendix 11. Averaged over all seasons and regrowth cycles, the 25% stem component of lucerne was higher (P<0.001) than chicory (12%) and red clover (no stem measured). An example of the change in stem% through each of 6 regrowth cycles is shown for 2000/01 (Figure 4.5). In all rotations lucerne stem% was higher (P<0.001) that for chicory and for both species it increased to a maximum prior to grazing.
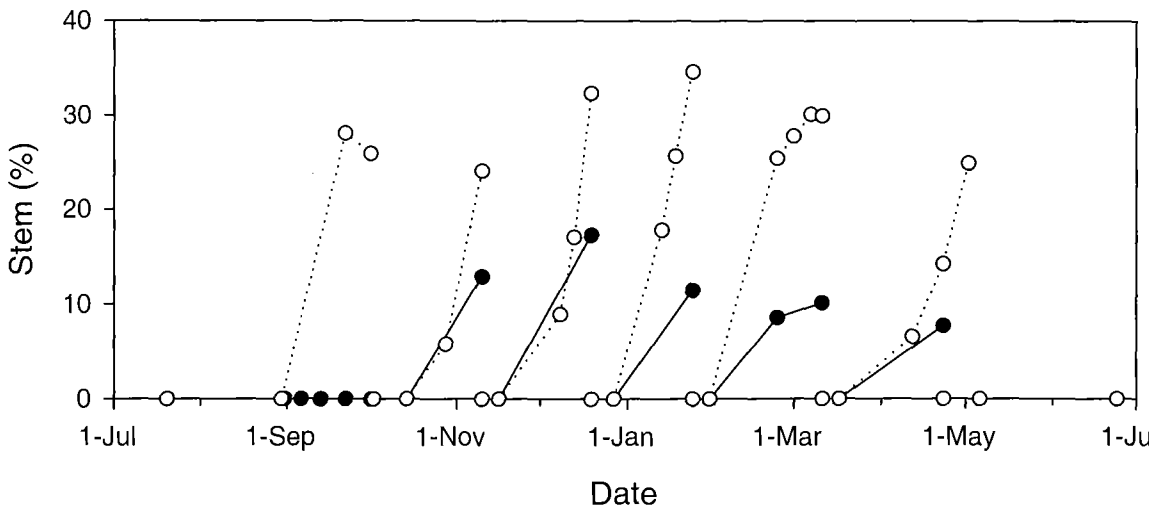
Figure 4.5 Stem percentage (%) of chicory (—●—) and lucerne (···O···) crops over the 2000/01 growing season at Lincoln University, Canterbury, New Zealand.

4.3.4   Herbage utilisation

Herbage utilisation from red clover (86–96%) was greater (P<0.001) than chicory (73–75%) from 1997/98–1999/00. There was no difference between chicory and lucerne (78–82%) in these seasons (Table 4.4). However, herbage utilisation from red clover declined (P<0.001) to the same level as chicory and lucerne in 2000/01 (65%). In 2002/02 utilisation of herbage from red clover (56%) was lower (P<0.001) than chicory (77%) and lucerne (72%) in 2001/02.

Table 4.4 Herbage utilisation (%) of chicory, lucerne and red clover crops averaged over all regrowth cycles and irrigation treatments for six growing seasons at Lincoln University Canterbury, New Zealand.

Species	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02
Chicory	-	73	75	73	63	77
Lucerne	-	82	82	78	68	72
Red clover	-	96	90	86	65	56
SEM_A		1.1	1.0	1.5	1.7	2.7
P_{AB}	< 0.001					
SEM_{AB}	5.7					

Note: Data for individual treatments for each season and regrowth are displayed in Appendix 5. Irrigation treatments were pooled for analysis so subscript A represents species and B represents season.

4.3.5 Nutritive value

4.3.5.1 Crude protein concentrations

The results (Appendix 6) showed no systematic change in crude protein (CP) concentrations with time or between irrigation treatments so results were pooled for comparison between species. Crude protein concentrations (Table 4.5) in the leaf fraction were highest for lucerne (29%) followed by red clover (25%) and chicory (17%). The leaf fraction had a substantially higher CP than stems of both chicory (7.7%) and lucerne (11.6%). The weed fraction of chicory (which was predominantly volunteer white clover) had a CP of 25% which was similar to the leaf fraction of red clover. The CP of residual herbage of chicory (10%) and lucerne (11.8%) were similar to the CP of the stem fractions of these two crops, but residual red clover herbage had higher CP (20%), which was close to the CP of the red clover leaf fraction.

4.3.5.2 Energy concentrations

The changes in energy concentration over time and differences between irrigation treatments were not systematic (Appendix 7) so results were pooled for further analysis between species. The energy concentration of the leaf fraction was similar for chicory (11.3 MJ ME/kg DM), lucerne (11.6 MJ ME/kg DM), red clover (10.9 MJ ME/kg DM)

and the weed fraction (Table 4.5). The stem fractions had a lower energy concentration than the leaf fraction for both chicory (9.4 MJ ME/kg DM) and lucerne (7.8 MJ ME/kg DM). The energy concentration of the stem fraction was also similar to that of the residual herbage for both chicory (8.6 MJ ME/kg DM) and lucerne (6.8 MJ ME/kg DM) but residual red clover herbage had an energy concentration (10 MJ ME/kg DM) similar to red clover leaf.

Table 4.5 Average crude protein (%) and energy (MJME/kg DM) concentration of leaf, stem, weed and residual fractions of chicory, lucerne and red clover crops grown at Lincoln University, Canterbury, New Zealand. Values in parenthesis represent standard errors for each value.

	Species	Leaf	Stem	Weed	Residual
Crude protein	Chicory	17.5 *(1.07)*	7.7 *(1.28)*	24.6 *(1.09)*	10.0 *(1.04)*
	Lucerne	29.1 *(0.77)*	11.6 *(0.84)*		11.8 *(1.28)*
	Red clover	24.6 *(1.10)*		24.6*	20.4 *(0.87)*
Energy	Chicory	11.3 *(0.20)*	9.4 *(1.39)*	11.4 *(0.33)*	8.6 *(0.67)*
	Lucerne	11.6 *(0.13)*	7.8 *(0.42)*		6.8 *(0.55)*
	Red clover	10.9 *(0.21)*		11.4*	10.0 *(0.09)*

Note: * = nutritive value of red clover weeds assumed to be the same as chicory weeds. Individual data points for treatments, seasons and regrowth cycles where nutritive analyses were determined are displayed in Appendix 6 and Appendix 7.

4.3.6   Annual protein and energy consumption

4.3.6.1   Annual crude protein (CP) consumption

Mean annual CP consumption, over the five perennial growing seasons of this experiment was greatest (P<0.01) for irrigated (4.6 t CP/ha) and dryland (4.4 t CP/ha) lucerne with at least 1.0 t CP/ha greater consumption than red clover and chicory (Table 4.6). Generally, there was a decrease in CP consumption over the duration of the experiment with irrigated lucerne showing the largest decrease (6.3 in 1997/98 to 3.4 t CP/ha in 2001/02). In comparison, dryland chicory showing the smallest decrease (2.16 to 1.93 t CP/ha).

Table 4.6 Annual crude protein (t/ha) consumption by grazing stock for chicory, lucerne and red clover crops over five growth seasons at Lincoln University, Canterbury, New Zealand.

Species	Irrigation	1997/98	1998/99	1999/00	2000/01	2001/02	Mean
Chicory	Dry	2.16	1.88	2.50	1.79	1.93	2.05
	Irr	2.66	2.52	2.34	2.26	2.36	2.43
Lucerne	Dry	4.84	4.75	4.47	3.92	3.79	4.35
	Irr	6.28	4.95	3.97	4.32	3.38	4.58
Red clover	Dry	4.04	3.37	2.59	1.83	1.67	2.70
	Irr	4.94	3.48	2.43	2.67	2.09	3.12
SEM_{AB}		0.195	0.222	0.219	0.225	0.178	0.127
P_{ABC}	0.01						
SEM_{ABC}	0.204						

Note: Subscript A represents irrigation, B represents species and C represents growth season.

4.3.6.2   Annual energy (ME) consumption

Annual energy consumption (Table 4.7) followed the same pattern as CP consumption where energy consumption of lucerne crops (142–261 GJ ME/ha) was greater (P<0.001) than chicory (99–169 GJ ME/ha) and red clover (74–218 GJ ME/ha) for all five seasons in both irrigated and dryland treatments.

Table 4.7 Annual energy (GJ ME/ha) consumption by grazing stock for chicory, lucerne and red clover crops over five growth seasons at Lincoln University, Canterbury, New Zealand.

Species	Irrigation	1997/98	1998/99	1999/00	2000/01	2001/02	Mean
Chicory	Dry	136	114	150	99	104	120
	Irr	169	157	135	123	121	141
Lucerne	Dry	203	198	185	158	157	180
	Irr	261	208	165	179	142	191
Red clover	Dry	179	150	116	82	74	120
	Irr	218	156	110	121	94	140
SEM_{AB}		10.4	12.1	11.0	10.3	8.1	6.6
P_{ABC}	0.001						
SEM_{ABC}	10.9						

Note: Subscript A represents irrigation, B represents species and C represents growth season.

4.4 Discussion

Results from this experiment show lucerne yield and persistence were superior to chicory and red clover under both irrigated and dryland conditions. Coupled with higher total harvested protein and energy, these results indicate lucerne was the most productive species and has the greatest potential to be included in a livestock grazing system in this dryland environment.

4.4.1 Irrigated yield (non-water limited)

Differences in annual and seasonal yield under irrigated conditions can be used to highlight the superior yield potential of lucerne in this environment. This is most appropriately displayed with data from the 1997/98 and 1998/99 seasons where regrowth was perennial and all crops were still pure swards of the sown species.

4.4.1.1 Annual yield

Annual yield of irrigated lucerne in 1997/98 and 1998/99 (average 25 t DM/ha) was 30% higher than chicory or red clover (mean 18 t DM/ha). Lucerne yield was higher than the national average of 14 t DM/ha (Douglas, 1986), but consistent with the yield of irrigated lucerne reported on the same soil by Hoglund *et al.* (1974) and other reports of irrigated lucerne yield exceeding 20 t DM/ha (Theobald and Ball, 1983; Thomson, 1977; Vartha and O'Connor, 1968). Chicory yields of about 17 t DM/ha were in the potential yield range extrapolated from short chicory experiments under high rainfall environments in the North island (Matthews *et al.*, 1990). Red clover yields (15–18 t DM/ha) were higher than annual yields (about 14 t DM/ha) reported for moist conditions in Otago and Southland (Allen *et al.*, 1976; Hay and Ryan, 1989). The likely reason for this difference is the warmer temperatures and extended growing season in Canterbury compared with Otago.

4.4.1.2 Seasonal yield

The greater annual yield of irrigated lucerne was due to greater yields than chicory and red clover in both spring (September–November) and autumn (February–May) regrowth

cycles (Section 4.3.2.1). Under irrigated conditions temperature and solar radiation interception are the main factors that control growth (Section 1.2.1). Temperature and solar radiation levels are high during late spring and summer (November–January) and all crops had the same yield during this period. This suggests that all three species had the same yield potential and implies they will exhibit the same radiation interception characteristics under favourable growth conditions (Monteith, 1977).

Temperatures were lowest in the winter (Figure 3.3), and growth was close to zero from June–August (Section 4.3.2.2). The relationship between the long-term mean LGR and temperature is displayed in Figure 4.6 where crop growth rates increased with temperature from September–January. The greater spring yield of lucerne came from faster growth rates than chicory and red clover at low temperatures (<9 °C) during September (Section 4.3.2) and the higher DM yield at the end of August (Figure 4.2) also indicates the potential yield of lucerne was least affected by low temperatures.
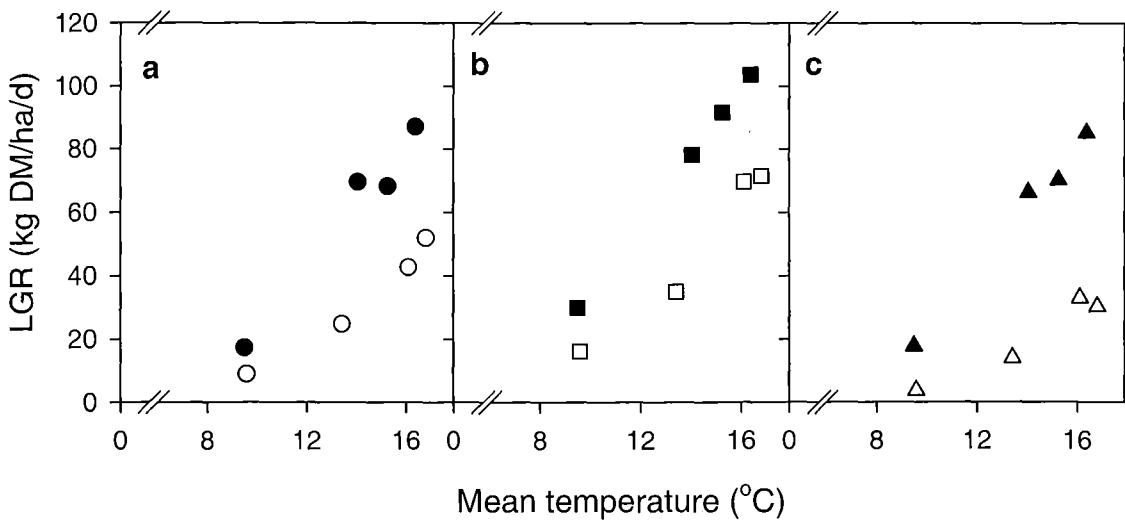
Figure 4.6 Long-term mean linear growth rates (LGR) plotted against mean daily air temperature from September–January (closed) and February–May (open) for, a) chicory (●○), b) lucerne (■□) and c) red clover (▲△) grown at Lincoln University, Canterbury, New Zealand.

Note: Long-term linear growth rates are the monthly values presented in Figure 4.3. Black symbols, from left to right, are September, November, December and January. White symbols from right to left are February–May.

For all species LGR decreased with decreasing autumn temperatures (Figure 4.6). However, lucerne had higher growth rates from February–May (70–20 kg DM/ha/d) compared with chicory (50–10 kg DM/ha/d) and red clover (30–10 kg DM/ha/d). Field observations suggest the greater spring and autumn growth rates of lucerne were due to a faster expansion of leaf area. This is sensitive to low temperatures and directly controls the interception of solar radiation, growth rates and yields (Section 1.2).

The LGR responded to changes in mean air temperature but LGR was higher in spring than at the corresponding temperature in autumn for all species (Figure 4.6). The change in temperature response occurred in February when mean temperatures were the same (Figure 3.3) but LGR decreased by 44, 36 and 66% for chicory, lucerne and red clover (respectively) over the same time. Radcliffe and Baars (1987) presented a similar difference in spring and autumn growth rate responses to temperature for ryegrass/white clover pastures and Peacock (1975) attributed this to different reproductive physiology in spring and autumn. Relating LGR to temperature was arbitrary to facilitate seasonal comparisons but mean daily air temperature was a result of photoperiod and solar radiation, which can also affect crop growth and interact with temperature.

For chicory, lucerne and red clover it is possible that the autumn decrease in LGR may be related to a change in the partitioning of dry matter. The lower LGR in the autumn probably resulted from a greater partitioning of DM to the roots to replenish reserves for over wintering and spring regrowth. The storage of assimilate is well documented for chicory (Li *et al.*, 1997a), lucerne (Hay, 1999) and red clover (Collins, 1996) and the greater reduction in LGR of red clover in the autumn indicated it may have been allocating a greater proportion of its assimilate to root storage. This is an issue with the physiology of perennial forages that will be dealt with later in this thesis (Chapter 6).

Chicory, lucerne and red clover are all advocated for use as specialist forage crops to increase yield during the summer period. All three species displayed similar irrigated yields from November–January (Section 4.3.2.1). The LGR ranged from 70–100 kg DM/ha/d over this period (Figure 4.3) and was substantially higher than the range of values reported for irrigated ryegrass/white clover pastures (33–

56 kg DM/ha/d) in Canterbury (Rickard and Radcliffe, 1976). Similarly, Baars *et al.* (1975) reported a range of summer growth rates from 55–88 kg DM/ha/d for lucerne, which was substantially higher than ryegrass/white clover pastures (12.6–38 kg DM/ha/d) under high rainfall conditions in the North island. This indicates that all of these pasture species would be suitable for increasing summer yield. However, the superior spring and autumn yield of lucerne means it would have less impact on cool season production so would be suitable for increasing production.

4.4.2 Dryland yield

4.4.2.1 Annual yield

Annual lucerne yields were 4–6 t DM/ha superior to chicory and red clover under dryland conditions in 1997/98 and 1998/99. The 21 t DM/ha annual lucerne yield (Section 4.3.1.1) is above the reported national average of 11 t DM/ha (Douglas, 1986) in dryland systems. This is because crops were grown on a Wakanui silt loam that has a high AWC (Section 2.5.2.2). A number of authors have reported dryland yields exceeding 20 t DM/ha on soils of high AWC (Douglas, 1986). Dryland chicory also had higher yields (14–15 t DM/ha) than the 7–11 t DM/ha reported for recently established stands on a shallow dryland soil in Canterbury (Hunter *et al.*, 1994). Similarly, annual dryland red clover yields (14–15 t DM/ha) were higher than the 6-8 t DM/ha reported from shallow soils (Allen *et al.*, 1976; Hunter *et al.*, 1994).

4.4.2.2 Seasonal yield

For a dryland crop superior annual yield may result from greater yield under periods of water adequacy or water limitation or both. It is possible to establish when water became limiting by comparing dryland yields with irrigated. The long-term means (Figure 4.3) indicate this occurred from January–April. However, these values are misleading because the irrigated crops thinned faster than dryland, reducing the long-term yield of irrigated crops. Also, the exact time when crops become water limited is dependant on the variable seasonal pattern of PSWD (Figure 3.1).

In 1997/98 dryland yield was the same as irrigated in the first two regrowth cycles (Figure 4.2a). Lucerne produced 1 t DM/ha greater yield than chicory and red clover in both of these regrowth cycles. Thus, 2 t DM/ha of its annual dryland yield advantage can be attributed to greater spring growth when water supply was adequate but low temperatures limited chicory and red clover growth more than lucerne (Section 4.4.1.2).

The other 2 t DM/ha of lucerne's annual yield advantage came after late November when dryland yields were lower than irrigated (Figure 4.2a). This indicated water was limiting production under dryland conditions. In this period lucerne had higher linear growth rates than chicory and red clover (Figure 4.4), highlighting lucerne as the most productive species under conditions of limited water supply. The PSWD was less in the 1998/99 season (Table 3.1), and dryland growth did not become less than irrigated until mid December. Additionally, lucerne produced more DM after December in 1998/99 regrowth period (Figure 4.2a), which again highlights this dryland advantage.

Summer LGR of all three crops was 50–80 kg DM/ha/day, which was substantially higher than the 15–30 kg DM/ha/day expected from dryland ryegrass/white clover pastures during summer in Canterbury on the same soil type (Hayman and McBride, 1984). Douglas (1986) demonstrated that the relative yield advantage of lucerne over pasture increases as precipitation decreases and it would be expected that red clover and chicory would also display a greater advantage over pasture under conditions of lower precipitation. However, Hayman and McBride (1984) reported the yield advantage of lucerne over pasture decreased with lower soil AWC. Thus, the dryland yield advantage of lucerne over chicory and red clover would be expected to be less on lighter (stony/shallow) soils.

The high yields of lucerne compared with pasture have been attributed to greater extraction of water, rather than a more efficient use of water (Douglas, 1986). However, the reasons for its advantages over chicory and red clover are unknown and will be explored in Chapter 5.

4.4.3   Botanical composition

The superiority of lucerne yield in the first two perennial growth seasons continued into the third, fourth and fifth seasons. However, annual and seasonal yield in these years was compromised by plant mortality leading to a change in botanical composition.

4.4.3.1   *Persistence*

Lucerne was the most persistent crop in this experiment displaying the highest sown species composition from 1999/00–2001/02 (Table 4.1), which further increased its yield advantage over chicory and red clover in these seasons (Figure 4.2c). Weed invasion began in red clover crops at the end of the second perennial growth season and red clover had disappeared completely by the final year. Weed species (including white clover) were less productive than sown species so the crops that showed the largest decline in botanical composition also had the greatest decrease in total DM yield (Section 4.3.1.3).

Almost all studies that present annual chicory, lucerne or red clover yields over a long period show the same downward trend in yield. For example, Li *et al.* (1997b) reported a chicory yield of about 9.0 t DM/ha (November–April) in the second and third growth seasons, declining to 4.5 t DM/ha in the fifth growth season. Similarly, Hume *et al.* (1995) showed chicory dominated yield for the first three growing seasons and declined to make no significant contribution by the end of the fifth. The poor result for red clover is typical of this species as it rarely persists longer than three growing seasons (Hay and Ryan, 1989).

In most cases the decline in population is attributed to root and crown diseases. For example, Skipp and Christensen (1990) measured 65% mortality in a stand of 'Pawera' red clover two years after sowing and associated plant death to stem nematode (*Ditylenchus dipsaci*) and a variety of soil fungi including *Verticillium dahliae* and *Fusarium spp.* Dying chicory plants from this experiment were identified with *Sclerotina minor* infection (N. Rabendraan, personal communication). Population decline is common for lucerne in New Zealand and has been attributed to a wide range of pests and diseases (Sheath and Hay, 1989). The rapid thinning of red clover

indicated it was the most susceptible to root diseases and lucerne was least susceptible. However, lucerne cultivar has an important bearing on persistence as modern cultivars have been bred for multiple resistance to pests and diseases and poor persistence would be expected had 'Wairau' been used (Purves and Wynn-Williams, 1989).

4.4.3.2   *Irrigation reduces persistence*

Irrigated crops displayed less persistence than dryland crops and this gave the negative irrigation responses in the final three seasons (Section 4.3.2.1). The large difference in irrigated and dryland lucerne persistence (Table 4.1) is consistent with reports of poor persistence in wet soil conditions (such as under irrigation). For example, Stephen *et al.* (1982) showed a wide range of lucerne cultivars to have a population of 89 plants/m^2 at the end of a five growing season period at a dry site compared with a population of 30 plants/m^2 at a wet site. Subsequently, botanical composition at the dry site was 79% lucerne in the second growth season and 81% in the fifth growth season. Botanical composition at the wet site declined from 99% in the second growth season to 40% in the fifth growth season. Similarly, Hayman and McBride (1984) reported a more rapid decline in irrigated lucerne yield (relative to dryland yield) on five soil types over a six year period in Canterbury. Likely mechanisms for reduced persistence with irrigation are more favourable soil conditions (moist) for growth and function of invading pests and increased competitiveness of weed species.

The changes in botanical composition also affected the herbage quality and utilisation of each species.

4.4.4   Protein and energy composition and consumption

4.4.4.1   *Protein and energy composition*

All three species had similar leaf ME composition (10.9–11.6 MJ/kg), which was consistent with their reputation as high quality forages (Barry, 1998; Waghorn and Barry, 1987). Lucerne and red clover also had the high leaf crude protein concentrations (24.6–29.1%) which was consistent with values reported for these legumes (Frame *et al.*, 1998a). Chicory had a lower leaf crude protein concentration

than legumes but its protein may be used more efficiently (Komolong *et al.*, 1992). Other studies have shown no differences in sheep growth rates from equal intakes of chicory or lucerne (Holst *et al.*, 1998; Scales *et al.*, 1995) so similar animal growth rates could be expected per kg leaf herbage intake from all three species.

Lucerne and chicory crops also yielded stems with a low digestibility and subsequent ME concentration (Table 4.5) due to a high concentration of structural carbohydrates (Halim *et al.*, 1989).

4.4.4.2   *Utilisation*

Sheep preferentially graze sward components with the highest feeding value first and the similarity in CP and ME concentrations of lucerne stem and residual fractions (Table 4.5) indicates sheep removed all the leaf fraction of the crop leaving only the stems. This highlights the suitability of the breaking point method of separating lucerne herbage into grazed and un-grazed fractions to give an indication of utilisation. Residual chicory and red clover had higher ME and CP concentrations than lucerne because the residual samples still contained some leaf. This implies greater stock preference for lucerne leaf and was supported by field observations where the lucerne leaf was the first part of the experiment that the sheep consumed.

Red clover had the highest forage utilisation (Table 4.4) in the first three growth seasons because it did not produce hard stems prior to grazing. Chicory had greater utilisation than lucerne because it yielded less stem (Figure 4.5). The reduction in red clover utilisation in later seasons was due to the decline in red clover stand density and the invasion of low palatability weed species (Table 4.1). Initially these weed species comprised largely of white clover and had similar herbage quality to the red clover (Table 4.5) but unpalatable weeds such as Shepard's purse and dandelion invaded in 2000/01 and 2001/02. Weed species in chicory plots comprised mostly of white clover which caused no decline in utilisation of chicory and the decreased stand density of chicory reduced the number of unpalatable stems.

Stem yield can be a problem with grazed chicory but the frequency of grazing controlled primary stem yield in this experiment. Lower utilisation would be a problem with less frequent grazing (Li *et al.*, 1994). The most important grazing for chicory is during November when hard grazing will remove primary flower stems and the subsequent secondary stems are smaller and contribute less to total DM yield. Fewer grazing stock were available in the later seasons of this experiment (2000/01 and 2001/02) so stock were less inclined to utilise all of the herbage yielded before they were removed. The increased lucerne utilisation (relative to other species) during this time (Table 4.4) indicated a preference for lucerne (which was also observed in the field) where stock consumed all of the palatable parts of lucerne herbage before moving to other species.

4.4.4.3   Protein and energy consumption

Protein, ME (plant quality), utilisation (plant composition and animal preference) and DM yield (plant productivity and persistence) can be combined (protein and energy consumption) to give an indication of annual animal yield potential from an area of forage crop.

An animals protein requirement is lower than its energy requirement and it is usually ME content of forage that limits animal growth (Geenty and Rattray, 1987). Thus, energy consumption will give the best indication of how much animal yield could be expected from these crops. Lucerne provided greater energy consumption for grazing stock in all five growth seasons under both irrigated and dryland conditions (Table 4.7). Protein is important for young growing stock and lucerne also provided the greatest protein consumption under irrigated and dryland conditions (Table 4.6). A common complaint about lucerne is the large amounts of stem that sheep won't eat and this study also showed lucerne to have a lower utilisation than chicory and red clover (Table 4.4). However, this was offset by the higher total DM yield and most of the ME and protein was concentrated in the leaf fraction (consumed) of lucerne which indicated lucerne would still give greater animal production than chicory or red clover.

4.4.5 **Conclusions**

Based on the results from this chapter the following conclusions can be dawn;

- Lucerne had 3–5 t DM/ha greater annual yield than chicory and red clover under irrigated conditions due to greater spring and autumn growth rates.

- The yield advantage of lucerne was maintained under dryland conditions due to greater growth rates during periods of water deficit.

- Lucerne had superior persistence with 10% weed infestation by the end of the fifth perennial growth season compared to 39% in chicory and 100% in red clover.

- Livestock energy and protein consumption were 30% higher from lucerne than chicory and red clover.

In summary, this chapter has shown that lucerne would be expected to make a greater contribution to farm productivity than chicory or red clover. However, there is a lack of information on the mechanisms that contributed to the seasonal yield advantage and variation encountered. The following chapter will study the mechanisms for differences in production between these species during periods of water deficit.

5 Water extraction of chicory, lucerne and red clover

5.1 Introduction

The greater dryland production of lucerne (Chapter 4) shows it was the most efficient species for using limited annual precipitation to produce yield. Part of this advantage came from greater cool season production with higher yields in the early spring and late autumn (Section 4.3.2.2). However, lucerne also had greater yields during periods of water shortage in the summer and autumn. There are two possible explanations for this; 1) lucerne had greater E_T or 2) it used E_T to produce yield more efficiently than chicory or red clover. Transpiration may be increased by reduced evaporation, drainage losses or greater water extraction. One of the justifications for using chicory, lucerne and red clover in this research was the possibility for increased water extraction by their deep roots (Section 2.1).

Differences in E_T may be indicated by WU calculated from soil water deficit (SWD) and precipitation data. However, this calculation also includes water losses, particularly evaporation, which confounds comparisons between species to explain differences in E_T. Evaporation losses are least in period sof low precipitation (Asseng et al., 2001) so water use efficiency (WUE) will be close to E_{T_eff} during such periods. An additional feature of periods of low precipitation is low E_T from the top 0.2 m of soil (Section 2.1.1.1) because the soil is already dry. This makes it possible to compare differences in E_T by comparing water extraction below this depth. The timing of water extraction differences may be compared using a framework presented by Monteith (1986), but this has not been tested for perennial crops, which already have established root systems (Section 2.5.2.4).

The objective of this chapter was to explain yield differences between chicory, lucerne and red clover under conditions of water shortage. The first step was to examine their SWD and WU. Low precipitation conditions occurred in 1997/98 (Section 3.1.3) so analyses of WUE and soil water extraction patterns were conducted in this season to investigate the reason for greater lucerne yields. Analysis included a validation of the 'Monteith framework' to test its suitability for explaining water extraction patterns of perennial crops.

5.2   Materials and Methods

The SWD and WU of chicory, lucerne and red clover were calculated for $I8_{97/98}$–$I8_{01/02}$ (Section 3.2.1). The comparison of water extraction patterns focused on $I8_{97/98}$ when all plots were still monocultures of sown species (Section 4.3.1.2). The validation of the 'Monteith framework' for perennials was made by comparison of water extraction patterns from the first sowing date treatment in $I9_{00/01}$ (establishment season) with the perennial regrowth for the same plots in the following year ($I9_{01/02}$; Section 3.2.1).

5.2.1   Measurements

5.2.1.1   Meteorological data

Full details of environmental conditions from 1 July 1996–30 June 2002 are given in Section 3.1.3. Briefly, annual rainfall was low (430 mm) for $I8_{97/98}$ and was <300 mm following the sowing of lucerne in $I9_{00/01}$. Portable rain-shelters meant $I9_{01/02}$ received <20 mm of rainfall. This gave suitable conditions to apply the 'Monteith framework' to water extraction patterns and compare WU with minimal errors caused by evaporation in calculations.

5.2.1.2   Soil water

Soil water measurements (Section 3.3.4) were made on each replicate of each crop on 98 dates between 12 August 1997 and 25 June 2002 in Iversen 8 with 18 of these measurement dates in $I8_{97/98}$. Measurements were also made at ~7 d intervals in Iversen 9 giving 68 measurement points from 25 October 2000–12 June 2002.

5.2.2   Analysis of crop water use

5.2.2.1   Water use and soil water deficit

The SWD was calculated as the difference between measured soil water profile (SWP) and drained upper limit (DUL). Water use was calculated from SWD and precipitation using a water balance. Full details of these calculations are given in Section 3.4.3.

5.2.2.2   Water use efficiency

The WUE of each species was calculated in $I8_{97/98}$, when plots were pure and in-season rainfall was lowest, minimising the magnitude of soil evaporation losses. Dry matter yields (Section 4.3.2) were accumulated from regrowth cycles 2–6 and regressed against accumulated WU (normalised for VPD) over the same period. Water use was normalised by dividing the WU in each regrowth cycle by the mean daylight averaged VPD (Section 2.5.1) for that cycle. The first regrowth cycle was excluded because soil water measurements started part way through it. There was a possibility the WU of lucerne was underestimated later in 1997/98 because the extraction front reached the maximum measurement depth (2.3 m) in the fourth regrowth cycle. To assess the probable extent of this underestimate extra WU was added (in 5 mm increments) onto lucerne WU values for regrowth periods 4 and 5 and compared with WUE in previous cycles.

5.2.3   Analysis of the soil water extraction patterns

5.2.3.1   Period of analysis

For the validation of the 'Monteith framework', models (Sections 5.2.3.2 and 5.2.3.4) were fitted to extraction patterns of establishing lucerne ($I9_{00/01}$) from sowing (24 October 2000) to the day of maximum SWD (5 May 2001). Models were fitted to the perennial regrowth season ($I9_{01/02}$) from the end of pre-season irrigation (11 August 2001) until the final grazing at the end of the season (12 Jun 2002). In $I8_{97/98}$ models were fitted to water extraction patterns from the installation of neutron probe access tubes (18 August 1997) until April 1998 when rainfall ended the dry period and the SWD started to decrease.

5.2.3.2   Plant available water capacity

The plant available water capacity (PAWC) was determined in each soil layer (0.1 m) using the upper limit (UL) from models fitted to θ_t (Section 5.2.3.3). This differed to DUL (Section 2.5.2.1) in some situations where the soil was not fully recharged at the start of the analysis period, but still gave a stable upper limit for describing water

extraction. The lowest recorded θ within the analysis period (θ_{min}) was used as the lower limit (LL) of PAWC. This was because θ_{min} from the fitted exponential model (Equation 5.2) underestimated LL when water extraction was not complete at the end of the analysis period (i.e. the asymptote was lower than θ_{min}). Total PAWC for the crop was calculated for each replicate in each season using Equation 5.1.

Equation 5.1 $$PAWC = \sum_{MED}^{top} (UL - LL) * d$$

Where d is depth (mm) converting volumetric water content to mm of water, top is the 0–0.2 m layer and MED is the maximum extraction depth. The MED was defined as the depth at which the exponential model (Equation 5.2) no longer gave an accurate ($R^2 < 0.75$) description of θ_t. Observations showed no systematic change in θ_t below maximum extraction depth indicating that no water extraction was occurring.

5.2.3.3   The model for water extraction within each soil layer

The pattern of soil water extraction in each of the 21 soil layers (Section 3.3.4) was described for each replicate of each treatment in $I8_{97/98}$, $I9_{00/01}$ and $I9_{01/02}$. This was done by fitting an exponential model, modified from (Passioura, 1983), to the change in soil water content over time (θ_t);

Equation 5.2 $$\theta_t = \theta_l + \theta_a \exp(-kl(t-t_c)s_c) \qquad s_c = 0 \quad \text{if } t \le t_c$$

$$s_c = 1 \quad \text{if } t > t_c$$

Where θ_l is the lower limit (LL) to water extraction, θ_a is the amount of water extracted (PAWC), $\theta_l + \theta_a$ is the UL of water extraction. The -kl is the extraction decay constant, t_c is the extraction start time (days) and s_c switches the function from a constant θ_t before t_c to an exponential decrease after t_c.

An example of this function is displayed in Figure 5.1. In Section A, θ_t is constant and this represents the UL for the season. This may be DUL or may be lower if the soil

layer did not completely refill prior to the beginning of analysis. Section B begins at t_c where s_c becomes 1 and exponential decrease in θ_t begins. At any time (t) plant available water (PAW) remaining in the soil layer is given by θ_t - θ_l. The -kl represents the fraction of PAW that is extracted each day and gives the curvature of the line.
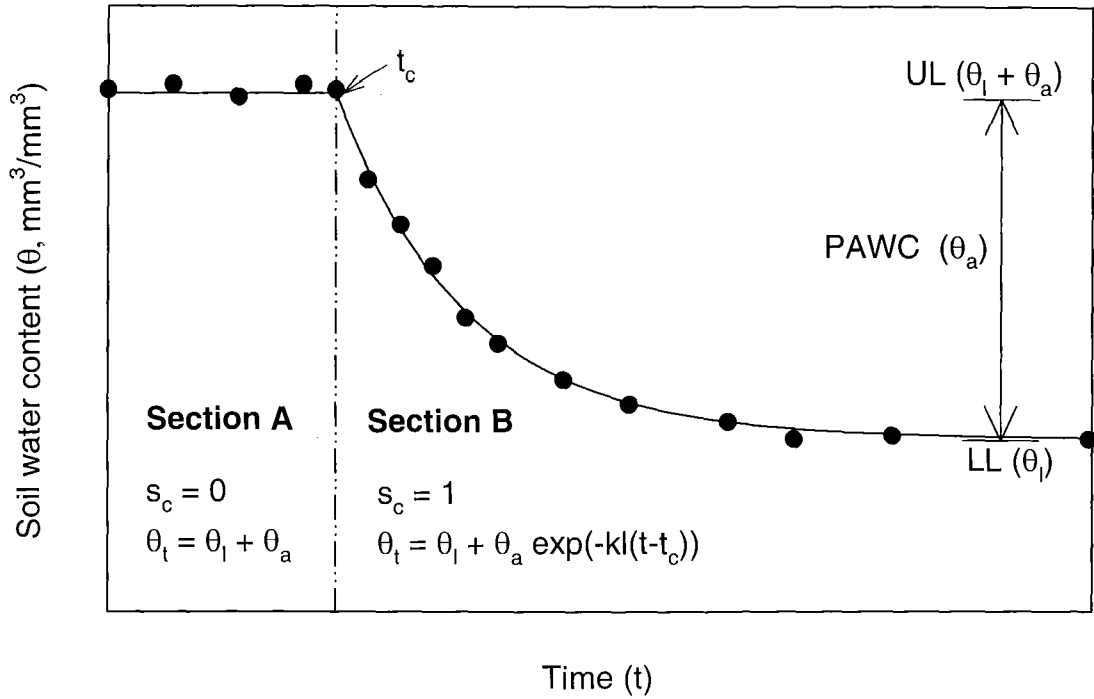
Figure 5.1 A theoretical example of the change in soil water content of a single layer of soil over time.

Note: UL is the upper limit, PAWC is the plant available water capacity, LL is the lower limit and t_c ($-\cdots-\cdots$) is the extraction start time. See Equation 5.2 for other abbreviations.

Equation 5.2 differs from functions used by previous authors (e.g. Robertson *et al.*, 1993b) by the inclusion of a switch (s_c) that changes the relationship from linear to exponential at the start of extraction (t_c). This broken stick function explains both the linear and exponential sections giving a full description of θ_t over the analysis period and a fitted value for t_c in a single curve fitting procedure. This removes the need to fit separate linear and exponential functions and run iterations to find the point of inflection (t_c). To facilitate fitting, the s_c parameter needs to be expressed as a logical statement ($t>t_c$), which returns a value of 0 if false and 1 if true.

5.2.3.4   The model for extraction front characteristics

The characteristics of the extraction front were described for individual replicates in $I8_{97/98}$, $I9_{00/01}$ and $I9_{01/02}$ using the method proposed by Monteith (1986). That is, t_c (d) for each soil layer (0.2–2.3 m) was plotted as a function of the layer depth (m) and a linear regression was fitted. The negative slope of the linear regression represents the extraction front velocity (EFV; mm/d) and x-axis intercept is the number of days from the start of the analysis period until the probable start of extraction in the top profile layer.

5.2.3.5   Seasonal water extraction pattern

The seasonal pattern of water extraction was shown by calculating daily water extraction for each replicate, using the variables described in the previous sections:

Equation 5.3   Water extraction $= \sum_{ED}^{top} ((\theta_t - \theta_l) * d) * -kl$

Where d is the depth of each layer, θ_l was taken for each layer from fitted functions, θ_t was calculated daily using Equation 5.2 and ED is the extraction depth calculated on each day using:

Equation 5.4 $ED = Y_{int} + (EFV * t)$

Where Y_{int} is the y-axis intercept of the EFV regressions (Section 5.2.3.4). A layer was included in extraction calculations when the extraction front was at least half way through it and ED stopped increasing when maximum extraction depth was reached. Lucerne extraction reached the maximum measurement depth and it was possible it extracted additional water below this depth so another calculation was made assuming a maximum extraction depth was 2.7 m and PAWC was the same as the previous layer at 0.12 mm^3/mm^3 in each of the five additional layers, below the measurement depth of 2.3 m.

5.2.4   **Statistical analysis**

One-way ANOVA (Section 3.5) was used to compare annual WU and maximum SWD of chicory, lucerne and red clover within each season. This was also used to compare total PAWC and profile mean –kl between species treatments in I9$_{97/98}$ and total PAWC between seasons in I9. Means were separated using Fisher's protected least significant difference (P<0.05).

The PAWC and –kl were compared over the depth of the profile with species as a main-plot and depth as a repeated measure (Section 3.5.1). The same analysis was used to compare Iversen 9 with establishment (2000/01) and perennial seasons (2001/02) as main-plots. Mean daily water extraction was compared as a split-plot with species as the main-plot and month as sub-plots. The interaction term of this ANOVA tests if species have different seasonal extraction patterns and allowed the calculation of a single LSD for species comparisons for each month.

5.3   Results

5.3.1   Soil water deficit, water use and dry matter yield

5.3.1.1   Soil water deficit (SWD)

Lucerne had a SWD of 80 mm when measurements began (18 August 1997) compared with 40 mm for chicory and red clover and SWD remained close to these levels until the end of October (Figure 5.2). The remainder of the $I8_{97/98}$ growth season received minimal rainfall and PSWD increased from 50 mm in November to 786 mm in March (Figure 3.1). The SWD of all crops quickly increased to 200 mm at the start of December and was 300 mm by late January. The SWD of lucerne continued to increase to a maximum of 406 mm on 10 March 1998, which was 65 mm greater (P<0.05) than chicory and red clover (Table 5.1). There were no species differences in SWD of irrigated crops during this experiment and the SWD of irrigated red clover is also displayed in Figure 5.2 for reference.

The SWD had only recovered to 240 mm for lucerne and 180 mm for chicory and red clover by the end of August 1998, so 150 mm of irrigation was applied to reduce the SWD for the up-coming growth season ($I8_{98/99}$). This returned the SWD of red clover to zero, chicory to 50 and lucerne to 100 mm in mid September. The remainder of this season was also dry and PSWD increased from 100 mm in September to 600 mm in February. The SWD of all three crops again increased rapidly with lucerne reaching 200 mm at the start of December and chicory and red clover reaching this level at the end of December. The SWD of lucerne increased to a maximum of 375 mm at the end of February, which was 95 mm greater (P<0.05) than for red clover and chicory (280 mm).

Table 5.1 Maximum soil water deficit (mm) of dryland chicory, lucerne and red clover measured over five growth seasons (1997/98–2001/02) in Iversen 8 at Lincoln University, Canterbury, New Zealand.

	1997/98	1998/99	1999/00	2000/01	2001/02
Chicory	335	286	236	272	264
Lucerne	403	375	249	357	381
Red clover	347	281	249	275	267
P	<0.05	<0.05	ns	<0.01	<0.01
SEM	22.5	24.6	20.4	16.8	18.7

Note: SEM = standard error of the mean, ns = not significant.

The I8$_{99/00}$ season was wetter than average with a maximum PSWD of 380 mm (Table 3.1). High rainfall (200 mm) during July allowed the SWD of chicory and red clover to recover to zero at the start of September when lucerne had only recovered to 50 mm (Figure 5.2). The SWD then increased to a maximum of about 240 mm for all species at the start of May 2000 (Table 5.1).

The SWD recovered to zero for all crops in mid September of the I8$_{00/01}$ season and a large rainfall event (75 mm) brought it back to zero in mid October. The remainder of the season was dry and the PSWD increased rapidly from zero in October to 580 mm in May. The SWD of all species increased to 200 mm by the end of January. The SWD of lucerne increased more than chicory and red clover after January to reach a maximum of about 357 mm at the end of March, 80 mm greater ($P<0.001$) than chicory and red clover.

There was still a large SWD at the beginning of the I8$_{01/02}$ season and no irrigation was applied to reduce this so the SWD only recovered to 210 mm for lucerne and 150 mm for chicory and red clover at the start of September. The 2001/02 season was wetter than average (annual PSWD of 324 mm), but the lucerne SWD still reached 380 mm, 120 mm more ($P<0.01$) than chicory and red clover.
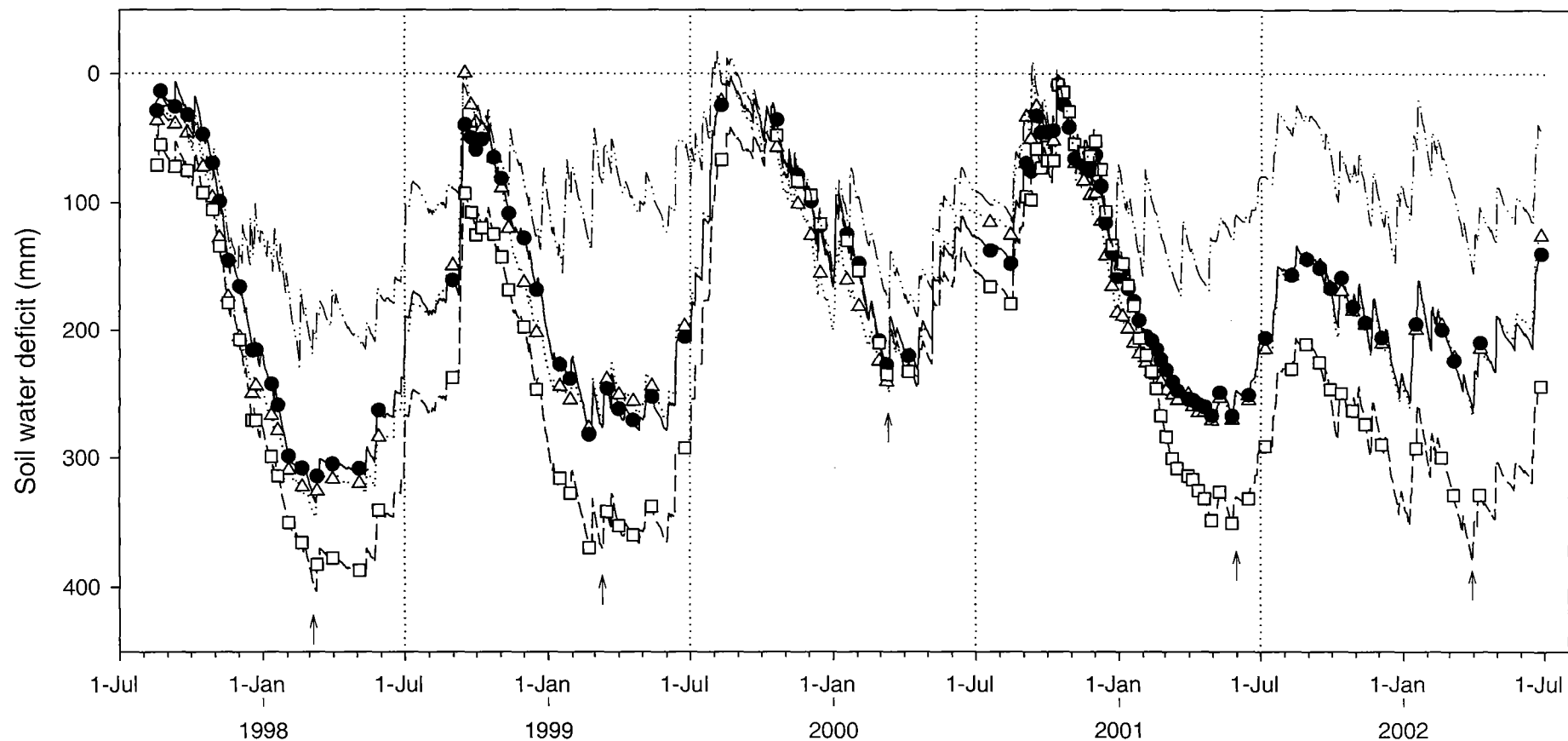
Figure 5.2 Soil water deficit to 2.3 m of dryland chicory (——●——), lucerne (– –   – –), red clover (····△····) and irrigated red clover (—··—··) crops grown on a Wakanui silt loam soil from 18 Aug 1997–24 June 2002 in Iversen 8 at Lincoln University, Canterbury New Zealand. Arrows mark the date of maximum soil water deficit.

5.3.1.2   Water use

Annual WU from each dryland crop was ~650 mm in $I8_{97/98}$ and $I8_{98/99}$ and ~750 mm for $I8_{99/00}$–$I8_{01/02}$ (Table 5.2). Chicory and red clover had a greater (P<0.05) WU (~765 mm) than lucerne (703 mm) in 1999/00. Figure 5.3 shows this difference occurred at the beginning of the season when chicory and red clover displayed a cumulative WU of ~200 mm by mid October compared with 100 mm for lucerne. The WU from all irrigated crops was ~900 mm in all seasons and the accumulated WU of irrigated red clover is displayed in Figure 5.3 for reference.

Table 5.2 Total water use (mm) of dryland chicory, lucerne and red clover crops grown over five perennial growth seasons from 18 August 1997–24 June 2002 on a Wakanui silt loam soil in Iversen 8 at Lincoln University, Canterbury, New Zealand.

	1997/98	1998/99	1999/00	2000/01	2001/02
Chicory	605	660	776	720	730
Lucerne	653	679	703	785	750
Red clover	612	651	760	727	704
P	ns	ns	<0.05	ns	ns
SEM	19.3	15.9	19.2	21.6	17.7

Note: SEM = standard error of the mean, ns = not significant.
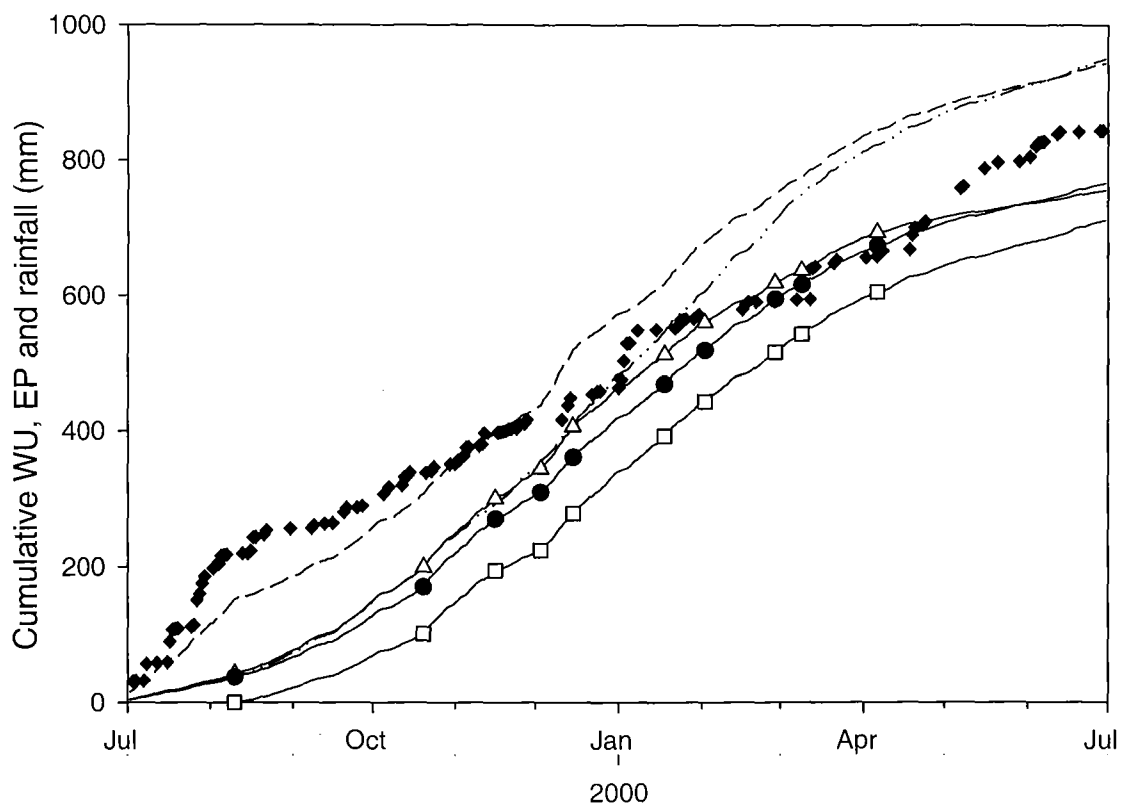
Figure 5.3 Cumulative Penman evapotranspiration potential (EP, —··—··), rainfall (◆) and cumulative water use (WU) of dryland chicory (—●—), lucerne (— —), red clover (—△—) and irrigated red clover (- - - -) crops from 1 July 1999–30 June 2000 in Iversen 8 at Lincoln University, Canterbury, New Zealand.

5.3.1.3   Water use efficiency

Chicory and red clover displayed a constant linear relationship ($R^2 = 0.99$) between accumulated DM yield and VPD normalised WU with a WUE of 29 kg DM/mm/kPa in $I8_{97/98}$ (Figure 5.4). The DM accumulation of lucerne showed the same relationship for regrowth cycles 2 and 3, but deviated above this in regrowth cycles 4–6. Adding 30 mm of WU to each of regrowth cycles 4 and 5, to account for the underestimation measured in Section 5.3.3.1, brought these cycles (and cycle 6) onto the same relationship as the rest of the data points.
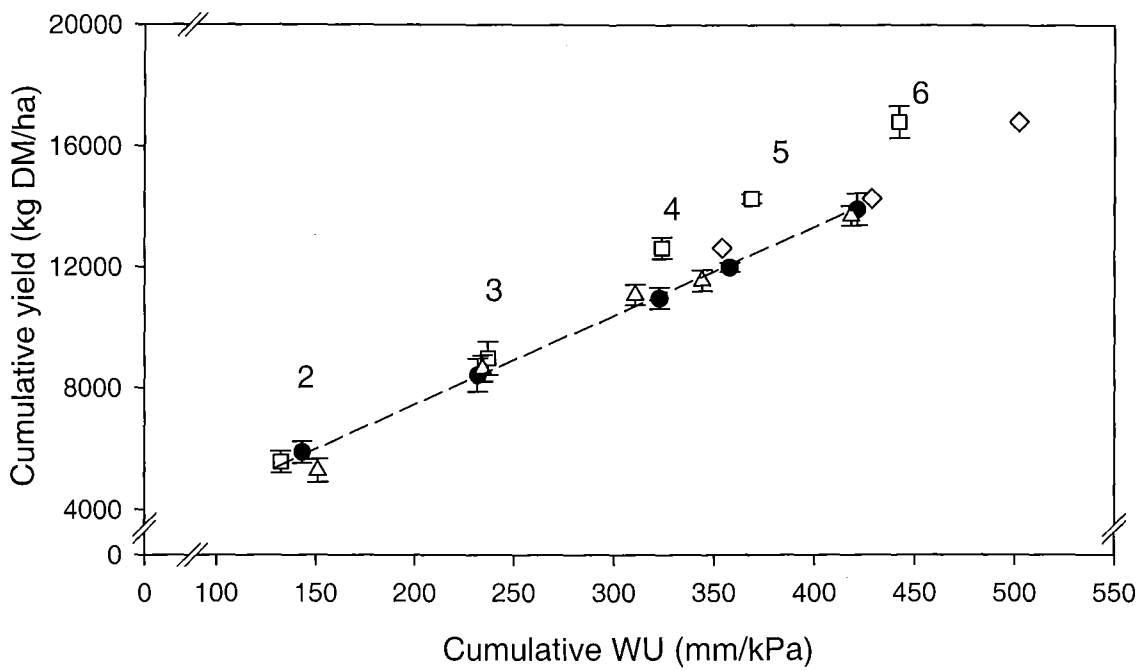
Figure 5.4 Accumulated yield in relation to accumulated water use (WU) normalised for vapour pressure deficit for dryland chicory (●), lucerne ( ) and red clover (△) grown from 13 October 1997–29 May 1998 in Iversen 8 at Lincoln University, Canterbury, New Zealand. Bars represent one standard error either side of each value. ◇ shows lucerne with an additional 30 mm added to each of regrowth cycles 4 and 5.

Note: Numbers represent the regrowth cycle to which values in their proximity are accumulated. Linear regression (– – – –) y = 1580(270.6) + 29.4(0.93)x, $R^2 = 0.99$, is fitted to all data points except lucerne from regrowth cycles 4–6. Bracketed values represent standard errors for coefficients.

5.3.2 Water extraction patterns of establishing and perennial lucerne

5.3.2.1 *Plant available water capacity*

Lucerne extracted water to 1.7 m depth in the establishment season ($I9_{00/01}$) and had a total PAWC of 308 mm (Figure 5.5). The PAWC (363 mm) was greater (P<0.05) in the perennial season ($I9_{01/02}$) due to greater (P<0.001) extraction below 1.5 m. The upper limit of PAWC was less (P<0.001) in the perennial season than the establishment season, showing incomplete recharge from 0.5–1.5 m depth between the two seasons (Figure 5.5b).
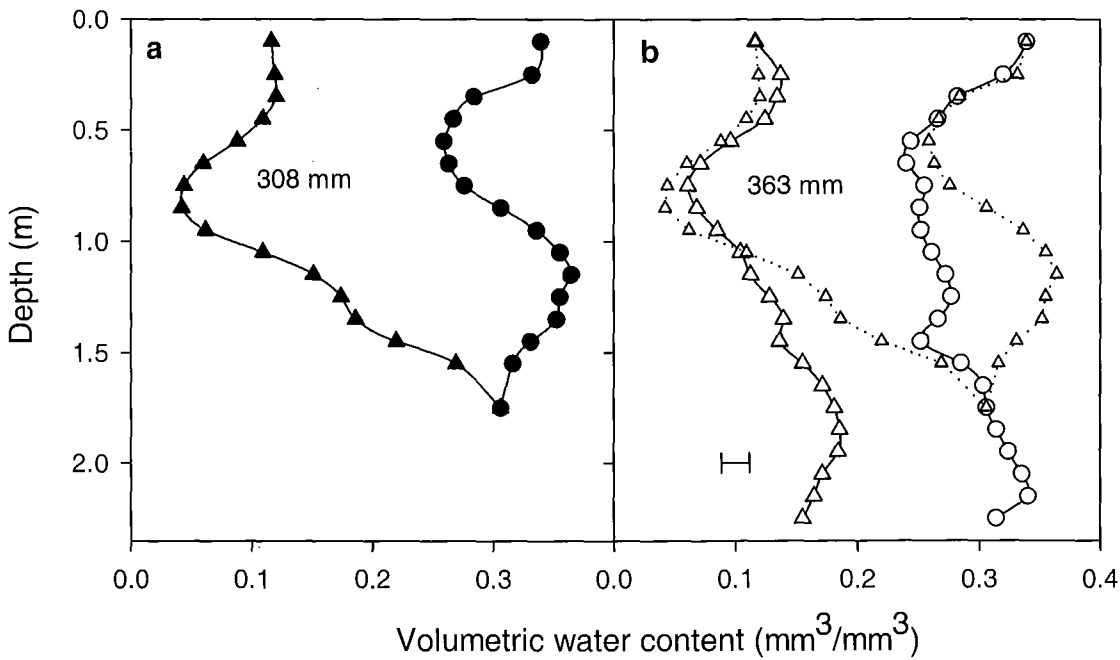
Figure 5.5 Upper (●○) and lower (▲△) limits of dryland lucerne water extraction measured from 24 October 2000–12 June 2002 for the establishment (a) and perennial (b) growth seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand.

Note: Shaded area and numbers represent the plant available water capacity for each season. The limits from the establishment season are superimposed onto the perennial season (   ) and bar is LSD for comparison of PAWC.

5.3.2.2   Seasonal extraction pattern

Some examples of exponential functions (Equation 5.2) used to explain the change in volumetric water content (θ_t) for the establishment and perennial growth seasons (I9$_{00/01}$ and I9$_{01/02}$) are shown in Figure 5.6. These functions gave a robust description of θ_t with a mean R^2 value of 0.96 (range 0.79–0.99) for 43 curves fitted in the establishment growth season and a mean R^2 of 0.98 (range 0.88–0.99) for 66 curves fitted in the perennial growth season. Extraction depth was the lowest depth at which the exponential model (Equation 5.2) gave a good explanation ($R^2 > 0.75$) of θ_t. An example of θ_t below the maximum extraction depth can be seen in the establishment season at 2.25 m depth where θ was unchanged at 37 mm^3/mm^3.
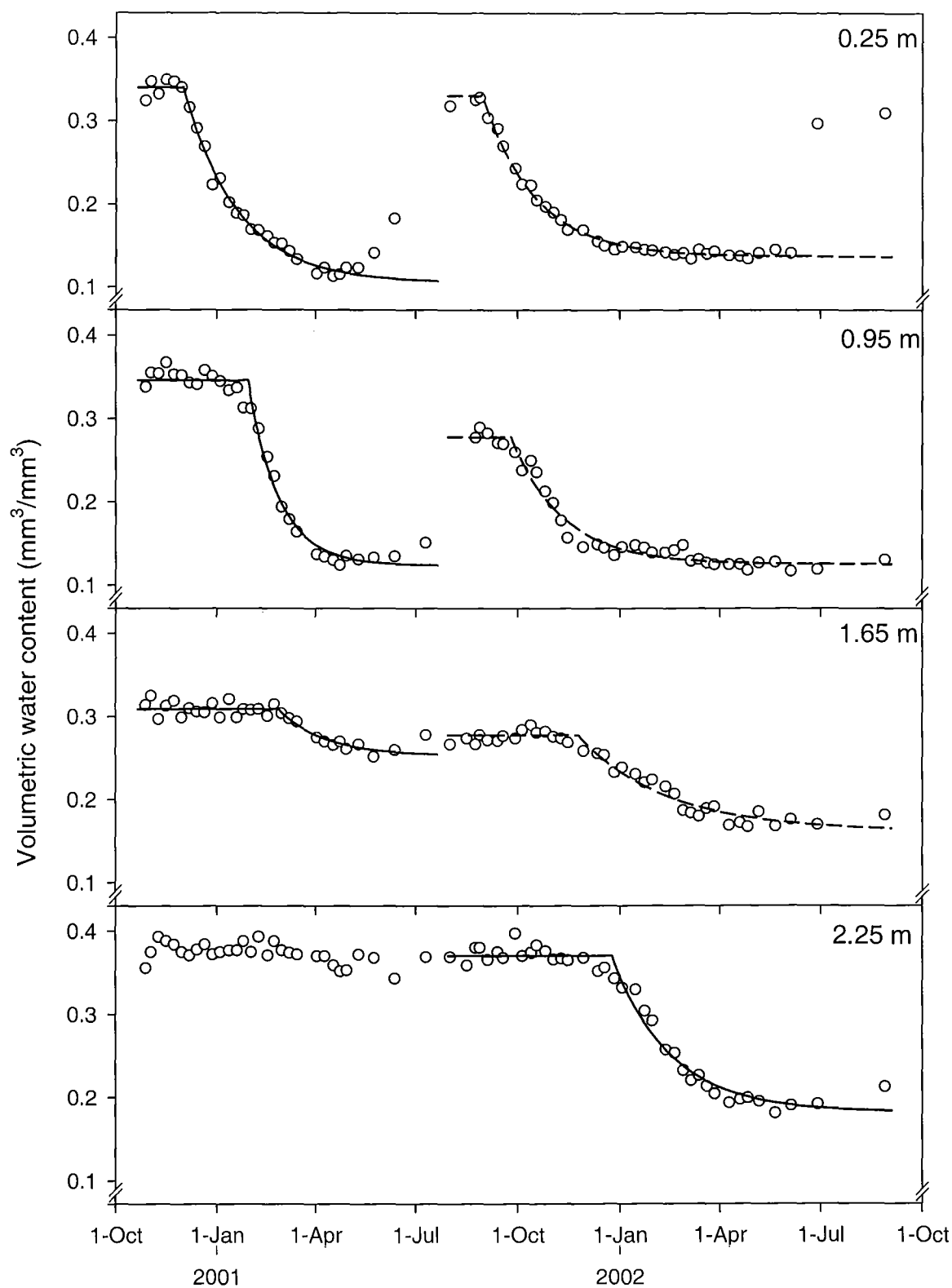
Figure 5.6 Water extraction pattern at various depths below a dryland lucerne crop in the establishment (——) and perennial (– – – –) growth seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand.

Extraction started on the 2 November 2000 and 1 August 2001 and the EFV was 12.5 mm/d ($R^2 = 0.94$) in the establishment season and 15.6 mm/d ($R^2 = 0.94$) in the perennial growth season respectively (Figure 5.7).
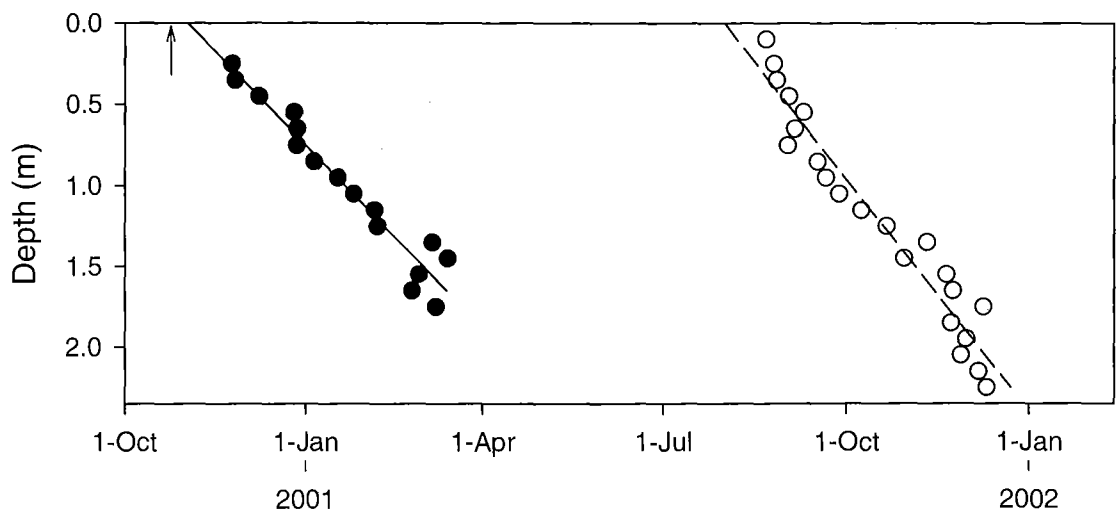
Figure 5.7 Extraction start time (t_c) for each depth interval of the soil profile below dryland lucerne in an establishment (●,—) and the following perennial (○,--) growth seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand.

Note: Start days were 24 October 2000 and 11 August 2001, Slope was -12.5 and -15.6 (mm/d), y-axis intercepts were 0.11 and –0.13, x-axis intercepts were 2 November 2000 and 1 August 2001 and R^2 values were 0.94 and 0.94 for establishment and perennial seasons respectively. Arrow marks the sowing date.

The -kl was variable over the depth of the profile ranging from 0.02–0.06 /d in the establishment season with three distinctive peaks at 0.65, 1.15 and 1.45 m depth (Figure 5.8). The -kl was less variable and generally lower (P<0.05) with a range of 0.01–0.22 /d over the depth of the profile in the perennial season.
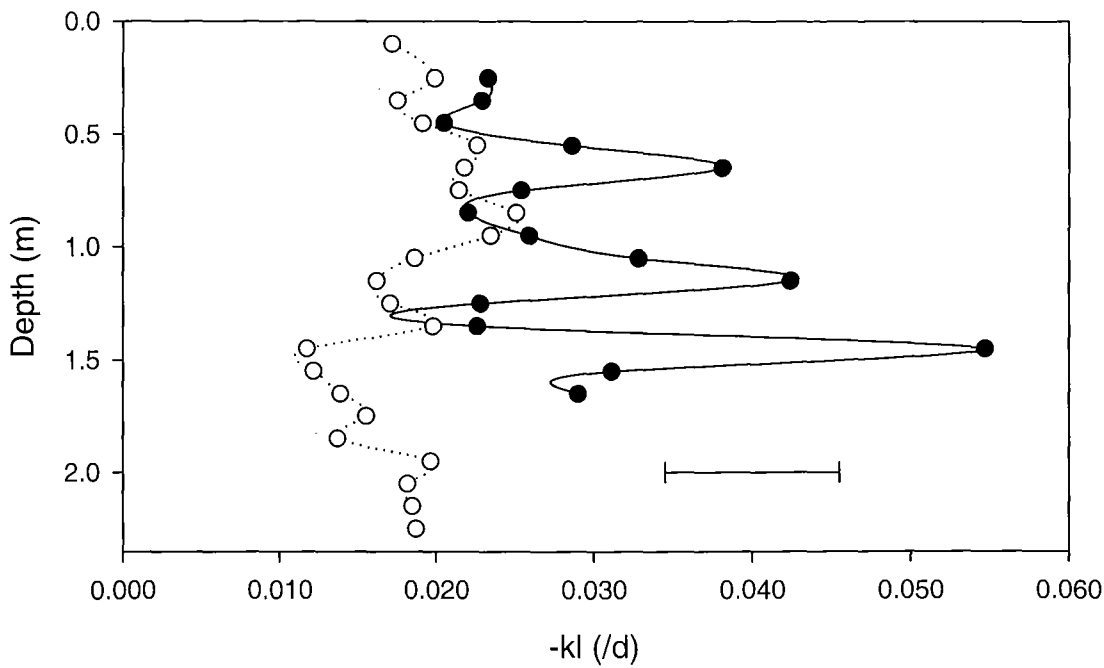
Figure 5.8 Extraction decay constant (-kl) of dryland lucerne over a 2.3 m soil profile in the establishment (—●—) and perennial (···○···) growth seasons at Lincoln University, Canterbury, New Zealand. Bar represents one LSD.

5.3.2.3   Daily water extraction

Water extraction of establishing lucerne ($I9_{00/01}$) began on 11 November 2000, 18 d after sowing, increased to 2.0 mm/d in February, 2 months after extraction started and reached a peak of 2.5 mm/d in March (Figure 5.9). The jaggered appearance of the water extraction pattern is an artefact of the calculation method (Section 5.2.3.5) giving a sudden increase in water extraction when a deeper layer is reached. In reality changes would be smooth and continuous, but the points are useful to illustrate the advance in the extraction front. Larger increases occur when extraction begins in a layer with higher -kl. The water extraction also increased from zero to 2 mm/d, 2 months after extraction started in the perennial season ($I9_{01/02}$), but extraction did not reach the peak rate of 2.5 mm/d, staying constant at ~2 mm/d from October–January. The extraction front reached 2.3 m in mid January 2002 and the daily water extraction showed a smooth decrease in the remainder of the season as θ_t declined throughout the profile.
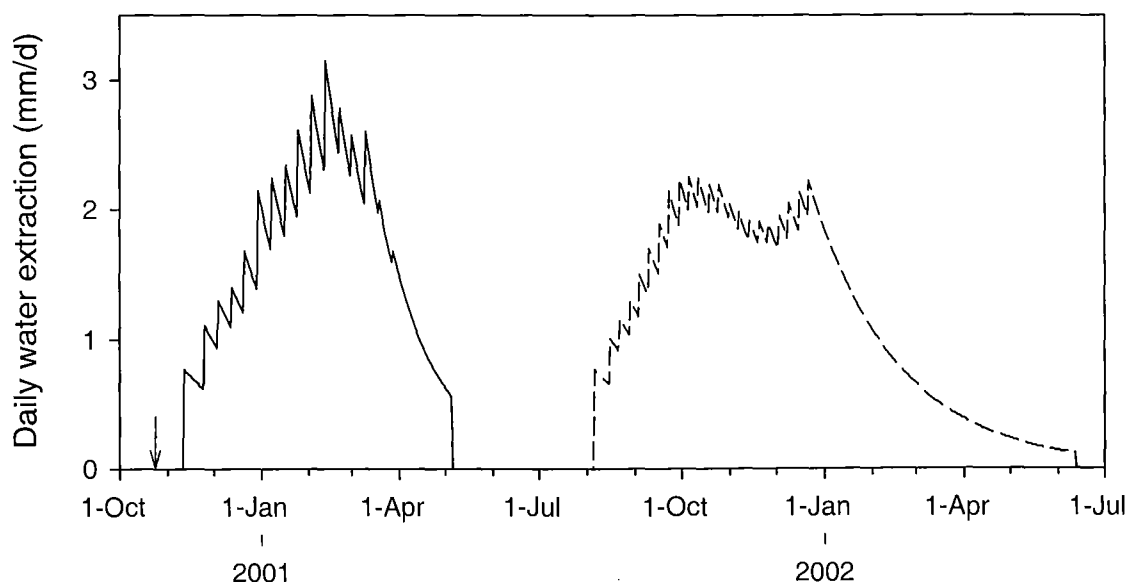
Figure 5.9 Daily water extraction of dryland lucerne in the establishment (———) and perennial (— — — —) growth seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand. Arrow marks sowing date on 24 October 2000.

5.3.3 Water extraction patterns of perennial chicory, lucerne and red clover

5.3.3.1 *Plant available water capacity*

The total PAWC of lucerne was 30 mm greater (P<0.05) than chicory and red clover in $I8_{97/98}$ and the distribution of PAWC over the profile is displayed in Figure 5.10. Lucerne had a greater (P<0.001) PAWC than chicory and red clover below 1.6 m and lucerne displayed water extraction at 2.3 m whereas chicory and red clover extracted water to about 1.9 m depth.
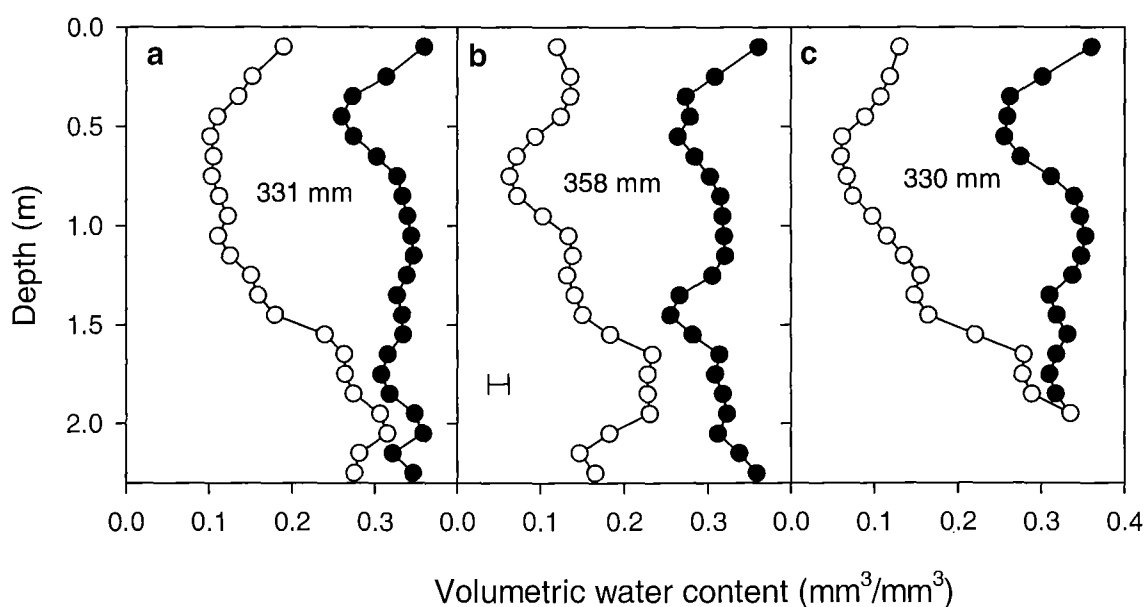
Figure 5.10 Mean upper (●) and lower (○) limits of chicory (a), lucerne (b) and red clover (c) water extraction measured on a 'Wakanui' silt loam soil from 18 August 1997–29 May 1998 at Lincoln University, Canterbury, New Zealand.

Note: Shaded area and numbers represent the total plant available water capacity. Bar is one SEM for comparison of plant available water capacity between species at any depth.

5.3.3.2   Seasonal extraction pattern

There was no systematic variation in -kl over the depth of the soil profile and all three species had a profile mean of 0.025 /d (Table 5.3). There was also no difference in the date that extraction started and the EFV of all three species was about 15 mm/d.

Table 5.3 Seasonal water extraction characteristics for three dryland perennial forage crops grown in Iversen 8 in the 1997/98 season at Lincoln University, Canterbury, New Zealand.

Species	Mean -kl (/d)	EFV (mm/d)	Extraction start date
Chicory	0.026	14.9	24 August 1997
Lucerne	0.025	16.9	1 September 1997
Red clover	0.028	12.1	19 August 1997
Probability	ns	ns	ns
SEM	0.003	2.07	13.2 (days)

5.3.3.3   Daily water extraction

The daily water extraction in $I8_{97/98}$ was displayed as monthly averages to simplify comparisons. All three crops increased water extraction from zero in July to a peak of 2.3 mm/d in December and decreased to 2 mm/d in January (Figure 5.11). Daily water extraction continued to decline from February–May and lucerne had 0.2–0.5 mm/d greater ($P<0.05$) water extraction (to 2.3 m depth) than chicory and red clover during this period. Assuming lucerne roots extracted to 2.7 m, this would have increased the daily water extraction advantage of lucerne to 0.5–2 mm/d more ($P<0.05$) than chicory and red clover from February–May.

The mean daily rainfall deficit (EP-rainfall) is displayed in Figure 5.11 to indicate potential demand, i.e. amount of daily water extraction needed for WU to equal EP. Mean daily rainfall deficit was negative (indicating soil water storage) in August and was the same as daily water extraction in September and October. The mean daily rainfall deficit was higher than soil water extraction for the remainder of the season, increasing to 4 mm/d in December, 4.7 mm/d in January and then declined to 1.8 mm/d in April.
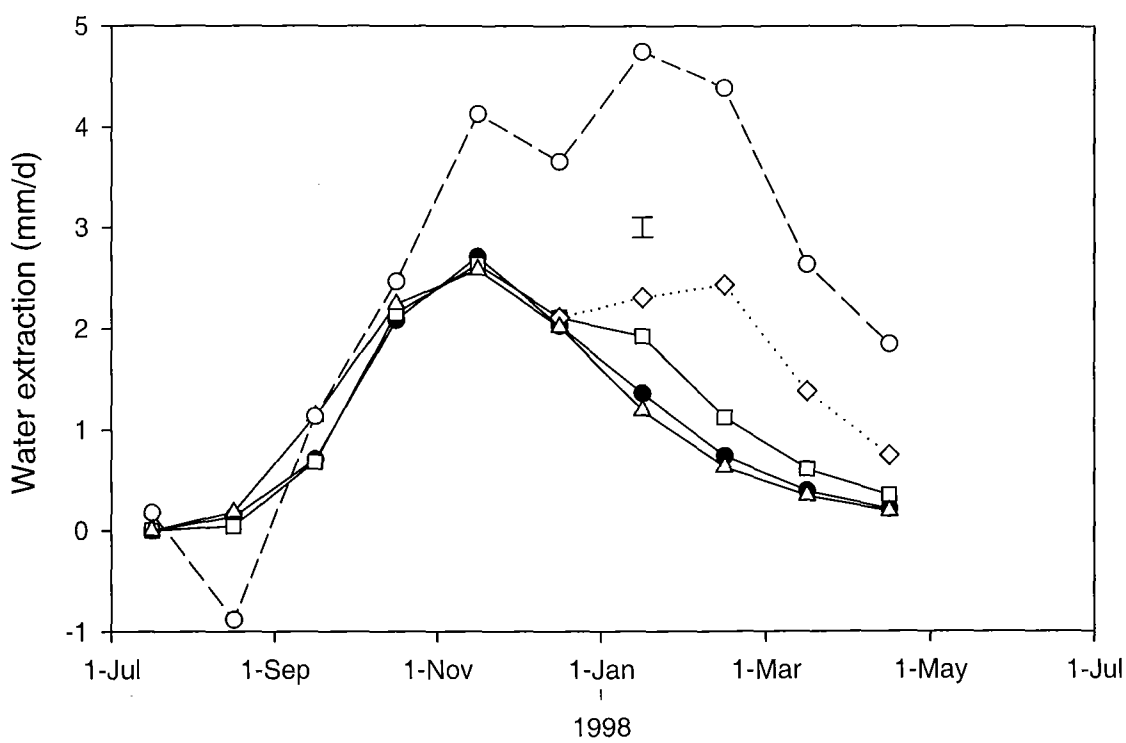
Figure 5.11 Monthly means of daily soil water extraction for chicory (—●—), lucerne (— —) and red clover (—△—) to 2.3 m depth, lucerne to 2.7 m depth (⋯⋯) and the monthly mean of daily rainfall deficit (−−○−−). Bar represents one LSD.

5.4   Discussion

The aim of this chapter is to explain why the dryland production of lucerne was greater than chicory and red clover (Chapter 4). The first step was to compare annual SWD and WU of the three species to give an indication of differences in water extraction and E_T.

5.4.1   Dry matter production in relation to water use

5.4.1.1   Soil water deficit and water use

Lucerne had a greater SWD than red clover and chicory in all but the wettest season (Table 5.1). This indicates a greater water extraction. Also rainfall receipts were the same for all three crops so this would also imply a higher WU. However, the increased water extraction potential of lucerne was offset by the failure of the soil profile to recharge to the DUL in the winter (Figure 5.2). Therefore, there was only a difference in WU (Table 5.2) in the wettest season ($I8_{99/00}$) where drainage in chicory and red clover meant WU appears to be greater than for lucerne (Figure 5.3). The values of WU also include evaporation losses, which confound species comparisons to explain the greater production of lucerne. The magnitude of these evaporation losses was expected to be smallest in $I8_{97/98}$ where precipitation was lowest (Table 3.1) and analysis of WUE in this season was expected to give a close representation of the crops E_T_eff.

5.4.1.2   Water use efficiency

The similar WU (Table 5.2) of the three species ($I8_{97/98}$) resulted in a higher WUE for lucerne and this was apparent during regrowth cycles 4–6 (February–May) in 1998 (Figure 5.4).   However, the most likely cause of this increased WUE is an underestimation of the actual WU. The extraction front of lucerne reached the bottom of the measured profile (2.3 m) in mid January (Table 5.3) and it is likely water was extracted below 2.3 m after this time. The relationship between DM production and WU (Figure 5.4) was used to give an indication of the amount of water extracted below 2.3 m with the assumption that the lucerne data from regrowth cycles 4–6 should sit on the same regression line as the other data points. This was achieved by adding 30 mm of extra WU to each of cycles 4 and 5 (Figure 5.4), which suggests an additional 60 mm of water was extracted by lucerne below the measured soil profile.

Another possibility is that lucerne did not extract more water below 2.3 m but had a higher WUE because it had lower evaporation losses and a higher proportion of WU was used for E_T. However, precipitation was <60 mm during the time when the differences in WUE occurred (Figure 3.2). Additionally, all crops were defoliated in common so the patterns of crop cover and its influence on the magnitude of evaporation differences between species would be expected to be small (Section 2.1.1.1). A further possibility is that lucerne actually had a greater E_T_eff. However, the WUE of lucerne was the same as chicory and red clover in the second and third regrowth cycles (Figure 5.4). This is consistent with literature, which also shows lucerne and red clover have the same E_T_eff (Badaruddin and Meyer, 1989; Briggs and Shantz, 1914).

5.4.2 Water extraction patterns

Another feature of a dry season is that a reduced proportion of E_T comes from in-season precipitation and more comes from soil water extraction below 0.2 m depth. Thus, comparison of water extraction patterns in low precipitation conditions gives an indication of differences in crop E_T and can be used to explain the cause of dryland production differences.

5.4.2.1 *Plant available water capacity*

Firstly, total water extraction was compared and lucerne had a total PAWC (358 mm) 30 mm higher that the chicory and red clover because it extracted more water than chicory and red clover below 1.6 m (Figure 5.10). Lucerne showed the same pattern in Iversen 9 where established lucerne had a PAWC of 363 mm (Figure 5.5). In both cases lucerne had a substantial PAWC in the bottom layer of the measured profile (2.3 m). It is likely that lucerne extracted additional 60 mm water below 2.3 m (Section 5.3.1.3). This would increase the PAWC of lucerne to 418 mm for the $I8_{97/98}$ season, which was 90 mm greater than chicory and red clover (Figure 5.10). This indicates the greater dryland production of lucerne was due to its greater extraction depth giving 90 mm more E_T that chicory and red clover.

The extraction depths reported are consistent with the literature where lucerne extraction often exceeds 2.3 m. For example, Kiesselbach *et al.* (1934) reported a water extraction depth of 4.5 m for lucerne compared with 1.8 m for red clover. The 1.9 m extraction depth of red clover was within the 1–3 m range reported by Frame *et al.* (1998a) and lucerne roots frequently exceed 2.3 m with one report of lucerne roots in a mine shaft 39 m below a lucerne field (Sheaffer *et al.*, 1988). To the knowledge of the author this is the first study of chicory water extraction to justify its reputation as a deep-rooted species (Hare *et al.*, 1987; Moloney and Milne, 1993). It is not known how deep lucerne extracted water from below 2.3 m depth. Assuming an additional 60 mm of water was extracted and a mean PAWC of 0.12 mm^3/mm^3 below 2.3 m (Section 5.3.1.3) equates to another 0.5 m extraction depth (adding to 2.8 m).

The PAWC was expected to decrease with depth (McKenzie *et al.*, 1990) due to decreasing plant root density (Bristow *et al.*, 1984; Evans, 1978). This was the case for the establishing lucerne crop where the total PAWC of 308 mm decreased to zero at 1.7 m depth (Figure 5.5). Soil texture also has an effect on lower PAWC. This is apparent in Figure 5.5 where the lower limit of $0.05 \text{ mm}^3/\text{mm}^3$ between 0.7 and 0.9 m is due to a sand layer at this depth. Sands usually have a low upper limit (Ratliff *et al.*, 1983) as well, but the layers of finer material underlying this layer would cause water to perch in the large pores of the sand (Section 3.1.2). This water is readily available for plant extraction (Webb *et al.*, 2000). A similar sand layer was encountered below 2 m depth (Figure 5.5) and this would explain why the PAWC was much higher at 2.3 m depth ($0.15 \text{ mm}^3/\text{mm}^3$) than in over-lying layers (i.e. $0.09 \text{ mm}^3/\text{mm}^3$ from 1.6–2 m depth), which assumedly have a higher root density. Hochman *et al.* (2001b) have published a series of PAWC expected for different crop/soil combinations for the use in simulation modelling in Australia. However, the high soil variability (Section 2.5.2.2) and the failure of the soils to return to DUL between growth seasons (Figure 5.2) reduces the generality of the PAWC for perennial crops on alluvial soils. This highlights the need for detailed descriptions of soil properties for precise studies of crop water relations on such soils.

The greater PAWC alone does not explain the greater dryland production of lucerne as the timing of water extraction and E_T are also important.

5.4.2.2   The 'Monteith framework' for perennials

A framework for describing the dynamic water extraction pattern of roots was presented by Monteith (1986) but this framework has not been validated for perennial crops. Therefore, this section compares the extraction pattern of establishing and perennial lucerne to assess the potential use of this framework for perennial species. The establishing lucerne crop in $I9_{00/01}$ started extracting water on 2 November 2000 and the extraction front progressed downward through the profile at 12 mm/d (Figure 5.7). The water content of each layer decreased exponentially from the start of extraction (Figure 5.6) and this was combined with EFV and PAWC to give a description of the seasonal water extraction pattern (Figure 5.9). The soil profile was partly recharged during the winter (Figure 5.5) and subsequently the perennial regrowth of lucerne ($I9_{01/02}$) displayed the same extraction pattern with an EFV of 15.6 mm/d. There was also an exponential decline in the soil water content after extraction started in each layer.

The models within the 'Monteith framework' gave good fits for both the exponential decline of θ_t (R^2 = 0.79–0.99) and the linear descent of the extraction front (R^2 = 0.64–0.98) for both the establishment and perennial regrowth seasons. These fits are comparable to the exponential (R^2 range 0.74–0.99) and linear models (R^2 range 0.88–0.99) reported for a wide range of annual crops (Dardanelli *et al.*, 1997; Meinke *et al.*, 1993; Robertson *et al.*, 1993b; Singh *et al.*, 1998; Thomas *et al.*, 1995).

Perennials already have roots present at depth and the physiological basis for the downward progress of water extraction must be different to that of annuals, where it is explained by the growth of the root system (Bland and Dugas, 1989; Robertson *et al.*, 1993c; Singh *et al.*, 1998). There are two possible mechanisms suggested for the downward movement of the extraction front in lucerne. Firstly, only the thick secondary roots, that have low water permeability (Kolek and Kozinka, 1992), are perennial. The fine (absorbing) roots have a short lifespan (Goins and Russelle, 1996) and die during periods of crop dormancy (Luo *et al.*, 1995). Thus, water extraction in spring requires renewal of fine roots. The downward progress of fine root initiation

would then result in downward progress of the extraction front, in a pattern analogous to annual crops.

A second possibility suggested by Sheaffer *et al.* (1988), is that water was preferentially extracted via the shortest path to the transpiring tops. However, this suggestion is inconsistent with a number of results that have shown constant water uptake over the depth of a rewetted soil profile containing active lucerne roots (Jodari-Karimi *et al.*, 1983; Kipnis *et al.*, 1989; Kohl and Kolar, 1976). Dirksen and Raats (1985) also showed the axial resistance to water movement in lucerne xylem (root length dependant) is negligible, compared with radial resistance (from soil to xylem) indicating path length does not have an effect on water extraction patterns.

Despite being unable to explain the exact mechanism of this occurrence these results show the 'Monteith framework' was suitable for the description of the perennial water extraction and highlights the top down pattern for chicory, lucerne and red clover.

5.4.2.3   *Comparison of extraction patterns*

All three crops (I8$_{97/98}$) started extracting water at the beginning of September and had the same EFV (Table 5.3), reaching 1.9 m depth by the start of January. They also had the same -kl indicating daily water extraction was the same from September–January (Figure 5.11). The extraction front of lucerne continued to descend reaching 2.3 m in February and probably proceeded to ~2.8 m by the end of April (Section 5.4.2.1). This was when lucerne accessed its greater PAWC and it was able to maintain greater daily water extraction than chicory and red clover from January–May. This period also coincided with the regrowth cycles 4–6 (Section 4.3.2) when lucerne had greater dryland yields than chicory and red clover (Figure 4.4). Thus, it is clear the dryland production advantage of lucerne came from a greater extraction depth giving greater crop E$_T$ during dry periods.

Daily water extraction was calculated for lucerne in Iversen 9 in the establishment and perennial regrowth seasons to demonstrate how differences in parameters (PAWC, EFV and -kl) influence water extraction patterns. The establishment season had a lower EFV

than the perennial season (Figure 5.7) but this was offset by a higher –kl (Figure 5.8) and PAWC (Figure 5.5). As a result water extraction increased from zero to 2.0 mm/d, 2 months after extraction started in both the establishment and regrowth seasons (Figure 5.9). The extraction rate increased to a maximum of ~2.7 mm/d in the establishment season, but low –kl values below 1.5 m depth meant extraction rates did not increase above ~2.0 mm/day from October–January in the perennial season. It is likely extraction below 2.3 m depth (Section 5.3.2.1) maintained water extraction at 2 mm/d during February. The abrupt decrease in water extraction rates at the end of the establishment season (Figure 5.9) is because of the low PAWC (Figure 5.5) of layers at the bottom of the profile (1.4–1.7 m depth). The PAWC was higher at the bottom of the profile (2.0–2.3 m) in the perennial season and this contributed more water extraction giving a gradual decline in water extraction rates.

5.4.2.4 *Water supply and demand*

The parameters from models fitted to water extraction patterns during continuous drying give a description of the water supply that the crops root system can provide its tops (Section 2.5.2). These parameters can be used in simulation models where water supply sets potential crop growth (Monteith *et al.*, 1989; Probert *et al.*, 1998b; Probert *et al.*, 1995). However the measured water extraction patterns may also be a result of water demand (Section 2.5.1) or crop control over water extraction (Ottman, 1999). These effects must be considered when adapting water extraction data into simulation model parameters.

The influence of crop water demand was displayed in Figure 5.11 where water extraction increased at the same rate as the rainfall deficit in cool periods at the start of the season (August and September). Crop cover also affects water demand (Monteith, 1986) and the effect of this on water extraction is displayed in Figure 5.8 with higher -kl values measured at times when the crop had full cover. These situations demonstrate data presented in this thesis cannot be readily used to indicate potential water supply for the crop/soil combination presented. This is because at times of defoliation and growth during cool periods crop demand is lower than potential water supply. Water extraction data from annual crops (no defoliation) grown under continual drying in the warm

season (higher atmospheric demand) is suitable for parametising potential water supply for crop modelling (Robertson *et al.*, 1993a) because demand is always greater than water extraction and therefore the potential water supply will be fully expressed.

The feedback of reduced water supply on subsequent water extraction was displayed in the rain-sheltered perennial regrowth ($I9_{01/02}$). The profile was not refilled to DUL by pre-season irrigation and roots were already present to 1.7 m depth (Figure 5.5) suggesting the PAWC could be rapidly extracted. The exclusion of all rainfall increased demand for water extraction from depth and it was expected the perennial crop would rapidly utilise the PAWC and become dormant for the remainder of the season. However, water extraction rate was no different to the establishment season for the first 2 months of extraction and became less than the establishment season after this time (Figure 5.9). The water extraction rate levelled off in December and this coincided with the expression of water stress in leaf area expansion (Figure 8.3) and DM production (Figure 8.2). The reduced leaf area reduces water demand, which reduces water extraction and reduced DM production may reduce root hair growth, which reduces water extraction. This demonstrates the feedback of previous water stress on measured water extraction, which must be considered if water extraction measurements are to be used to represent crop/soil supply potentials.

The onset of water stress and conservative water extraction occurred in December when there was still PAW in the soil profile. The reduction of growth rates to reduce demand and prolong water supply is referred to as a conservative water use strategy of lucerne to ensure water supply and persistence during dry periods (Dardanelli *et al.*, 1997). Hoffmann *et al.* (2003) has also demonstrated the conservative water use of lucerne and speculates it is a root signal reducing water uptake resistance by deep roots when upper soil layers become dry. The signal response reduced water use could also be stomatal control of transpiration demand or control over the presence of root hairs (Section 5.4.2.2). Another possibility is lower root densities at depth in soil profile are unable to supply sufficient water to meet crop demand. Throughout a continuous drying cycle the absence of rainfall additions to the topsoil layers mean the crop becomes water stressed and feedbacks gradually accumulate, reducing water extraction in deeper layers.

5.4.3 **Conclusions**

This chapter gives a description of the seasonal pattern of soil water deficit under chicory, lucerne and red clover crops and the annual water use calculated from this data. It also analyses the water extraction patterns of these three species to understand differences in dryland yields. Specific conclusions from this chapter are;

- Lucerne maintained a higher SWD (2.3 m depth) than chicory and red clover during the five seasons of this experiment but did not have a greater WU due to incomplete soil water recharge between growth seasons.

- Analysis of PAWC, considering likely water extraction below 2.3 m depth, indicated lucerne transpired ~90 mm more water than chicory and red clover in the 1997/98 season.

- The 'Monteith' water extraction framework fitted both annual and perennial crops well, showing it was suitable for describing water extraction patterns of perennial crops and highlighting the top down extraction pattern of chicory, lucerne and red clover during a growth season.

- The greater extraction depth of lucerne gave greater water supply than chicory and red clover from January–April when the extraction fronts of chicory and red clover reached their maximum.

The analysis presented in this chapter demonstrates the superior production of lucerne during periods water shortage was due to greater transpiration. This, along with the greater production of lucerne in the cool period of the spring and autumn contribute to the greater annual yields of dryland lucerne. The analysis of water extraction patterns also provides useful information on crop water supply during periods of water shortage. The aim of this thesis now concentrates on understanding how water shortages reduce lucerne yields. This is done by studying the influence of environment (solar radiation, temperature) on lucerne yield formation under non-limiting water conditions and then quantifying how water shortages affect these relationships.

6 Dry matter production and partitioning of lucerne

6.1 Introduction

The superiority in DM production and water extraction of lucerne over chicory and red clover was established in the previous two chapters. In Chapters 6–8 the focus is on examining the yield forming processes of lucerne in relation to the main environmental factors of solar radiation, temperature and water (Figure 6.1). Specifically the relationship between intercepted radiation and shoot yield (shoot RUE) is examined in this chapter, followed by an analysis of the components of radiation interception (R/R_o) in Chapter 7. The influence of water stress on RUE and R/R_o are then determined in Chapter 8.

In this chapter the null hypothesis (H_o) is that: the shoot RUE of lucerne is constant throughout a growth season. This is based on the generalisation used for annual crops, that shoot RUE is conservative in the absence of water or nutrient limitations (Sinclair and Muchow, 1999). However, this relationship usually only considers above ground DM. There is a growing body of literature that rejects this H_o for perennial crops and lucerne in particular (Section 2.3.2.3). Thus, any systematic variation in shoot RUE would indicate the alternative hypothesis (H_a) that: shoot RUE is not constant throughout a season. In this situation the change in shoot RUE needs to be examined in relation to seasonal changes that may influence total DM production and/or partitioning.

To examine these relationships shoot DM production and radiation interception were analysed from field (Iversen 8 and 9) measurements taken throughout a number of lucerne regrowth cycles over a number of seasons. An experiment was also conducted using lucerne grown in columns (Experiment 3) to give independent data to examine the seasonal pattern of DM partitioning between shoot and perennial organs. The remobilisation of DM from perennial organs to shoots may influence shoot production and shoot RUE (Figure 6.1). This phenomenon is difficult to quantify but treatments of different regrowth duration were imposed on the tube experiment to facilitate different levels of perennial reserve storage and potential for remobilisation. This enabled differences in shoot production to be attributed to differences in remobilisation.
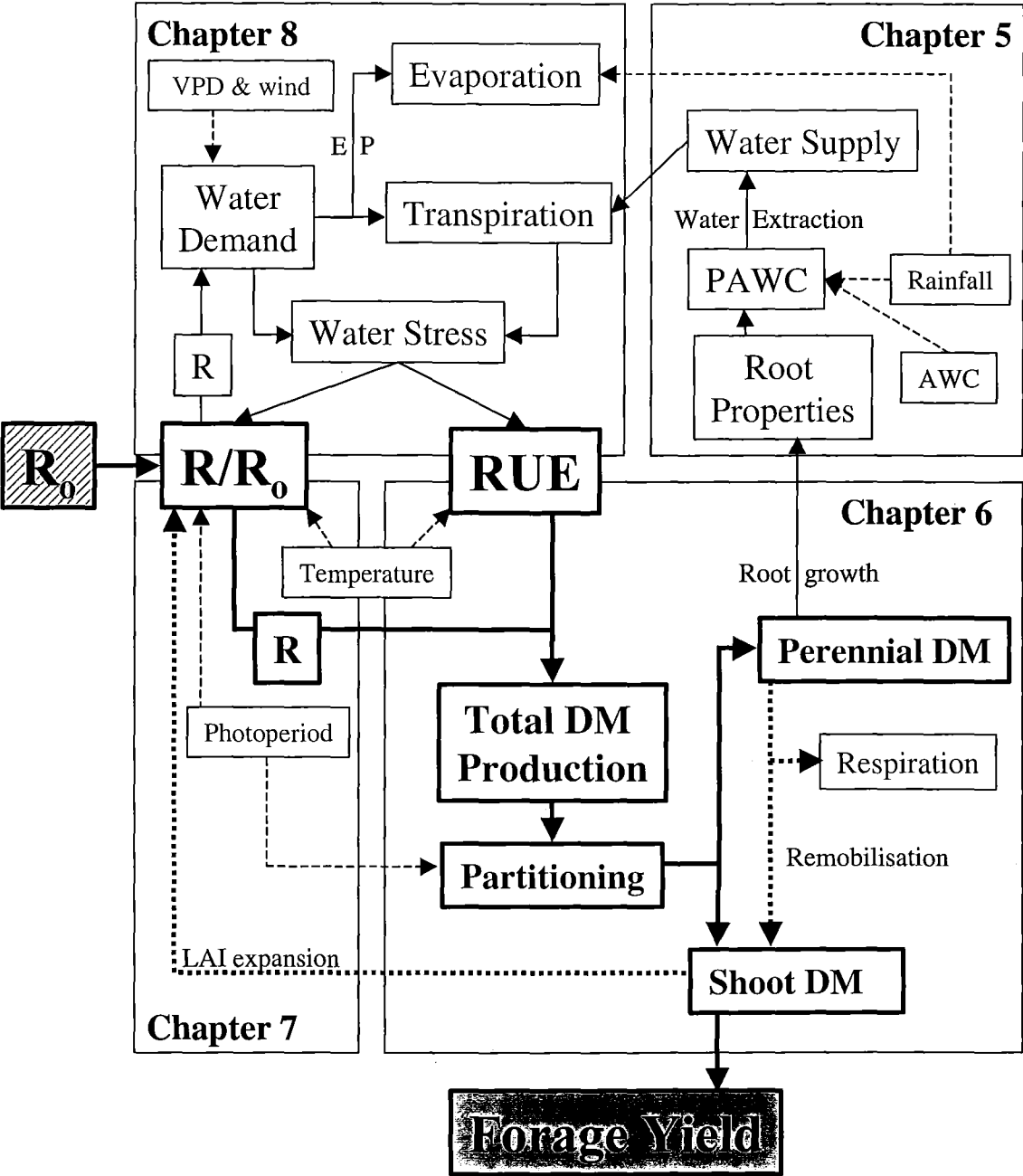
Figure 6.1 Flow diagram of the influence of environmental factors (grey hatched boxes) and crop processes (white boxes and arrows) on lucerne forage yield. Bold arrows and boxes represent processes that determine potential yield and dotted arrows are crop feedbacks on potential yield processes. The other processes display crop and environmental factors defining water shortage and their influence on the processes of potential yield. Grey boxes show the chapter in which the processes are dealt with.

Note: DM = dry matter, R_o = incident radiation, R = amount of radiation intercepted, RUE = radiation use efficiency, AWC = available water content PAWC = plant available water content, EP = potential evapotranspiration, LAI = leaf area index, VPD = vapour pressure deficit.

6.2   Materials and Methods

6.2.1   Shoot radiation use efficiency in the field

Dry matter production measurements (Section 3.3.2) were taken within individual regrowth cycles from $I8_{97/98}$–$I8_{01/02}$ (Section 3.2.1) and the first sowing date treatment in $I9_{01/02}$. Radiation interception was measured in $I8_{00/01}$, $I8_{01/02}$, $I9_{01/02}$ and extrapolated from the relationship between standing DM and R/R_o for $I8_{97/98}$–$I8_{99/00}$ (Section 3.3.5).

Shoot RUE for field experiments was calculated for individual regrowth cycles from harvested shoot DM and total radiation interception (g DM/MJ total radiation). Shoot DM was regressed as a function of accumulated radiation interception and the slope of the regression represented shoot RUE. Shoot RUE was calculated from the mean of three replicates for irrigated treatments (Section 3.2.1) for 36 individual regrowth cycles. The seasonal pattern of shoot RUE was examined by plotting values on the mid-point of the regrowth cycle.

6.2.2   Experiment 3: Column grown lucerne

Experiment 3 was designed to measure total DM production of lucerne, determine the seasonal pattern of DM partitioning between shoot (leaf and stem) and perennial organs (roots, crowns and crown stems) and the influence of partitioning on shoot RUE.

6.2.2.1   Establishment

Lucerne was grown in plastic columns, located in pits within a 20x15 m lucerne field. Six pits (1 m deep, 0.7 m wide, 1.4 m long) were excavated by shovel and a wooden retaining frame inserted. The bottom 0.2 m of the pit was back filled with course roading chip (SC16 Special) to provide a soak for water. The bottom of the pit was in a sandy layer of the soil profile and there were no problems of water ponding around the base of columns.

Columns were 0.8 m long, 0.15 m diameter PVC tubes with a woollen fabric ('Geotextile') wired over the bottom. Eight rows of four columns were arranged inside each pit (Plate 2) and filled with a 30% perlite, 70% sand mixture. Pits were prepared and columns arranged and filled with sand/perlite in December 2000. Twenty 'Grasslands Kaituna' lucerne seeds were sown per column on 2 January 2001, which were thinned to eight plants per column following emergence in February 2001 and thinned again to leave the three largest plants per column (100 plants/m^2) in March 2001. This experiment was designed to measure the perennial growth of lucerne and the period from sowing (2 January 2001) to 30 June 2001 was termed the establishment season and not analysed in this thesis.
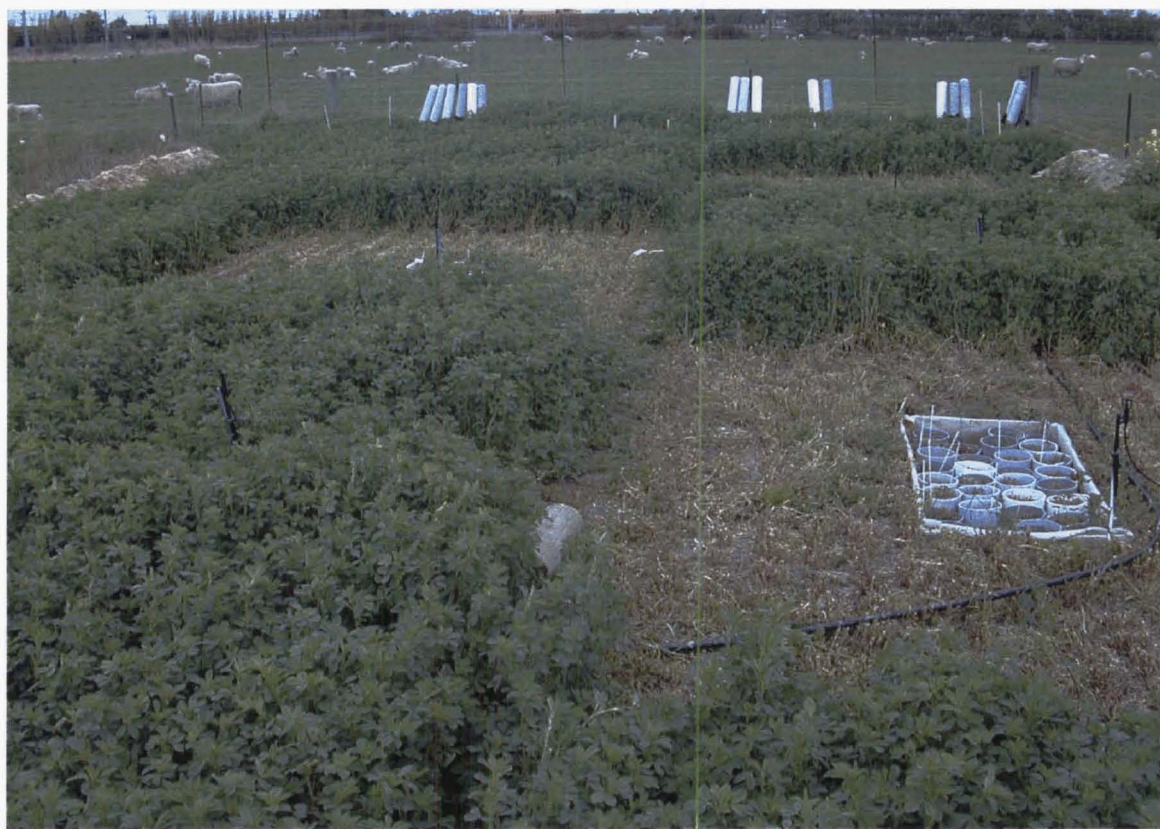
Plate 2. Experiment 3 with short regrowth treatments defoliated.

1.1.1.2 *Experimental*

Each pit represented an experimental plot and individual columns represented repeated destructive sample units within each treatment. There were two treatments of different regrowth cycle durations (short and long, Section 6.2.2.4) replicated in each of the three pits. Intensive repeated measurements were conducted in the perennial regrowth season from 1 July 2001 to 8 May 2002.

6.2.2.3 Irrigation

The maximum drained volumetric water content (θ) of the sand/perlite was 0.2 mm^3/mm^3 (determined from lab measurements) equating to a 160 mm water holding capacity for a 0.8 m column. Volumetric water content of the columns was monitored using 0.5 m TDR roads (Section 3.3.4) and irrigation was applied with the aim of keeping θ above 0.1 mm^3/mm^3. Irrigation was applied directly to each column with an open-ended hose. Flow was adjusted at the tap to 0.2 l/s so application amounts could be regulated by the time water was applied to each column.

6.2.2.4 Defoliation

Two defoliation frequencies were imposed to generate long and short regrowth cycles. The short regrowth cycles were implemented by defoliation when 50% of marked stems (Section 6.2.2.9) had initiated flower buds and the criteria for defoliation in the long duration was when 50% of stems had open flowers. Lucerne did not initiate flowers in the spring so the first regrowth cycle was conducted five days either side of the normal defoliation time in field experiments (25 September in short and 5 October in long regrowth duration treatments). Details of the timing of defoliation are given in Table 6.1. Columns were defoliated 50 mm above crown level with a set of hand shears and the buffer area surrounding the pits was mown.

6.2.2.5 Fertiliser

A basal fertiliser mixture was incorporated in with the sand/perlite (2.7 m^3) prior to putting the mixture into columns. This fertiliser consisted of 1.8 kg of superphosphate (0,9,0,12), 2.4 kg of Osmocote (0,0,37,0), 2.7 kg of dolmite lime and Micomax, which provides a slow release of all trace elements. This basal fertiliser was expected to last for nine months and subsequent fertiliser was applied in nutrient solution from October 2001 onwards. Nutrient solution was prepared by adding (in 20 ml aliquots) KH_2PO_4 (257 $\mu mol/l$), K_2HPO_4 (57 $\mu mol/l$), K_2SO_4 (502 $\mu mol/l$), $MgSO_4.7H_2O$ (234 $\mu mol/l$), $MgCl_2.6H_2O$ (246 $\mu mol/l$), $CaCl_2.2H_2O$ (784 $\mu mol/l$), $MnSO_4.5H_2O$ (10 $\mu mol/l$), $CuSO_4.5H_2O$ (1.0 $\mu mol/l$), $ZnSO_4.7H_2O$ (1.0 $\mu mol/l$), H_3BO_3 (3.1 $\mu mol/l$), $Na_2MoO_4.2H_2O$ (0.5 $\mu mol/l$), $CoSO_4$ (0.2 $\mu mol/l$) and Fe sequestrine (38 $\mu mol/l$) to 20 l

of water. Nutrient solution was applied at two weekly intervals at a rate of 100 ml per column and application was following irrigation to avoid leaching of nutrients.

Table 6.1 Regrowth timing and sampling intensity of irrigated column grown lucerne under short and long regrowth durations at Lincoln University, Canterbury, New Zealand.

		Regrowth	Date of Mid point	Date of defoliation	Interim samples	Columns per final sample
Short regrowth cycle treatment						
Establishment season				23-Mar-01	-	9
				14-Jun-01	-	3
Perennial season	*Spring*	*1*	*4-Aug-01*	*25-Sep-01*	*3*	*9*
		2	15-Oct-01	4-Nov-01	2	3
		3	23-Nov-01	12-Dec-01	1	3
	Summer	*4*	*27-Dec-01*	*11-Jan-02*	*1*	*9*
		5	30-Jan-02	19-Feb-02	2	3
	Autumn	*6*	*19-Mar-02*	*17-Apr-02*	*2*	*9*
		7	23-May-02	29-Jun-02	-	3
Long regrowth cycle treatment						
Establishment season				4-May-01	-	9
Perennial season	*Spring*	*1*	*21-Jul-01*	*7-Oct-01*	*3*	*9*
		2	1-Nov-01	27-Nov-01	2	3
	Summer	*3*	*19-Dec-01*	*10-Jan-02*	*2*	*9*
		4	6-Feb-02	5-Mar-02	2	3
	Autumn	*5*	*6-Apr-02*	*8-May-02*	*2*	*9*
		6	3-Jun-02	29-Jun-02	-	3

Note: - is displayed where destructive samples were only taken on the date of defoliation and no interim samples were taken. Three columns (one from each replicate) were sampled on each sampling occasion except on the defoliation of the first regrowth cycle spring, summer and autumn where nine columns were sampled (three from each replicate).

6.2.2.6   Dry matter sampling

Plants were cut 50 mm above crown and the harvested shoot material individually bagged, weighed and recorded for each identified column. This provided a yield history of each column that was used as a covariate for data stabilisation (Section 6.2.3.1).

Destructive samples were taken on each defoliation date and one–three interim occasions between defoliations (Table 6.1). For most destructive samples only one column was taken per replicate. However, three columns were taken for destructive samples at the time of defoliation in the first spring, summer and autumn regrowth cycles (Table 6.1). Columns were sequentially removed from the rows at the northern end of the pits to preserve the integrity of the canopy in the remainder of the columns.

Buffer columns were established at the same time as the rest of the experiment and were inserted into the pit in the place of the first row of columns as they were removed. These buffers were moved along the pit after the removal of columns from subsequent rows to ensure there was at least one row of buffer columns (not measured) at the northern end of each pit.

Sample columns were removed in the evening and stored in a chiller (4 °C) over night for dissection the following day. The 'Geotextile' fabric was removed from the base of each column and the contents, including whole plants with shoots attached, were slid into a large stainless steal shower tray. Whole plants were removed from the sand/perlite mixture and gently washed clean with cold water. The amount of fine root material left in the sand/perlite mixture after sampling was determined from a sub-sample (10% of whole sample) by decanting off the perlite and fine roots and then separating roots from perlite. Separation of roots from perlite was only conducted on a few occasions and fine roots represented a small fraction of total root DM (<5%).

6.2.2.7   Sample separation

All three plants from each sample column were separated into shoot and perennial fractions; shoot consisted of leaves, stems (above defoliation height) and basal buds. Perennial material was defined as crown stem (below defoliation height), crowns,

taproots and thick lateral roots. Fine roots were not considered as perennial material, because they may be shed during the season, and were removed from the root-system by pulling roots between thumb and forefinger. Any roots that could be stripped off with a gentle pull were excluded from perennial material. Dead material was excluded. Perennial material was cut into pieces (10–20 mm) with a set of hand prunners and samples were dried in a forced air oven at 70 °C for 24–48 hours when taproots and crowns were dry.

6.2.2.8 *Fractional radiation interception measurements*

Fractional radiation interception (R/R_o) was measured in each group of columns at 5–10 d intervals using a ceptometer (Delta-T devices LTD. 128 Low Road, Burwell, Cambridge CB5 0EJ, England). One measurement was taken above and three below the canopy near the centre of each pit to determine R/R_o. Measurements were taken near solar noon (12–1 pm).

6.2.2.9 *Node, bud and flower appearance*

Main-stems were marked on five plants from different columns at the start of each regrowth period and the number of nodes, buds and flowers (Section 7.2.1.3) were recorded 3–4 times per regrowth cycle. Marked stems were also observed (not recorded) frequently toward the end of regrowth cycles to determine when defoliation criteria had been reached (50% open bud or flower, Section 6.2.2.4).

6.2.3 Calculations for Experiment 3

6.2.3.1 *Data stabilisation*

Data from each of the three measurement dates, when three samples were taken per pit (Section 6.2.2.6), was used to establish the relationship between shoot DM production history and DM at the time of sampling. Shoot DM at the time of sampling from the nine individual columns was regressed against the sum of previous shoot production (not including the current regrowth). In contrast root DM at the time of sampling was regressed against previous shoot production including the current regrowth cycle. There

were strong linear relationships (mean R^2 = 0.80) with y-intercepts close to zero (Appendix 12) and this was used as justification for a linear transformation of measured DM production using production history as a covariate. This was achieved by the following steps;

1. For each regrowth cycle the mean shoot DM production was calculated for each replicate (pit) and shoot DM of individual columns was represented as a fraction of the mean. This gave a weighting factor for each column in each regrowth cycle (i.e. columns with shoot DM less than the mean attained a value less than one and vice versa).

2. For each column the weighting factors from each regrowth cycle were averaged to give a value representing the columns production history relative to the other columns in the same replicate.

3. Root and shoot DM values for each column were multiplied by the reciprocal of their mean weighting factor to remove column specific production differences.

6.2.3.2   *Converting column DM production to area scale*

All dry matter values were represented in kg DM/ha to be consistent with the rest of the thesis. There were 32 columns in each 1.4 x 0.7 m pit (32 columns/m^2) so DM values (g/column) were multiplied by 320 to convert to kg/ha. Root production was measured in a smaller area (within the columns), but it was assumed that production was limited most by aerial space (based on non-limiting water and nutrient supply) and the same factor (320) was used to convert root DM to kg/ha.

6.2.3.3   *Radiation interception*

Radiation interception (MJ total radiation/m^2) was calculated from fractional radiation interception (Section 6.2.2.8) and incident radiation (R$_o$) values (Section 3.3.5). Daily values of intercepted radiation (R) were summed to give accumulated radiation interception over the entire perennial growth season.

In most instances R/R_o measurements were too infrequent to produce an adequate description of the pattern of R/R_o within each regrowth cycle. To address this problem R/R_o was simulated daily for the duration of this experiment using the APSIM-Lucerne simulation model (Robertson *et al.*, 2002) to give the pattern of R/R_o for each regrowth cycle. This pattern was then adjusted to represent daily R/R_o by forcing simulated values to pass through measured values as follows; a forcing factor was calculated by dividing measured R/R_o by simulated R/R_o on the same day. Preceding values of simulated R/R_o (back to the previous measurement) were multiplied by the forcing factor so the simulated pattern passed through the measured values.

6.2.3.4   *Dry matter production and accumulation*

Shoot and perennial DM production were calculated independently for each measurement period as the difference between DM at the end of the period and the start. Shoot DM production for the first measurement period after a defoliation was assumed to start from zero. Shoot and perennial DM production (including periods of negative production) were added together to give total DM production. Dry matter accumulation was DM production summed over the entire perennial growth season.

6.2.3.5   *Radiation use efficiencies.*

Both shoot RUE and total RUE were calculated for both treatments by fitting a linear regression to DM accumulation (Section 6.2.3.4) against accumulated radiation interception over the entire perennial regrowth season. All RUE calculations use total solar radiation (g DM/MJ total radiation).

6.2.3.6   *Seasonal partitioning pattern*

The seasonal pattern of DM partitioning was calculated as the fraction of total DM production that was partitioned to shoots. This shoot fraction was calculated with DM production from the first (7–10 d after defoliation) to the final (at defoliation) DM measurement date within each regrowth cycle. This gave an indication of the fraction of new DM production that was partitioned to the shoot and perennial organs, but excludes the influence of perennial DM redistribution and loss, which was expected to

occur between defoliation and the point of first measurement (Section 2.3.2.1). A running mean of shoot fraction was calculated using the two defoliation treatments to give an estimation of the seasonal pattern of DM partitioning. This running mean was used to compare with field data, which experienced a regrowth duration approximately equal to the mean of the two treatments in Experiment 3.

6.2.3.7   *Node appearance*

Node appearance was measured (Section 7.2.1.3) on 3–4 occasions during each regrowth cycle for both defoliation treatments and regressed as a function of thermal time accumulation to calculate the phyllochron (Section 7.3.3.1).

6.2.4   Quantifying potential yield

A series of analyses were conducted using data from column (Experiment 3) and field grown lucerne (I8 and I9) to quantify the relationships that contribute to potential forage yield (Figure 6.1). These relationships combine to quantify shoot RUE variation throughout the season.

6.2.4.1   *Total DM production at optimal temperature (total RUE_{opt})*

The first stage of shoot production is the conversion of intercepted radiation to total DM (Figure 6.1). The relationship between total DM production and intercepted solar radiation was represented by a total RUE. This RUE may be influenced by temperature so initial calculations of total RUE were at optimal temperatures (RUE_{opt}). Optimal temperature was assumed to be during January/February when temperatures were highest (~17°C mean daily air temperature). The total RUE_{opt} was calculated from field measurements of shoot RUE (Section 6.2.1) during January/February (shoot RUE_{opt}). The shoot RUE_{opt} was then multiplied by the reciprocal of the fraction of total DM partitioned to shoots (Section 6.2.3.6) during January/February to give total RUE_{opt}. This total RUE_{opt} quantifies the relationship between intercepted radiation and total DM production and needs to be partitioned between shoot and perennial organs to quantify potential forage yield.

6.2.4.2   Shoot DM production at optimal temperature (shoot RUE_opt)

Shoot RUE_{opt} was calculated throughout the season to demonstrate the influence of seasonal variation in partitioning on potential shoot DM production. Shoot RUE_{opt} was calculated by multiplying the total RUE_{opt} by the running mean of the shoot fraction (Section 6.2.3.6) to produce a seasonal pattern. This incorporated the influence of solar radiation on total production and partitioning upon shoot DM production. However, temperature may also limit DM production (Figure 6.1) and this was determined by comparing the shoot RUE_{opt} with the shoot RUE measured over a range of temperatures in the field.

6.2.4.3   Temperature response of shoot RUE

Any differences between the calculated shoot RUE_{opt} and shoot RUE measured in the field were assumed to be due to temperature induced limitations to DM production. A residual analysis was carried out to reconcile the response of RUE to temperature. The measured shoot RUE was adjusted to remove an assumed temperature response, and determine if this response accounted for systematic differences between measured shoot RUE and shoot RUE_{opt}. The temperature responses of RUE used for adjustment assumed a linear increase in RUE by a factor of zero at 0 °C to unity at 18 °C (the highest regrowth cycle mean temperature recorded during this experiment). Temperature was represented by the regrowth cycle mean of daily mean air temperature (T_a) and shoot RUE values were adjusted using Equation 6.1:

Equation 6.1   adjusted shoot RUE = shoot RUE $* 18/T_a$

The temperature adjusted shoot RUE was compared with shoot RUE_{opt} to determine if the assumed relationship gave a suitable description of the influence of temperature on RUE.

6.3 Results

6.3.1 Shoot radiation use efficiency in the field

There was a strong relationship between radiation interception and shoot DM accumulation with a mean R^2 of 0.93 ± 0.07 for field measurements. The shoot RUE (Figure 6.2) was ~0.8 g/MJ from September–December. It then increased to ~0.95 g/MJ in January (circled values) followed by a decrease to ~0.4 g/MJ in March/April. Mean temperature increased from 8 °C in September to 17 °C in February and back to 8 °C in June. Clearly the shoot RUE was not constant and a linear regression fitted to the data had a slope less than zero (P<0.05). Thus, the H_o of a constant shoot RUE across the season was rejected.
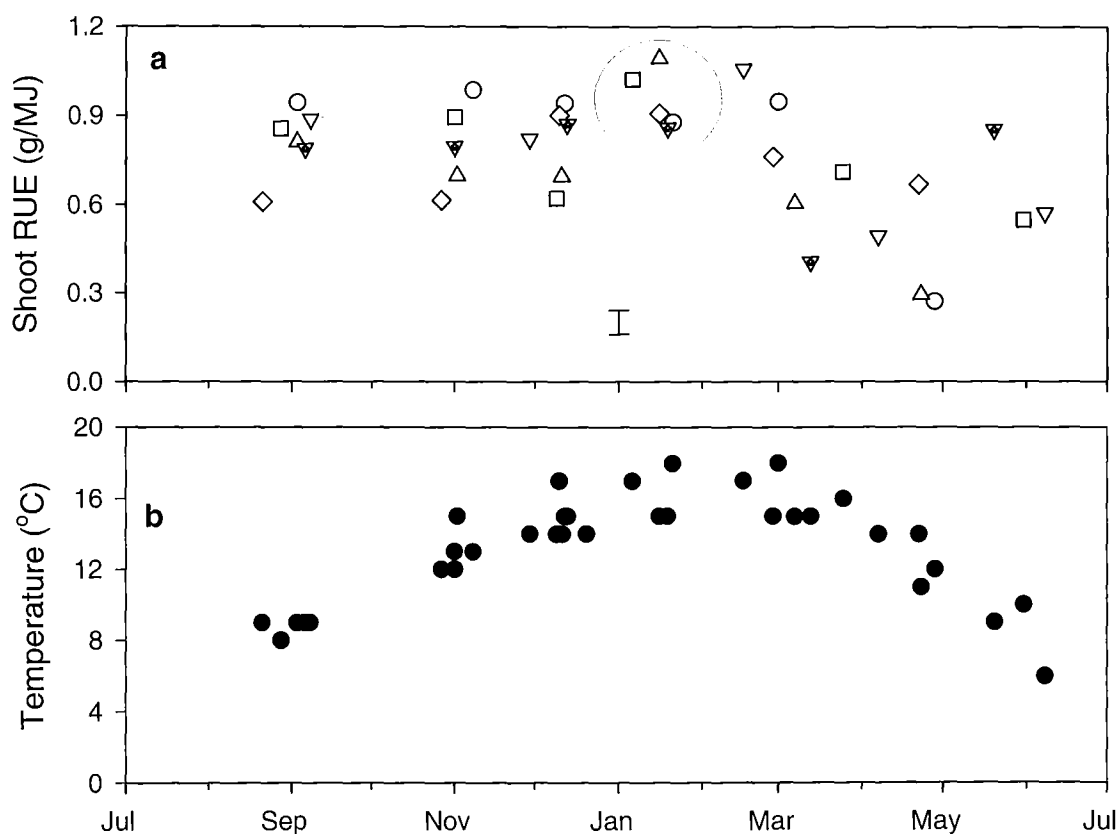
Figure 6.2 a) Shoot radiation use efficiency of irrigated 'Kaituna' lucerne grown in the field over five seasons (1997/98 to 2000/01) at Lincoln University, Canterbury, New Zealand. b) Mean regrowth cycle temperature (●).

Note: The circled values were averaged to give a shoot RUE for the period of highest temperature prior to the autumn decline. The bar represents the pooled standard error of shoot RUE from fitted regressions. Different symbols represent measurement season and experiment (Table 3.3).

6.3.2   Total dry matter production and partitioning (Experiment 3)

6.3.2.1   *Observed dry matter*

Short regrowth cycles had an annual shoot production of 16.7 t DM/ha producing between 2.0–3.0 t DM/ha of shoot in the first six regrowth cycles and an additional 1.0 t DM/ha in the final regrowth cycle (Figure 6.3). There was one less cycle in the long regrowth treatment but the first four of these yielded 4.0–5.0 t DM/ha with 2.0 and 1.0 t DM/ha in cycles 5 and 6 (respectively) giving an annual shoot yield of 22.0 t DM/ha.
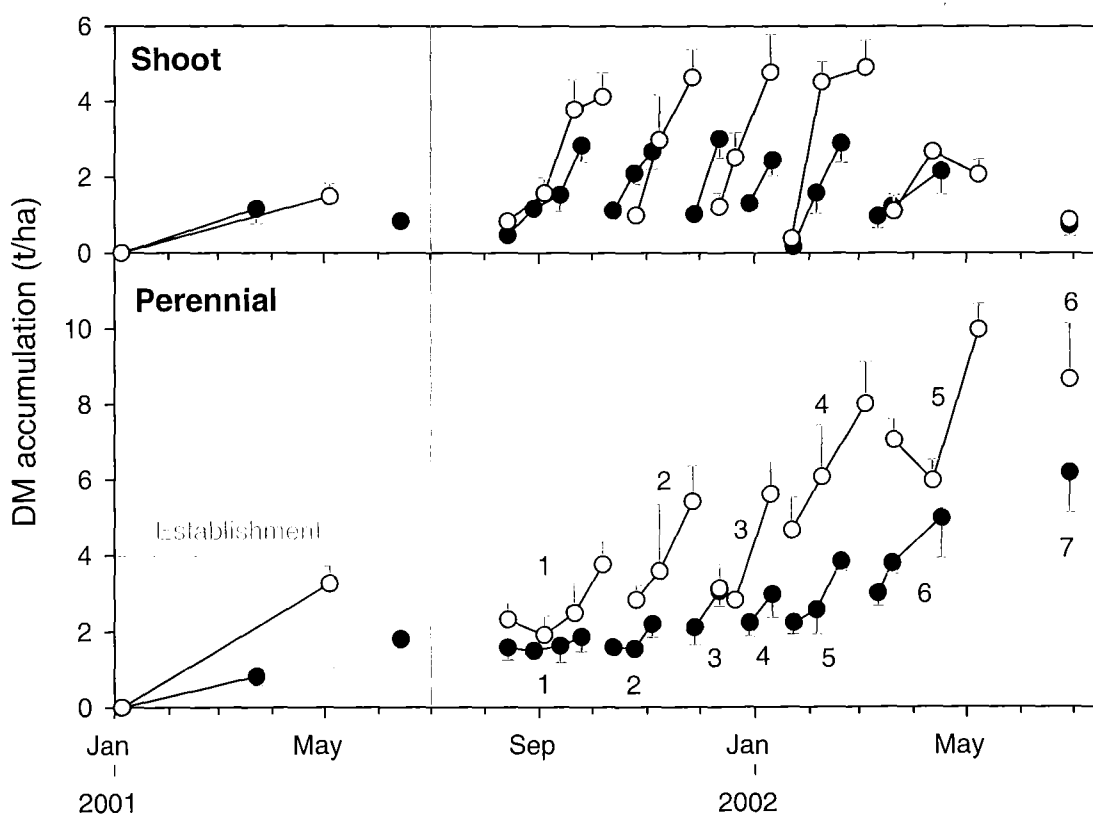
Figure 6.3 Shoot and perennial dry matter (DM) accumulation of irrigated lucerne grown in isolated columns under short (●) and long (○) regrowth durations during an establishment and perennial regrowth season at Lincoln University, Canterbury, New Zealand.

Note: Breaks in the data set represent defoliation. Bars above or below data points represent one standard error.

A distinct pattern was apparent in perennial DM production in the perennial regrowth season (Figure 6.3). There was always a reduction in perennial DM from the time of defoliation of one regrowth cycle to the first (and sometimes second) measurement of the following regrowth cycle. For example, perennial DM in the long regrowth treatments decreased from 4.0 t DM/ha at the end of the first regrowth cycle (7 October 2001) to 3.0 t DM/ha at the subsequent measurement, 19 d later. Perennial DM decreased by 1.0–2.0 t DM/ha after each defoliation in the long regrowth treatment but only 0.3–1.0 t DM/ha in the short. Each reduction was followed by an increase in perennial DM to a higher value than at the end of the previous regrowth cycle. The long regrowth cycles produced 1.5–3.5 t DM/ha in the later part of each regrowth cycle reaching a perennial DM of 10.0 t DM/ha by May in the perennial regrowth season. Short regrowth cycles produced 0.3–2.0 t DM/ha in the later part of each regrowth cycle leading to a perennial DM of 5.0 y DM/ha in May.

6.3.2.2 *Fractional radiation interception*

The pattern of simulated R/R_o in each treatment is displayed in Figure 6.4 along with the measured values and the adjusted pattern that was used for calculating accumulated radiation interception. Simulations gave a good description of the pattern of R/R_o for the first five short regrowth cycles. However, simulations under predicted the increase in R/R_o for long regrowth cycles and needed to be adjusted up for the first four regrowth cycles. Simulations gave an overestimate on R/R_o during March/April and had to be adjusted down for both treatments.
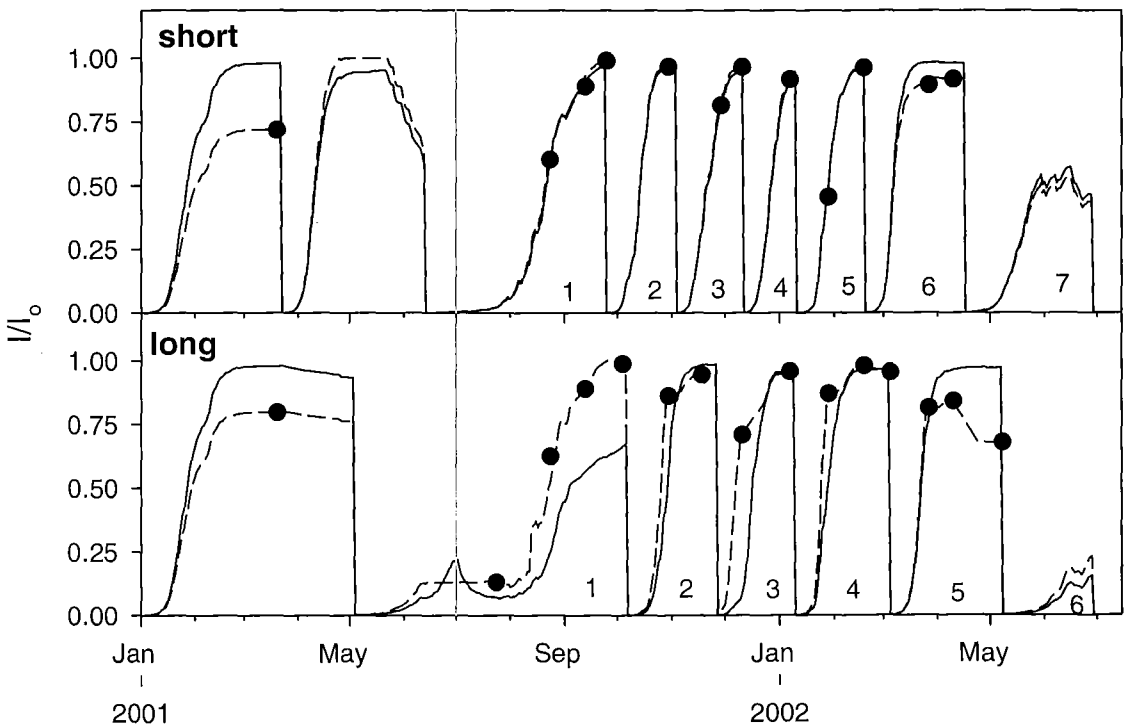
Figure 6.4 Fractional radiation interception (R/R_o) measured (●), simulated (———) and adjusted (– – – –) over short and long regrowth cycles for irrigated lucerne grown in grouped columns at Lincoln University, Canterbury, New Zealand. Numbers refer to regrowth cycles.

6.3.2.3   Total and shoot RUE

There was a strong linear relationship between accumulated DM production and radiation interception ($R^2 = 0.99$) during the perennial regrowth season (Figure 6.5). The short regrowth duration treatment had a greater ($P<0.05$) shoot RUE (0.84 g/MJ) then long treatments (0.78 g/MJ), but there was no difference between total RUE (1.0 g/MJ). The difference between shoot and total RUE indicated that the long defoliation treatment retained 22% of net DM production as perennial material compared with 14% for short the defoliation treatment.
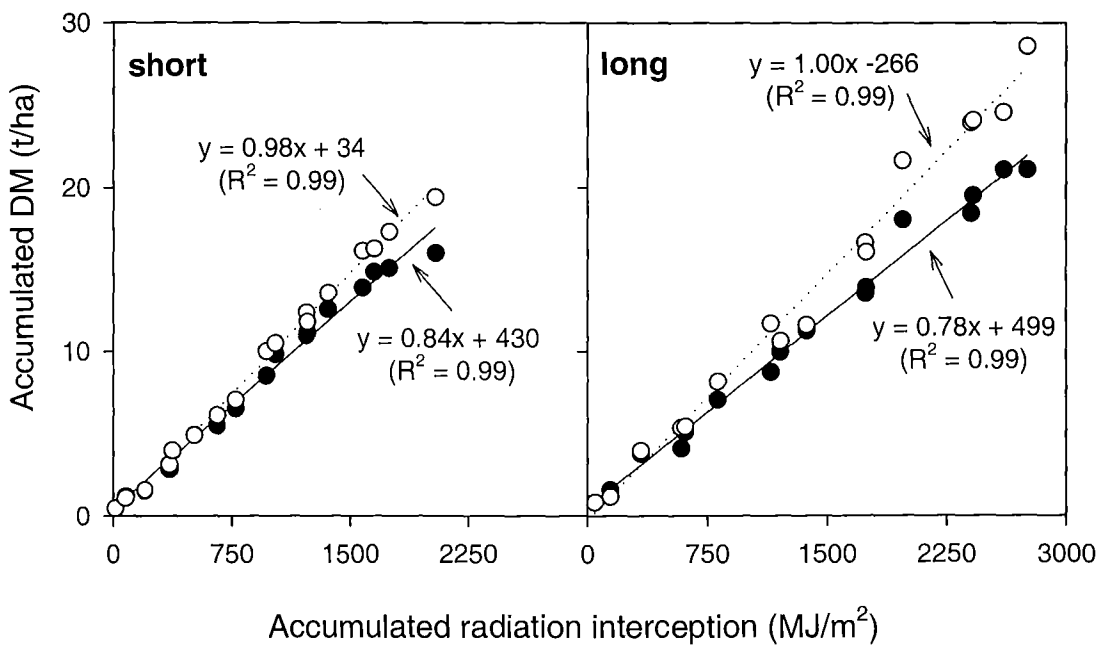
Figure 6.5 Accumulated shoot (●) and total (○) dry matter (DM) in relation to accumulated total solar radiation interception of irrigated lucerne grown in isolated columns under short and long regrowth durations at Lincoln University, Canterbury, New Zealand. The slope of the regressions represent the RUE (g/MJ).

6.3.2.4 Seasonal partitioning pattern

The measurements from Experiment 3 showed a distinct seasonal pattern in the fraction of total DM production (Section 6.2.3.6) that was partitioned to shoots (Figure 6.6). Specifically, the shoot fraction of the short regrowth treatment was 0.9 in the first regrowth cycle, decreased to 0.6 in December/January and decreased again to 0.4 in March. The long regrowth treatments followed a similar seasonal pattern but shoot fractions were consistently lower than those of the short regrowth treatments.
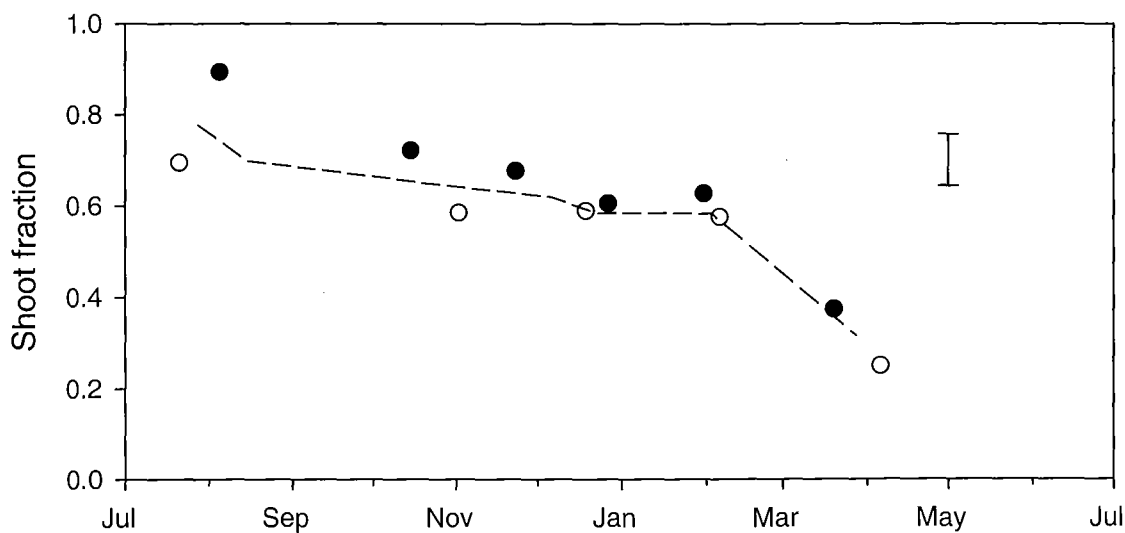
Figure 6.6 Shoot fraction of total dry matter production for irrigated lucerne grown in isolated columns under short (●) and long (○) regrowth durations at Lincoln University, Canterbury, New Zealand. – – – – is a running mean from both treatments and the bar represents the pooled standard error.

6.3.2.5   Seasonal phyllochron pattern

The phyllochron of both treatments was ~30 °Cd from September–February but showed a substantial increase (~60 °Cd) in March (Figure 6.7).
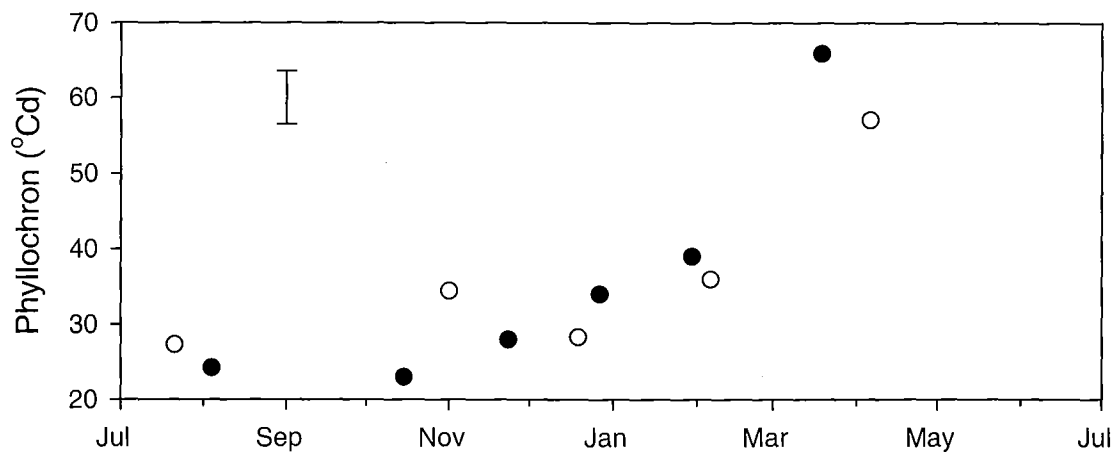
Figure 6.7 Phyllochron of irrigated lucerne grown in isolated columns with short (●) and long (○) regrowth durations at Lincoln University, Canterbury, New Zealand. Bar represents pooled standard error.

6.3.3   **Quantifying potential yield**

6.3.3.1   DM production at optimal temperature (total RUE$_{opt}$)

The potential DM production of a lucerne crop at optimal temperature was described by a total RUE$_{opt}$ of 1.6 g/MJ. This was calculated from a shoot RUE of 0.95 g/MJ measured in the field during January when temperatures were highest (Figure 6.2), multiplied by the reciprocal (1.70) of the shoot fraction of 0.6 that was measured at the same time in the column experiment (Figure 6.6).

6.3.3.2   Shoot DM production at optimum temperature (shoot RUE$_{opt}$)

The potential shoot production of lucerne at optimal temperature was described by the seasonal pattern of shoot RUE$_{opt}$ (total RUE$_{opt}$ * shoot fraction), which decreased from 1.4 g/MJ in September to 1.0 g/MJ in December/January and decreased abruptly to 0.6 g/MJ in mid March (Figure 6.8).

6.3.3.3   Temperature response of shoot RUE

The measured shoot RUE was lower than the shoot RUE$_{opt}$ from September–December indicating a possible temperature limitation (Figure 6.8). The shoot RUE adjusted for a linear temperature response (Section 6.2.4.2) was ~1.7 g/MJ in August/September, decreased to ~1.0 g/MJ from November–February and decreased abruptly during February to ~0.6 g/MJ in March/April (Figure 6.8). These values followed the seasonal pattern of shoot RUE$_{opt}$ closely except in September when the temperature adjusted shoot RUE was higher than the shoot RUE$_{opt}$. The temperature adjustment reduced the residual mean square difference to 29% of the observed mean RUE compared with 63% for the unadjusted values
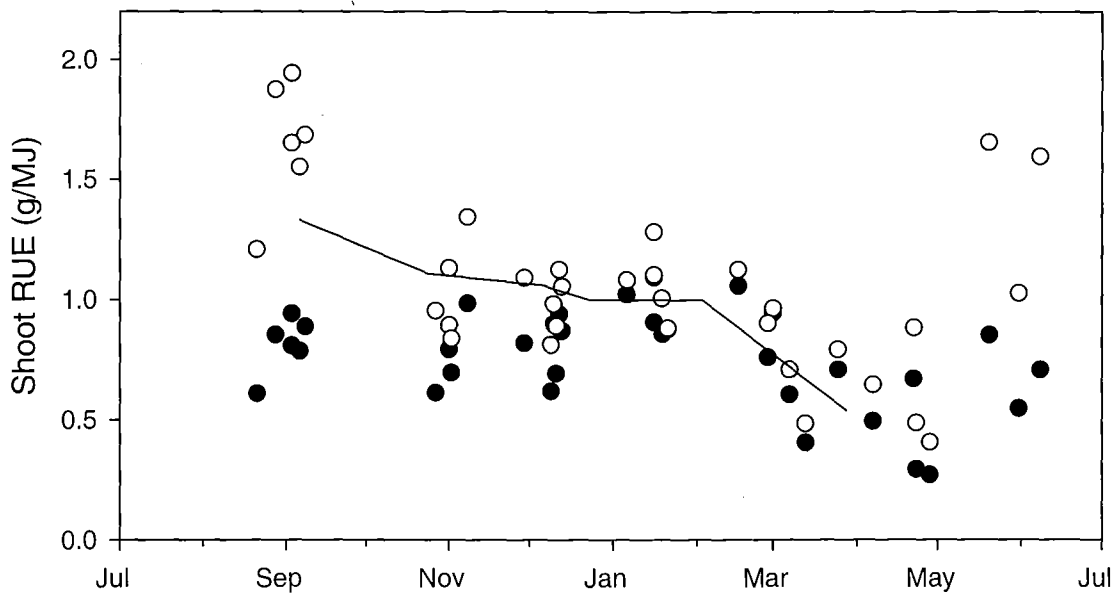
Figure 6.8 Measured (●) and temperature adjusted (○) shoot radiation use efficiency (RUE) observed in the field and shoot RUE$_{opt}$ (———) calculated for irrigated lucerne at Lincoln University, Canterbury, New Zealand.

Note: Shoot RUE$_{opt}$ is the shoot RUE calculated assuming no temperature limitations (Section 6.2.4.2) and the temperature adjustment of field measured RUE is described in Section 6.2.4.3.

6.4 Discussion

The aim of this chapter was to quantify the potential forage (shoot) yield of lucerne by defining the relationship between radiation interception and shoot DM production. This can then be combined with radiation interception to quantify actual forage yield. Furthermore, the influence of water shortage can then be explained by quantifying the effect of water stress on these processes (Figure 6.1).

6.4.1 Potential shoot yield

Shoot RUE changed throughout each growth season (Figure 6.2), which tends to a rejection of H_o (Section 6.1). This contrasts Sinclair and Horie (1999) who advocated the use of a constant RUE for quantifying annual crop production. The changing shoot RUE indicated temperature limited DM production and/or changes in partitioning influenced shoot production of lucerne (Figure 6.1). It is then necessary to quantify the environmental responses of these processes to quantify the seasonal pattern of shoot RUE. The following three sections discuss the three steps used to quantify the influence of environment on potential forage production (Section 6.2.4).

6.4.1.1 *The influence of radiation on total DM production*

The first step was to quantify the relationship between total DM production and radiation interception. A total RUE_{opt} of 1.6 g/MJ was derived (Section 6.3.3.1) and this value was assumed to represent the potential total DM production excluding temperature limitations and respiration losses. These assumptions are justified by the calculation of total RUE_{opt} from a shoot RUE of 0.95 g/MJ collected in the field during January/February over five growth seasons (Figure 6.2). This was the warmest time of the year and it was assumed the temperature was optimal for lucerne growth. This value of shoot RUE was then adjusted to include root production by multiplying by the reciprocal of the shoot fraction (Figure 6.6) at the same time of the year. The shoot fraction was calculated from the first measurement period (10–14 d after defoliation) to the end of the regrowth cycle and was assumed to exclude the influence of respiration associated with the initiation of regrowth shoots following defoliation (Section 2.3.2.2).

The total RUE_{opt} of 1.6 g/MJ is high compared with other C_3 species, which have a RUE ranging from 0.8–1.4 g/MJ under optimal conditions (Sinclair and Muchow, 1999). However, most RUE values exclude root production. Assuming roots account for 20% of total production this range increases to 1.0–1.7 g/MJ. Leguminous crops tend to have a lower RUE than other crops (Sinclair and Horie, 1989), but other authors have reported lucerne CO_2 exchange rates similar to C_4 species (Asseng and Hsiao, 2000; Loomis and Connor, 1992; Varella, 2002). This indicates lucerne is capable of high assimilation and justifies the high total RUE_{opt} (Section 2.3.1.1). The only other report of total RUE of lucerne was a constant value of 1.15 g/MJ for regrowth periods in the summer and autumn (Khaiti and Lemaire, 1992). This suggests total RUE is constant for each regrowth period, but unfortunately the authors did not present temperature data to determine it RUE was restricted by low temperatures.

Given a potential total RUE of 1.6 g DM/MJ of total solar radiation intercepted, the influence of partitioning on shoot RUE can be examined to explain seasonal variation in potential shoot production.

6.4.1.2 *The influence of partitioning on shoot production*

Partitioning was displayed by the shoot fraction, which represents the percentage of DM partitioned to shoots between the first measurement point (10–14 d after defoliation) and the subsequent defoliation. There was a distinct seasonal pattern of DM partitioning (Figure 6.6) with ~80% of total DM production partitioned to the shoots during September. This decreased throughout the season to about 60% in January and then showed a substantial decline to ~35% in March. The second step in quantifying seasonal variation in shoot RUE (Section 6.2.4) is to quantify the influence of this partitioning pattern on DM production. This was done by multiplying total RUE_{opt} by the running mean of the shoot fraction to give a seasonal pattern of shoot RUE_{opt}. The resulting shoot RUE_{opt} decreased from a maximum of 1.4 g/MJ in September to ~1.0 g/MJ in January and then dropped sharply to ~0.5 in March (Figure 6.8). This abrupt decrease in shoot RUE in autumn is consistent with Khaiti and Lemaire (1992) who measured a decrease in shoot RUE from 0.9 g/MJ in summer to 0.6 g/MJ in autumn as a result of a decrease in DM partitioned to shoots from 80% in summer to

45% in autumn. A number of other authors have also demonstrated a reduced shoot RUE of lucerne in the autumn (Section 2.3.1.1).

The greater partitioning of reserves to perennial organs in the autumn is a well documented phenomenon for lucerne (Section 2.3.2.2). It is the result of perennials needing to have sufficient reserves to survive the winter and initiate new shoots in the spring. The influence of the reduced shoot RUE on potential forage production was displayed by lower autumn growth rates at the same temperature in the spring/summer (Figure 4.6). There are a range of examples of reduced lucerne shoot production in the autumn that have been published (Chen *et al.*, 2003; Fick *et al.*, 1988; Smeal *et al.*, 1991). The higher potential shoot production in the spring is not well documented although it is expected the yield of lucerne crops will be greatest in spring rotations and decrease in summer and autumn regrowth periods (Frame *et al.*, 1998a).

The seasonal pattern of partitioning can be used to quantify the influence of partitioning on potential shoot production (shoot RUE_{opt}) and the change in the partitioning process is probably related to photoperiod. It was not possible to determine the environmental response for certain, but evidence of the influence of photoperiod on partitioning may be taken from other perennial crops. For instance, seasonal variation in partitioning patterns of asparagus have been related to photoperiod (Woolley *et al.*, 2002). These authors showed a substantial increase in perennial DM production when photoperiod decreased below 14 hours in the autumn.

6.4.1.3   The influence of temperature on RUE

The third step in quantifying the seasonal variation in shoot RUE was to determine the influence of temperature on potential production (Figure 6.1). A temperature limitation on DM production will be displayed by a decrease in total RUE and (assuming temperature has no influence on DM partitioning) an equivalent decrease in shoot RUE. Thus, the extent of temperature limitations was determined by comparing shoot RUE_{opt} with shoot RUE measured in the field. Shoot RUE_{opt} followed the same pattern as shoot RUE measured in the field from January to March (Figure 6.2) indicating temperature had a minimal influence on DM production during this time of the season. However,

shoot RUE$_{opt}$ was higher than shoot RUE measured in the field from September–December suggesting temperature was limiting RUE at this time.

The temperature response was quantified by adjusting shoot RUE values measured in the field for an assumed linear increase in response to temperature using a factor that increased from zero at 0 °C to unity at 18 °C. This gave a seasonal pattern of shoot RUE that closely resembled the shoot RUE$_{opt}$ (Figure 6.8) and suggests the potential production of lucerne could be quantified by a total RUE that increases from 0 g/MJ at 0 °C to 1.6 g/MJ at 18 °C. Mean regrowth period temperatures did not exceed 18 °C during this experiment but it was assumed that 18 °C was optimal and RUE would remain at 1.6 g/MJ until an upper optima (>18 °C) was reached. This can be combined with the seasonal partitioning pattern to quantify shoot RUE and potential forage yield during the season.

The temperature adjusted shoot RUE was still lower than the shoot RUE$_{opt}$ (Figure 6.8) in September. This may be due to the use of mean daily temperature over the whole regrowth cycle giving too much weight to the low temperature period at the start of the cycle (Figure 3.3). Another possibility is the partitioning of DM to the shoots in the field was greater than the 80% measured in the columns in Experiment 3.

The influence of the temperature response of potential shoot production was demonstrated in Figure 4.6 where linear growth rates increased with temperature as a result of the increased RUE. Radiation use efficiency is related to net assimilation (Monteith, 1977) and justification of the temperature response of RUE can be taken from net assimilation which was expected to rise over low temperature ranges (Section 2.3.1.2). Further justification of a temperature response is given by Wilson *et al.* (1995) who used a temperature response in RUE to simulate maize production in Canterbury. However, other authors have shown no temperature response in RUE and in a detailed review of the topic Sinclair and Muchow (1999) did not mention it as a factor that influences annual crop production. Similarly, Khaiti and Lemaire (1992) stated total RUE was insensitive to temperature, but did not report the range of temperatures experienced. Jamieson *et al.* (1998c) had no need to use a temperature limitation on

RUE to simulate wheat growth in Canterbury, but it may not be valid to compare wheat (cool season annual) with lucerne (warm season perennial).

The simulation model APSIM-lucerne (Robertson *et al.*, 2002) quantifies potential shoot production using a shoot RUE that reaches an optimum at 10 °C. This temperature response is based on the temperature response of wheat (Section 2.3.1.2) and is justified in model validation because a higher temperature optimum under-estimates spring-time production in cool areas (M.J. Robertson, personal communication). However, APSIM does not account for seasonal changes in partitioning and Figure 6.8 demonstrates spring-time production may be predicted accurately if both temperature and partitioning are accounted for in shoot RUE values.

6.4.2   The influence of perennial dry matter on shoot production

The utilisation of perennial DM to initiate new regrowth also influences shoot production (Figure 6.1).

6.4.2.1   *Perennial DM consumption*

The long regrowth treatment accumulated a greater root mass than the short rotations (Figure 6.3). This indicated a greater reserve of carbohydrate and amino acids for initiating regrowth (Section 2.3.2). For the long regrowth treatment, the decrease in perennial DM was 1.0–2.0 t DM/ha between defoliation and the first measurement period (10–14 d later) compared with 0.3–1.0 t DM/ha for short regrowth treatments. This indicated the long regrowth treatments utilised more perennial reserves to initiate the subsequent regrowth. Perennial reserves were accumulated in the latter part of a regrowth period (Section 2.3.2.2) and the long regrowth treatment had a longer duration for accumulation of perennial reserves.

The utilisation of perennial DM may be a result of remobilisation of nitrates and carbohydrates to the shoots or respiration losses for maintaining root function (Khaiti and Lemaire, 1992; Ta *et al.*, 1990). The resolution of measurements in Experiment 3 was insufficient to determine the fate of perennial DM but the additional reserves

increased subsequent shoot production regardless of whether it was respiration or remobilisation. This remobilisation increased shoot production above that possible from fresh assimilation by the shoots and thus increased the shoot RUE early in the regrowth cycle. The utilisation of perennial reserves for respiration could also increase shoot production and RUE. This would occur if the respiratory cost of maintaining the function of perennial organs was met by reserves and not fresh assimilate. This would allow more fresh assimilation to be retained in the shoots thus increasing shoot RUE.

The influence of perennial DM consumption on potential shoot production was indicated by the different defoliation treatments in Experiment 3. The clearest demonstration was given in Figure 6.3 where both the long and short treatments were defoliated on 11 January 2002. In the subsequent regrowth cycle the long treatments rapidly produced 5.0 t DM/ha of shoots by the mid February compared with only 3.0 t/ha for the short treatment at the same time. This greater production was attributed to the greater perennial reserves available for initiating regrowth and utilisation of these reserves to give higher shoot RUE at the beginning of the regrowth cycle.

As a consequence, the long regrowth treatment increased R/R_o faster following defoliation (Figure 6.4) due to the greater production of shoots giving faster canopy expansion (Figure 6.5) and subsequent DM production. The flow on effect was that the greater DM production of the long treatment indicates there was more assimilate available for the replenishment of perennial reserves leading to greater shoot production at the start of the subsequent regrowth cycle and so the cycle goes on. Conversely, the short regrowth treatment was unable to accumulate substantial perennial reserves. This limited the rate of early regrowth shoots and the ability of the crop to establish reserves for the following regrowth cycle. The overall consequence of this was an annual production of 22 t DM/ha in the long regrowth treatment compared with 16.7 t DM/ha in the short treatment.

6.4.2.2 *Respiration losses*

Between 20 and 65% of total DM production was partitioned to perennial organs between the first measurement point and defoliation. However, long-term perennial DM production will be less than this due to respiration losses 10–14 d after defoliation. It was not possible to calculate the extent of these losses for an individual regrowth period. However, it was possible to estimate them for the duration of the season. This was done using the total RUE_{opt} (Section 6.3.3.1) to represent the gross production of lucerne. The DM accumulations presented in Figure 6.5 were adjusted to remove temperature limitations using Equation 6.1. The slope of the adjusted relationships (temperature adjusted RUE) was then used to represent the net DM production (Table 6.2). This value included perennial DM that was remobilised into shoots and conserved in total DM values but excludes perennial DM lost to respiration. Therefore the difference between these two values represents the total production lost to respiration during the initiation of regrowth. Values were 0.3 g/MJ (Table 6.2) for both treatments. This represented a 19% loss of total DM production by respiration from perennial organs following defoliation. The long treatments had a greater total DM production and fewer defoliation/regrowth cycles so respiration and its influence on shoot production were greater for individual regrowth cycles in the long regrowth treatment (Section 6.4.2.1).

Table 6.2 Radiation use efficiency (RUE) of various fractions of column grown lucerne assuming optimal temperature.

RUE (g DM/MJ)	Calculation	Short	Long
Total RUE_{opt}	A[!]	1.6	1.6
temperature adjusted total RUE	B[*]	1.3	1.3
respiration loss	A–B	0.3	0.3
temperature adjusted shoot RUE	C[*]	1.05	0.95
gross root RUE	A–C	0.55	0.65
net root RUE	B–C	0.25	0.35

Note: ! The calculation of total RUE_{opt} is described in Section 6.2.4.1. * temperature adjusted RUE represents the slope of the relationships presented in Figure 6.5 with DM accumulation adjusted to remove temperature limitations using Equation 6.1.

Total (gross) root production can be represented by the difference between total RUE_{opt} and temperature adjusted shoot RUE. This was 0.55 and 0.65 g/MJ for short and long regrowth treatment respectively (Table 6.2). The greater root production in the long treatments was a result of the prolonged regrowth cycle allowing more DM partitioning to the roots at the end of the regrowth cycle. It is also important to highlight the influence of this partitioning on shoot RUE, such that the higher shoot RUE in the short treatment (Figure 6.5) is a result of less DM being partitioned to the roots rather than a more productive plant which is implied by the higher shoot RUE.

The gross root production can be related to net root production (the difference between temperature adjusted total RUE and shoot RUE) to show the fraction of DM partitioned to perennial organs that was subsequently lost by respiration. The short treatments had a net root production of 0.25 g/MJ (Table 6.2) indicating 55% of DM partitioned to the roots was lost to respiration. For the long treatment net root production was 0.35 g/MJ suggesting 45% of DM partitioned to perennial organs was lost by respiration. This difference highlights the influence of management on potential DM production. The more frequent defoliation treatment (short regrowth) had a greater demand for perennial DM utilisation to initiate regrowth so a greater proportion of perennial DM was used. This, combined with the lower amount of DM partitioned to perennial organs, gave substantially lower perennial DM at the end of the season (Figure 6.3). It would be expected that the perennial reserves available for initiation of spring regrowth are less in the short duration treatment and subsequently spring-time shoot production will be reduced.

This section demonstrates the influence of management on crop production and a complete explanation of lucerne yield would need to quantify both the accumulation of perennial reserves and the influence of its utilisation on shoot RUE. The accumulation/utilisation of perennial reserves may also influence crop persistence if perennial reserves are used to defend the plant against pathogens.

6.5 Conclusions

In this chapter the relationship between radiation interception and total DM production has been examined to quantify the potential DM production of lucerne. The influence of other environmental variables in DM production and partitioning was also examined to quantify seasonal changes in potential shoot production under non-water limited conditions. Specific conclusions are:

- Shoot RUE was not constant and increased from ~0.8 g/MJ from September–December to ~0.95 in January and then abruptly decreased to ~0.6 in March/April.

- Potential total DM production under non-temperature limited conditions could be quantified with a total RUE_{opt} of 1.6 g/MJ.

- Partitioning of total DM production to shoots declined from 80% of total production in September to 60% in December/January and 35% in March/April.

- Total RUE_{opt} could be multiplied by the seasonal pattern of shoot fraction to give a seasonal pattern of shoot RUE_{opt} that quantified potential shoot production assuming non-limiting temperatures.

- Field measured shoot RUE was lower than shoot RUE_{opt} at the beginning of the season, indicating temperature was limiting DM production.

- Adjusting measured shoot RUE for a temperature response using a factor that increased from zero at at 0 °C to unity at 18 °C gave a close agreement between measured RUE and shoot RUE_{opt}. This indicated a suitable quantification of the temperature response of lucerne RUE.

- Lucerne plants subjected to longer regrowth cycles gave greater yields, partitioned a greater fraction of DM production to perennial organs, utilised more perennial DM

following defoliation and initiated regrowth faster than crops defoliated more frequently.

- Lucerne plants subjected to longer regrowth cycles respired 45% of total DM partitioned to the roots compared with 55% for short regrowth cycles over the duration of the first perennial regrowth season.

This chapter has quantified production potential of lucerne based on total RUE. This can now be combined with intercepted radiation to quantify production under non-water limiting conditions in Chapter 7.

7 Canopy expansion of lucerne

7.1 Introduction

In the previous chapter the seasonal pattern of potential forage production was quantified. This needs to be combined with actual radiation interception (R) to quantify seasonal forage production (Figure 6.1). Radiation interception is the product of incident solar radiation (R_o) and the fractional interception (R/R_o) of this by a crop canopy. The R/R_o of a lucerne canopy varies throughout a season through changing canopy architecture and in particular LAI (Section 2.4.1.1). It is possible to quantify the influence of environment and management on R/R_o by assuming a constant extinction coefficient and then relating LAI dynamics to environmental variables.

The dynamics of lucerne LAI has components of stem population, main-stem node appearance, branching, senescence and leaf size (Equation 2.5). Stem density may be considered a constant within a regrowth period or growth season but the other components of LAI change in response to environmental and crop factors. These responses need to be quantified to explain the dynamics of LAI and quantify changes in R/R_o. The simplest way to quantify LAI is to assume all of its components respond similarly to temperature and then the dynamics of LAI can be quantified by a direct relationship with Tt (Ritchie, 1991). More complex methods of quantifying LAI development account for differing temperature and/or photoperiod responses of the components of LAI (Section 2.4.2). However, justification of different approaches is not often presented. This makes it difficult to know which is the most appropriate and thus which data to collect for quantification.

The objective of this chapter was to quantify the influence of environment on the seasonal patterns of LAI expansion. A number of quantification methods were tested under irrigated conditions. The components of the most suitable were related to environmental variables to contribute to the quantification of seasonal changes in LAI.

7.2   Materials and methods

7.2.1   Measurements

7.2.1.1   Stem population

The methodology of measuring stem population is described in Section 3.3.3. Stem population was measured on three to five occasions for each regrowth cycle in $I8_{00/01}$, $I8_{01/02}$ $I9_{00/01}$ and $I9_{01/02}$, giving 220 observation dates within 34 regrowth cycles.

7.2.1.2   Leaf area index

Measurements of GAI were taken with a canopy analyser (Section 3.3.5.2) and converted to LAI using the calibration presented in Appendix 3. Green area index was measured at 3-5 d intervals in $I8_{00/01}$, $I9_{00/01}$ and $I9_{01/02}$, giving a total of 104 observation dates in 18 regrowth cycles.

7.2.1.3   Main-stem node appearance and flowering

Main-stem nodes were counted on 15 marked main-stems (on different plants) per treatment (5 per replicate). Measurements were taken in lucerne treatments in $I8_{97/98}$–$I8_{01/02}$, for all four sowing date treatments (excluding the seedling phase) in $I9_{00/01}$ and from the first sowing date in $I9_{01/02}$. The mean of 15 stems from each regrowth cycle was used to give a single observation point. Stems were marked and counting began within five days of the removal of sheep from the previous grazing cycle. At this time stems were 20–50 mm long. An intentional bias was made to mark the largest stems because smaller stems often senesced at the base of the canopy as it developed over top of them. Measurements were taken at 3–7 d intervals and continued until the end of each regrowth cycle. Main-stem nodes were counted from the base of the stem (starting with the first node) up to the node with the most recent fully expanded leaf. The presence of flower buds or open flowers was also recorded and the flowering date was defined as the time when 50% of marked stems had open flowers.

7.2.1.4   Secondary nodes and senesced leaves

Secondary nodes and senesced leaves were counted on the marked main-stems for regrowth cycles 2–5 in $I8_{00/01}$. Secondary nodes were also counted for regrowth cycles 5 and 6 in $I8_{01/02}$. Secondary nodes were counted at each node on the main-stem and these were added to the number of main-stem nodes to give total nodes per main-stem. On the few occasions where tertiary nodes appeared they were recorded as additional secondary nodes. The number of nodes (main-stem and secondary) without leaves or with more than 50% of their area yellow/brown were counted to measure leaf senescence.

7.2.2   **Thermal time calculations**

7.2.2.1   Thermal time calculation

Thermal time (Tt in °Cd) was calculated daily using the method described by Jones and Kiniry (1986) which accounts for the sinusoidal pattern of diurnal temperature fluctuation. To do this temperature was interpolated to three hourly intervals from daily temperature minimum (T_{min}) and maximum (T_{max}):

Equation 7.1   Temp_3hour = t_range_fract * diurnal range

$$t\_range\_fract = 0.92 + 0.0114*P - 0.07*P^2 + 0.005*P^3$$

$$diurnal\ range = T_{max} - T_{min}$$

Where *P* is the period (1-8) for the corresponding temperature calculation, e.g. the temperature from 0:00–3:00 hours is period 1 and from 15.00–18:00 is period 6. The Tt was calculated for each period from the relationship between T and Tt described by a temperature threshold (Figure 7.1). The mean of Tt at each of the eight daily periods is taken to represent daily Tt and then summed to give accumulated Tt over a measurement period.

7.2.2.2   Determining a suitable temperature threshold

Thermal time is a widely used concept but its suitability is dependant on the use of an appropriate temperature threshold (Bonhomme, 2000a). An incorrect temperature threshold causes systematic variation or increased dispersion in development rates when they are related to Tt over a range of temperatures. This concept was utilised to test the suitability of the conventional lucerne temperature threshold (Tt$_{b5}$, Sharratt *et al.*, 1989) with an alternative (Figure 7.1) proposed by Moot *et al.* (2001), Tt$_{b1/5}$. The conventional threshold has a base temperature (T$_b$) of 5 °C and accumulates Tt at a rate of 1.0 °Cd per °C above this to an optimum (T$_o$) of 30 °C and declines to zero at a maximum (T$_m$) of 40 °C (solid line in Figure 7.1). The alternative is a broken stick threshold that uses the same response as the conventional threshold at T>15 °C but accumulates Tt at 0.71 °Cd per °C above a T$_b$ of 1 °C for T<15 °C (dotted line in Figure 7.1).
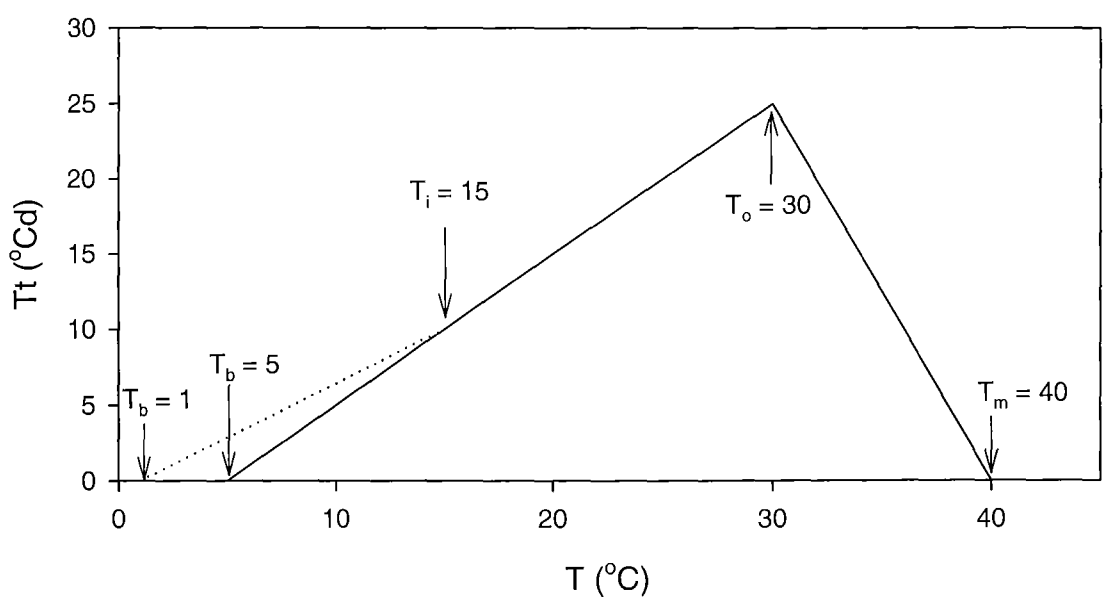
Figure 7.1 Temperature (T) thresholds used for the calculation of thermal time (Tt)

Note: T$_b$ is base temperature, T$_i$ is the inflection point T$_o$ is optimal temperature and T$_m$ is maximum temperature. The solid line represent Tt$_{b5}$ and the dotted extension represents Tt$_{b1/5}$.

Phyllochron (morphological development Section 7.2.4.1) was used as a variable to test the suitability of these thresholds (Tt_{b5} and $Tt_{b1/5}$) because it was the most intensively measured variable in this study and the least sensitive to non-developmental factors (Section 2.4.2). Two tests were used; the first was a linear regression of phyllochron as a function of mean temperature to assess if either of the models introduced systematic variation ($b \neq 0$) to phyllochron. The second test compared the coefficient of variation (CV) of phyllochron predictions from each model, with the lowest CV% used to indicate a more consistent phyllochron. The most appropriate temperature threshold was then used to calculate the phyllochron for all subsequent analyses.

7.2.3   Quantifying leaf area index expansion

Several analyses were carried out to determine which components of LAI expansion were needed to give an accurate quantification of seasonal changes in LAI. The first analysis was a simple plot of LAI against Tt accumulation. This tests the assumption that all components of LAI expansion are development driven and LAI responds in a conservative manner to the accumulation of Tt regardless of the time of the growth season. The second analysis used main-stem node as an input variable (i.e. LAI was plotted as a function of the number of nodes present at the time of measurement) testing the assumption that any changes in LAI expansion were due to variation in the phyllochron. Variation in branching and/or senescence and/or main-stem population may also affect LAI formation so the third analysis plotted LAI as a function of the number of leaves per square metre. The relationship with the least variation was considered to give the best quantification of LAI dynamics. Subsequent analysis was to quantify the environmental response of the components of this relationship.

7.2.4   Environmental responses of main-stem node appearance

7.2.4.1   Temperature effect (Phyllochron)

Main-stem node number was regressed as a function of Tt for points where node accumulation was linear (defined as the observation period). The slope of the regression gives the main-stem node appearance rate (nodes/°Cd). The phyllochron

(°Cd) is the reciprocal of this rate and represents the Tt requirement for appearance of a single main-stem node.

7.2.4.2 *Phyllochron in relation to photoperiod*

Phyllochron was presented as a function of mean photoperiod (Pp) calculated daily and averaged over the observation period (Section 7.2.4.1). Data points were initially assigned to a grouping depending on whether the mid point of the observation period occurred in an increasing (IPp, 22 June–21 December) or decreasing (DPp, 22 December–21 June) Pp. These groups were split into two sub-groups distinguished by the occurrence of their mid point in a long day (Pp>13 hours, 22 September–21 March) or short day (Pp<13 hours, 22 March–21 September) period. There were no Pp response differences between sub-groupings for increasing Pp results so only three groupings were used. These were; increasing Pp (IPp), decreasing Pp long day (DPp>13) and decreasing Pp short day (DPp<13).

Tests were conducted to quantify Pp responses by fitting three different regressions to these data;

1. Non-linear Pp response: was assessed by fitting a second order polynomial to the phyllochron for all observations.

2. Linear Pp response: separate linear regressions were fitted to Pp groupings IPp and DPp.

3. Hysteresis: A separate linear regression was fitted to each of the three Pp groupings (IPp, DPp<13, DPp>13).

The suitability of each model was based on maximizing R^2 values.

7.2.4.3   Induction of photoperiod response

Presenting phyllochron as a function of mean Pp for the observation period implicitly assumes that the rate of main-stem node appearance responds to Pp on a daily basis. If this was correct the rate of node appearance would decline within a measurement period where changing Pp was causing an increasing phyllochron and vice versa. To test this hypothesis, periods with sufficient data points were split at the midpoint and separate linear regressions of node appearance were fitted to each as a function of Tt. The ratio of the slopes (first section/second section) was used to indicate a reduction (x>1) or increase (x<1) in node appearance rate. Slope ratios were compared between the three groupings to assess if the phyllochron was responding to Pp on a daily basis.

If the phyllochron was not responding to Pp on a daily basis it implies that any Pp response is induced at a set point in the crops development. To test this hypothesis phyllochron was plotted as in Section 7.2.4.2, but Pp was represented by the Pp on the day of appearance of the first node to relate to a set point. The day of first node was estimated from extrapolation of the regressions fitted to node appearance (Section 7.2.4.2). The three tests (Section 7.2.4.2) were re-applied to assess if this representation of Pp gave an improved quantification of the phyllochron response to Pp. Photoperiod was also represented by the Pp on days 300 °Cd either side of the appearance of the first node and at 50 °Cd intervals between these points. The representation that maximised the R^2 was considered the point in the crops development at which the photoperiod response was induced.

7.2.5   Environmental response of leaf appearance

7.2.5.1   Relating leaf appearance to thermal time and photoperiod

It was assumed that the effects of Tt and Pp on leaf appearance were equivalent to the responses of main-stem node appearance. Thus, rather than determining separate Tt and Pp responses for branching and senescence they were presented as a function of main-stem node number. This implicitly incorporates Tt and any Pp responses and if their response to Tt or Pp changes relative to that of main-stem node appearance it will be displayed as a change in the relationship with main-stem node appearance.

7.2.5.2 Branching

Branching was described by fitting a linear regression to total number of nodes as a function of the number of main-stem nodes (Hammer *et al.*, 1995). The slope of the regression indicates the number of leaves that appear per main-stem node and the slope–1 shows how many secondary nodes appear per main-stem node. The point where the fitted regression intercepts the 1:1 line represents the point where visible branching begins.

7.2.5.3 Senescence

The number of senesced leaves was represented as a function of main-stem node appearance and regressions were fitted to describe the rate of leaf loss. Data points for the second regrowth cycle (28 September–9 November 2000) were omitted from the regression because they coincided with a period where lucerne was infected with downy mildew (*Pseudoperonospora cubensis*).

7.3 Results

7.3.1 Thermal time

7.3.1.1 *Morphological development of lucerne in response to temperature*

The relationship between Tt accumulation and morphological development of lucerne is presented in Section 7.3.3.1 where it is analysed in detail. However, to justify its use as a representative of development for testing temperature thresholds it is noted that there was a strong linear relationship between main-stem node appearance and Tt accumulation.

7.3.1.2 *Thermal time temperature threshold*

The Tt_{b5} temperature threshold (Table 7.1) had a CV of 25% and a slope of 0.84 indicating an underestimate of Tt at lower temperatures. In contrast, the $Tt_{b1/5}$ temperature threshold had a lower CV of 22% and a slope of zero. This indicates no systematic error over the observed mean temperature range (7.5–18 °C) so this threshold was used to calculate Tt for the remainder of this thesis.

Table 7.1 Test values for comparison of two temperature thresholds used to calculate thermal time for irrigated 'Kaituna' lucerne grown at Lincoln University, Canterbury, New Zealand.

Threshold	CV%	Slope (b)	P value
Tt_{b5}	25.0	0.84	0.07
$Tt_{b1/5}$	22.2	-0.03	0.96

Note: n = 33. CV% is the coefficient of variation in phyllochron calculated from each threshold. b is the slope a linear regression fitted to phyllochron as a function of mean temperature. P is the probability that b is not different to zero.

7.3.2   Quantifying leaf area index expansion

7.3.2.1   *Leaf area index in relation to thermal time*

Leaf area index showed a general increase in response to Tt accumulation. However, the linear regression had an R^2 of 0.60 displaying a substantial amount of variation both within and between seasons (Figure 7.2).
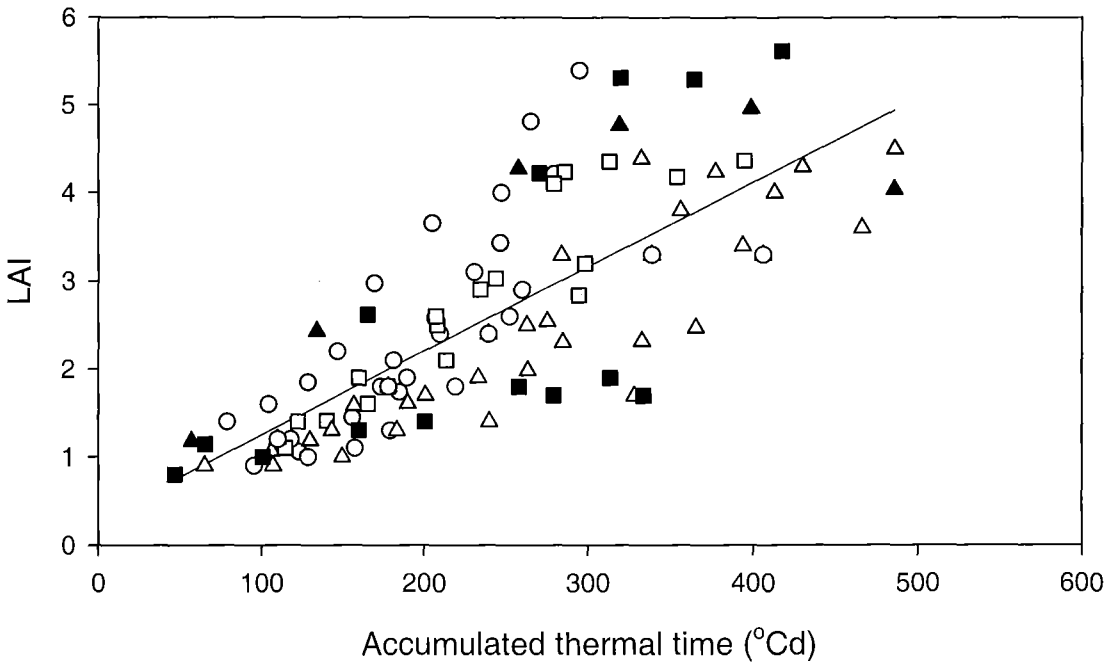
Figure 7.2 Leaf area index (LAI) expansion in response to thermal time (Tt_{b5}) accumulation for irrigated lucerne from $I8_{00/01}$ (   ), $I8_{01/02}$ ($\bigcirc\square\triangle$), $I9_{00/01}$ ($\bullet\blacksquare\blacktriangle$) and $I9_{01/02}$ ($\bigcirc\square\triangle$) at Lincoln University, Canterbury, New Zealand.

Note: Spring regrowth cycles are marked with circles, summer with squares and autumn with triangles. Linear regression (——); $R^2 = 0.60$.

7.3.2.2   *Leaf area index in relation to main-stem node appearance*

The expansion of LAI against main-stem node number (Figure 7.3) showed a variable exponential increase (R^2 = 0.72). For example, at 10 main-stem nodes LAI ranged from 1.5–4.0.
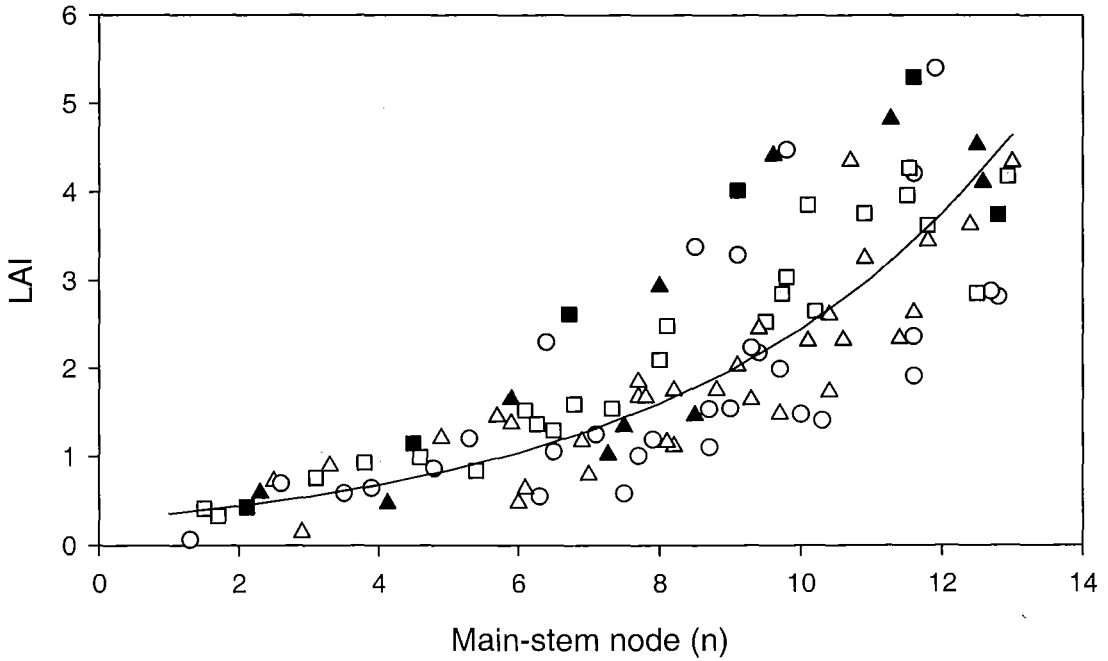
Figure 7.3 Leaf area index (LAI) in relation to main-stem node number for irrigated lucerne ($I8_{00/01}$, $I8_{01/02}$, $I9_{00/01}$ $I9_{01/02}$) grown at Lincoln University, Canterbury New Zealand. Symbols as for Figure 7.2.

Note: Exponential regression (———), y = 0.29 * exp (0.21*x); R^2 = 0.72.

7.3.2.3   *Leaf area index in relation to net leaf appearance*

The expansion of LAI showed a strong linear increase in relation to net leaf appearance (Figure 7.4) with an R^2 of 0.93 but the response differed depending on the time in the regrowth season. Regrowth cycles during the summer (1 January–4 March) continued to show a linear increase reaching a LAI of 4.0 with 9000 leaves/m^2. However, spring regrowth cycles showed a lower (P<0.001) LAI for the same number of leaves. The slope of the fitted regressions indicate mean leaf size was 400 mm^2 in summer and 170 mm^2 in spring.
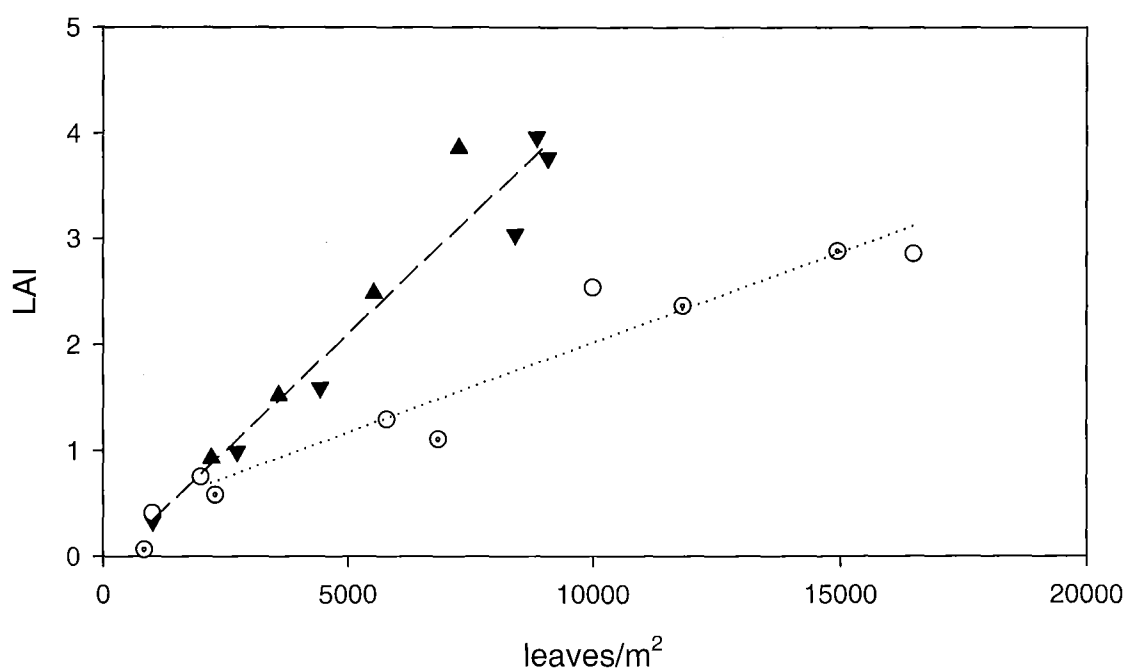
Figure 7.4 Leaf area index (LAI) in relation to the net number of leaves for irrigated lucerne grown at Lincoln University, Canterbury, New Zealand.

Note.   Symbols represent individual regrowth periods; ⊙ = 28 September–9 November, 2000 (659 stems/m^2), ○ = 14 November–27 December, 2000 (649 stems/m^2), ▲ = 1 January–9 February, 2001 (584 stems/m^2), ▼ = 2 February–14 March, 2001 (593 stems/m^2). Linear regressions were fitted to points grouped by shading colour; white shading = spring periods (·····), a = 0.31(0.20), b = 0.00017(0.00002) R^2 = 0.92, grey shading = summer values (– – –) a = -0.10(0.24), b = 0.00044(0.00004), R^2 = 0.94. Bracketed values represent standard errors of coefficients.

7.3.2.4   Stem population

Stem population (Table 7.2) of irrigated treatments was ~650 /m^2 in I8$_{00/01}$ but declined to ~247 in the following season (I8$_{01/02}$). The irrigated treatment in I9$_{01/02}$ had ~750 stems/m^2. Dryland treatments in I8$_{00/01}$ had ~650 stems/m^2 throughout the season and stem density in dryland treatments in I9$_{01/02}$ declined from ~1000 stems/m^2 at the beginning of the regrowth cycle to 473 stems/m^2 in the sixth regrowth cycle. Stem population was stable within a rotation but there was a change in the proportion of short (<0.1 m), medium (0.1–0.3 m) and long (>0.3 m) stems (Appendix 13).

Table 7.2 Stem population of lucerne in dryland (Dry) and irrigated (Irr) crops from four different paddock/season combinations (I8$_{00/01}$, I8$_{01/02}$, I9$_{00/01}$, I9$_{01/02}$) at Lincoln University, Canterbury, New Zealand.

	Regrowth	1	2	3	4	5	6	7
I8$_{00/01}$	Dry		835	769	714	617	573	541
	Irr		688	649	583	593	586	618
I8$_{01/02}$	Dry					536	397	-
	Irr					293	247	-
I9$_{00/01}$	Dry	459[a]	793	785	715	-	-	-
	Irr	497[a]	803	628	703	-	-	-
I9$_{01/02}$	Dry	1107	972	734	637	604	473	-
	Irr	793	846	748	716	592	563	-

Note: values marked with a superscript "a" were seedling growth phases. Regrowth cycles marked with "-" did not occur in that season and blank cells were not measured.

7.3.3 Main-stem node appearance in relation to environment

7.3.3.1 Temperature

Main-stem node appearance is shown in Figure 7.5 where $Tt_{b1/5}$ was accumulated from 1 July for each season. The R^2 of all regressions was > 0.90 indicating the phyllochron was constant within each regrowth cycle. However, there was a decrease in the slope of regressions in the later part of each growth season. In addition node accumulation became non-linear at the time of flowering (Section 7.2.1.3) or after a frost ($T_{air}<0$ °C).
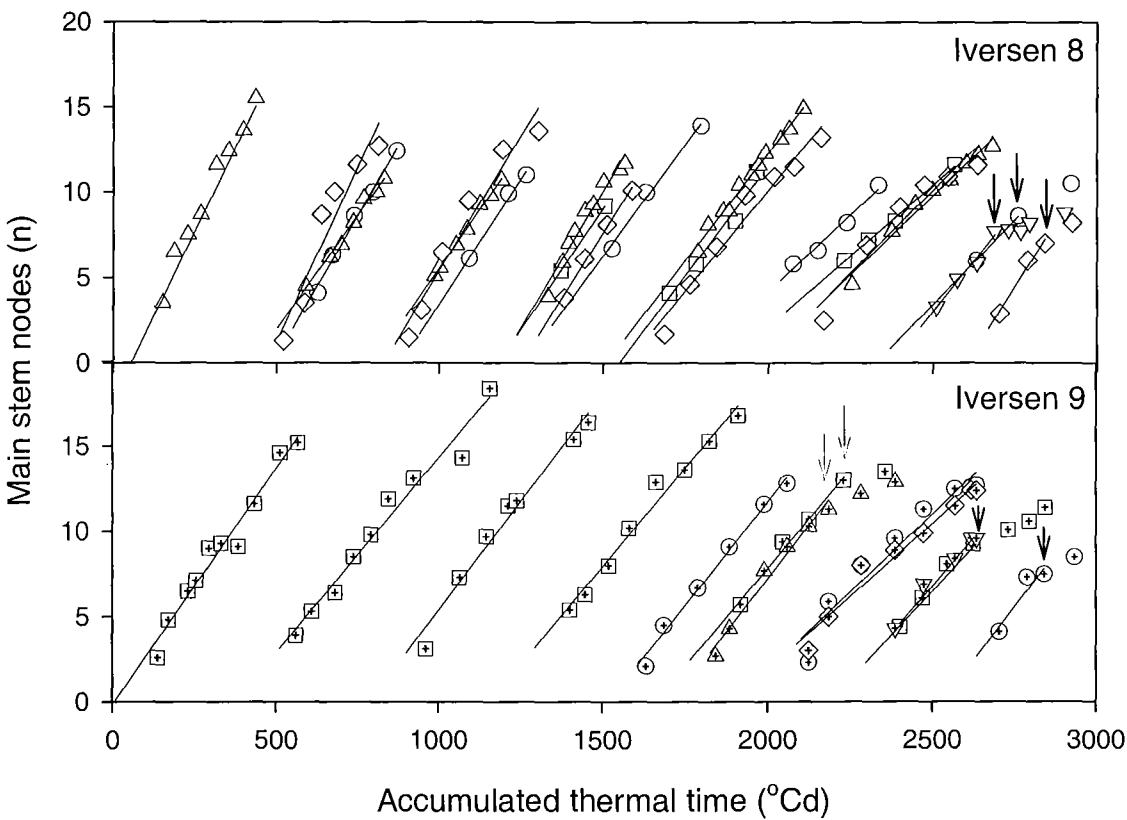
Figure 7.5 Main stem node appearance of irrigated 'Kaituna' lucerne regrowth measured at Lincoln University, Canterbury, New Zealand. See Table 3.3 for symbols, black arrows mark days of <0°C frosts, grey arrows indicate time of flowering in two crops.

The decrease in the rate of node appearance can be demonstrated by the seasonal variation in phyllochron (Figure 7.6) with values of about 35 °Cd from the start of the season (1 July) until the summer solstice (21 December). After this the phyllochron increased to be 60 °Cd at about the autumn equinox and then decreased to 35 °Cd at the end of the season in June.
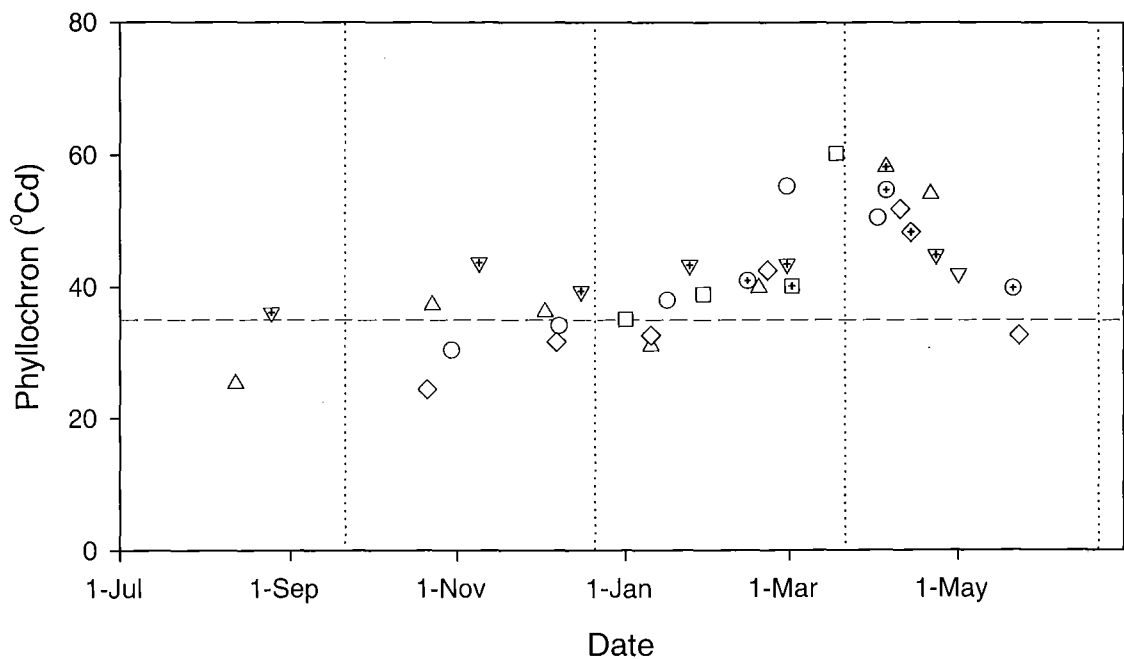
Figure 7.6 Phyllochron of irrigated 'Kaituna' lucerne regrowth crops measured from 1 July 1997- 24 June 2002 at Lincoln University, Canterbury, New Zealand. − − − marks a phyllochron of 35 °Cd, vertical lines (⋮) mark equinox and solstice. See Table 3.3 for symbols

7.3.3.2 Photoperiod

The apparent influence of photoperiod on phyllochron (Figure 7.6) was investigated further and there was a differential response depending on the sign of Pp change. Figure 7.7a shows phyllochron gradually increased (1.2 °Cd/hour) in response to IPp, had a faster increase (6.6 °Cd/hour) in response to DPp>13 (from the summer solstice to the equinox) and a rapid decrease (9.1 °Cd/hour) in response to DPp<13 (from the equinox to the winter solstice). The hysteresis test (Table 7.3) gave a better fit (R^2 = 0.54) than the linear test (R^2 = 0.41) that assumed the same response to Pp regardless of the direction of change (Figure 7.7b). A second order polynomial model, assuming a curved response, gave the poorest description (R^2 = 0.29) of the change in phyllochron.

Table 7.3 Results of three different models used to explain the change in phyllochron of irrigated lucerne in response to photoperiod at Lincoln University, Canterbury, New Zealand. Graphical representation of relationships are displayed in Figure 7.7.

Test	Grouping	Relationship	R^2
Hysteresis	IPp	y = 15.1 + 1.2x	0.15
	DPp>13	y = 142.0–6.6x	0.67
	DPp<13	y = -59.5 + 9.1x	0.80
			<u>0.54</u>
Linear	Pp<13	y = -86.5 + 11.1x	0.53
	Pp>13	y = 114.3–4.9x	0.31
			<u>0.42</u>
Non-linear	All data	y = 1.5x^2+38.9x-212	0.28
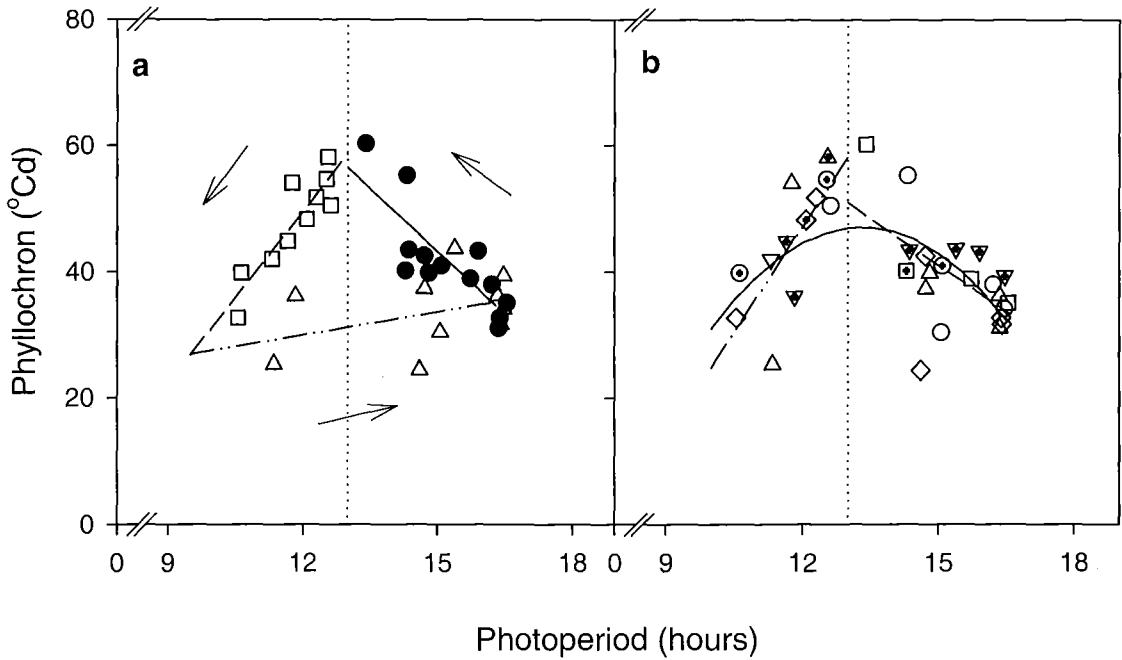
Figure 7.7 Phyllochron of irrigated 'Kaituna' lucerne regrowth in response to mean photoperiod at Lincoln University, New Zealand; a) hysteresis model with linear response (—···—··$\triangle$ = IPp, —— ● = DPp>13, — — — = DPp<13). b) Non-linear (——) and linear photoperiod (—···—·· = Pp<13, — — — = Pp>13) models.

Note: a) arrows indicate direction of photoperiod change. b) see Table 3.3 of symbols. Coefficients or all fitted relationships are displayed in Table 7.3.

7.3.3.3   Induction of photoperiod response

The slope ratios within a rotation (Section 7.2.4.3) were different to 1 within (P<0.001) but not between (P = 0.13) all three Pp groups (Table 7.4). This indicates the rate of node appearance changed during the regrowth cycle but it was not responding to daily Pp. On this basis the existence of an induction point was tested.

Table 7.4 Phyllochron slope ratio for irrigated lucerne grown at Lincoln University, Canterbury, New Zealand.

	IPp	DPp>13	DPp<13
Number	10	6	4
Ratio	1.31	1.36	1.60
Probability	< 0.001[a]		
	0.13[b]		

Note: Slope ratio represents the slope of nodes regressed against thermal time for the first half of an observation period divided by the slope of the second half of the observation period. Probability super scripts; a) is a test of the null hypothesis that the slope = 1, b) tests the null hypothesis that the slopes of the three groups are the same.

The hysteresis model (Section 7.2.4.2) gave the highest R^2 for the change in phyllochron when Pp response was induced at a set point relative to the appearance of the first node (Figure 7.8). Inducing Pp response from 150 to 50 °Cd prior to the appearance of the first node gave an improvement in the description of the hysteresis model as shown by the increase in R^2, compared with inducing Pp each day during the observation period (dotted line in Figure 7.8).
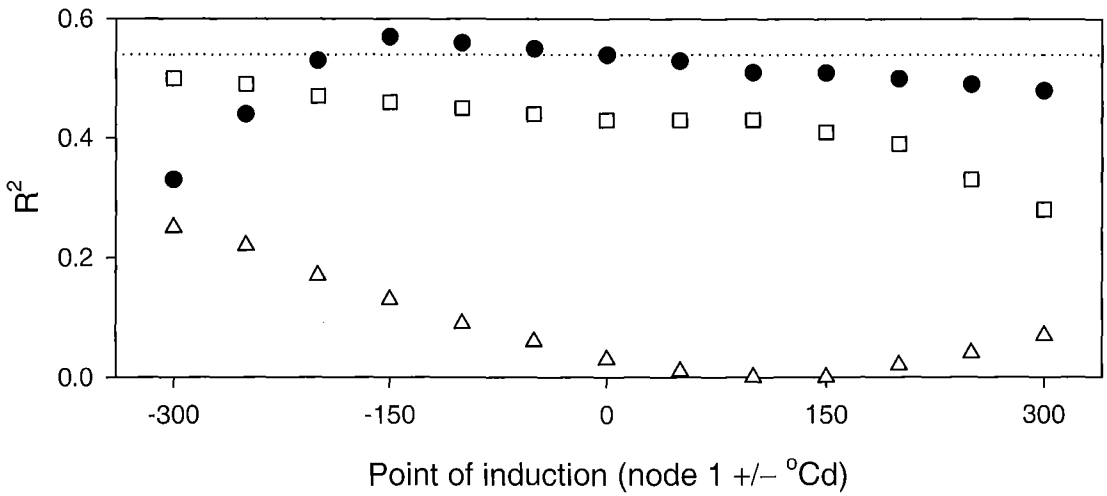
Figure 7.8 Results from hysteresis (●), linear (□) and non-linear ( ) photoperiod response models induced to photoperiod at a set Tt relative to the appearance of the first node. The dotted line marks R^2 of the hysteresis model responding to photoperiod throughout each observation period.

7.3.3.4   Phyllochron in relation to photoperiod 150 °Cd before the first node

The relationship between phyllochron and Pp 150 °Cd before the first node (the point of induction) is displayed in Figure 7.9. The arbitrary Pp groupings assigned for the hysteresis test (Section 7.3.3.2) are represented by the same symbols but different groupings were used for regressions. A regression was fitted to data points where Pp induction occurred on a decreasing Pp between 16.0 and 13.5 hours and phyllochron decreased from 60 to 40 °Cd (5.6 °Cd/hour) over this range. A second regression was fitted to all other data points that were within the range of 25–40 °Cd but the slope of this regression was not different (P=0.07) to zero so these were represented by a single phyllochron of 37 ± 7 °Cd.
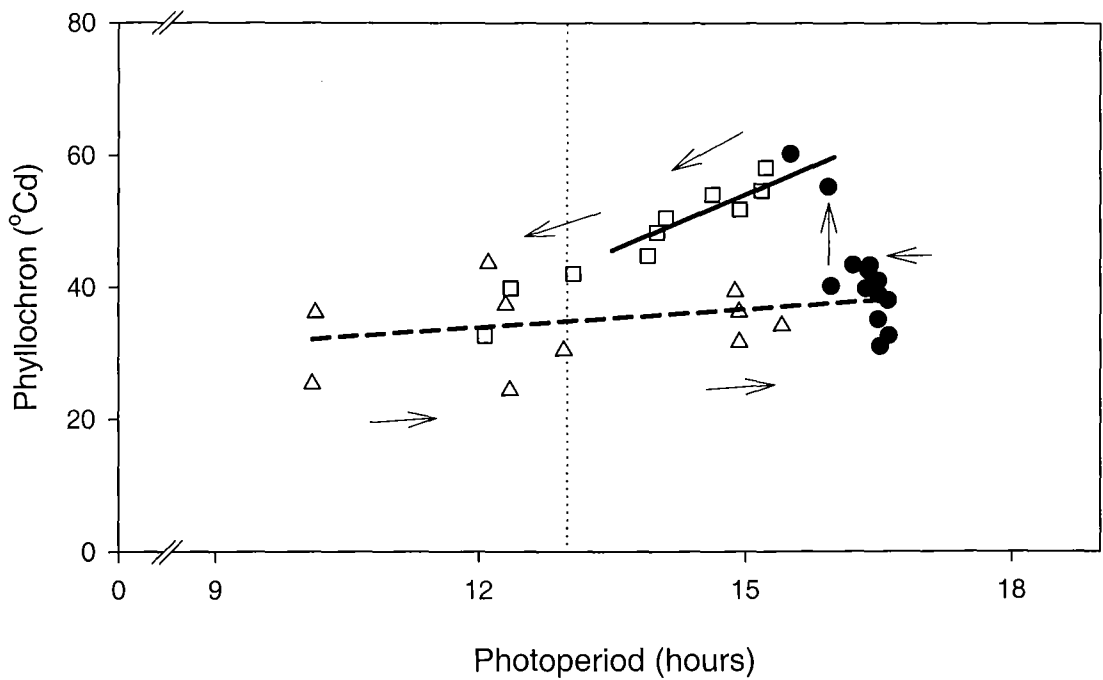
Figure 7.9 Phyllochron of irrigated 'Kaituna' lucerne regrowth in response to photoperiod 150 °Cd before the appearance of the first node at Lincoln University, New Zealand. Symbols are grouped as for Figure 7.7.

Note: Regressions are fitted to DPp<16>13.5 (———), y = -30.6(20.7) + 5.6(1.4)x and the remaining data (– – –) y = 23.3(7.2) + 0.9(0.5)x. Bracketed values are standard errors.

7.3.4   Leaf appearance in relation to environment

7.3.4.1   *Branching*

Total number of nodes became greater than main-stem node number after the appearance of the fifth main stem node. This is demonstrated in Figure 7.10 where points exceeding the 1:1 line are a result of branching. There were three distinct branching patterns displayed in the six data sets analysed. These were explained with three different (P<0.01) linear regressions. Two spring regrowth cycles in $I8_{00/01}$ (stem density was about 650 stems/m^2) expressed branching at 5.5 main-stem nodes and produced 2.5 secondary nodes per main-stem node. The two summer regrowth cycles from $I8_{00/01}$ (590 stems/m^2) also initiated branching at 5.5 main-stem nodes but only produced 1.7 branch nodes per main-stem node. The autumn regrowth cycles from $I8_{01/02}$ (260 stems/m^2) expressed branching at node 4.5 and produced 2.5 secondary nodes per main-stem node.
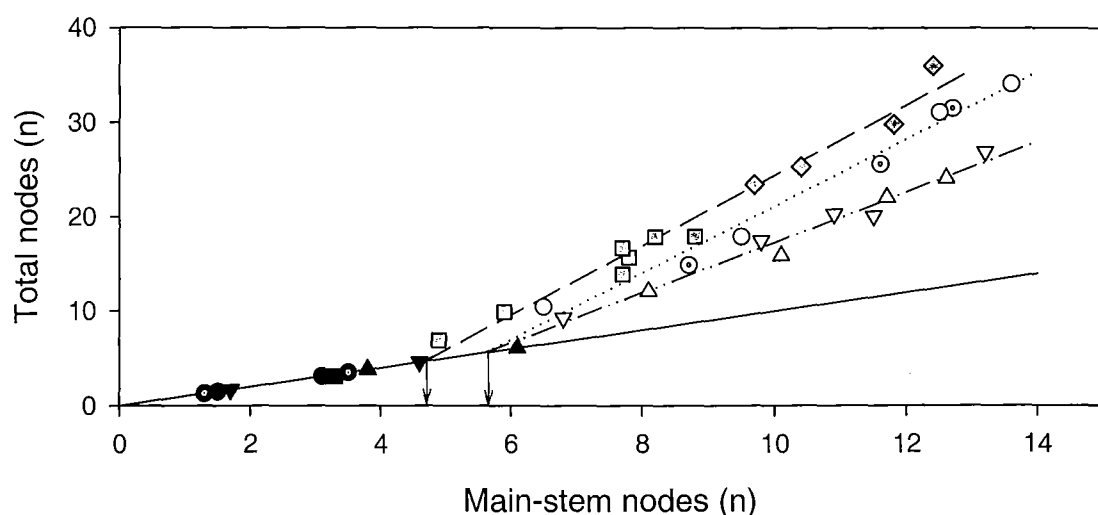
Figure 7.10 Total node number per stem in relation to main-stem node for irrigated 'Kaituna' lucerne from six different regrowth cycles in Iversen 8 (see note) at Lincoln University, Canterbury, New Zealand.

Note: ⊙ = 28 September–9 November 2000 (659 stems/m^2), ○ = 14 November–27 December 2000 (649 stems/m^2), ⊡ = 1 January–9 February 2001 (584 stems/m^2), ▽ = 2 February–14 March 2001 (593 stems/m^2), ◆ = 15 February–3 April 2002 (293 stems/m^2) ■ = 8 April–24 June 2002 (247 stems/m^2). Linear regressions were fitted to points grouped by shading colour. White shading (⋯⋯⋯) a = -14.3(2.62), b = 3.5(0.24), R^2 = 0.98. Dark grey shading (– – –) a = -9.4(1.77), b= 2.7(0.16), R^2 = 0.98. Light grey shading (–··–) a = -12.7(1.88), b = 3.7(0.21), R^2 = 0.97. Black shaded points (——) y=x.

7.3.4.2   Senescence

Senescence demonstrated a bi-linear relationship with main-stem node appearance (Figure 7.11) which was described by a broken stick regression (R^2 = 0.93). This indicated senescence was 0.3 leaves/main-stem node from stem initiation to node 9.3 but increased to 1.08 leaves/main-stem node beyond this.
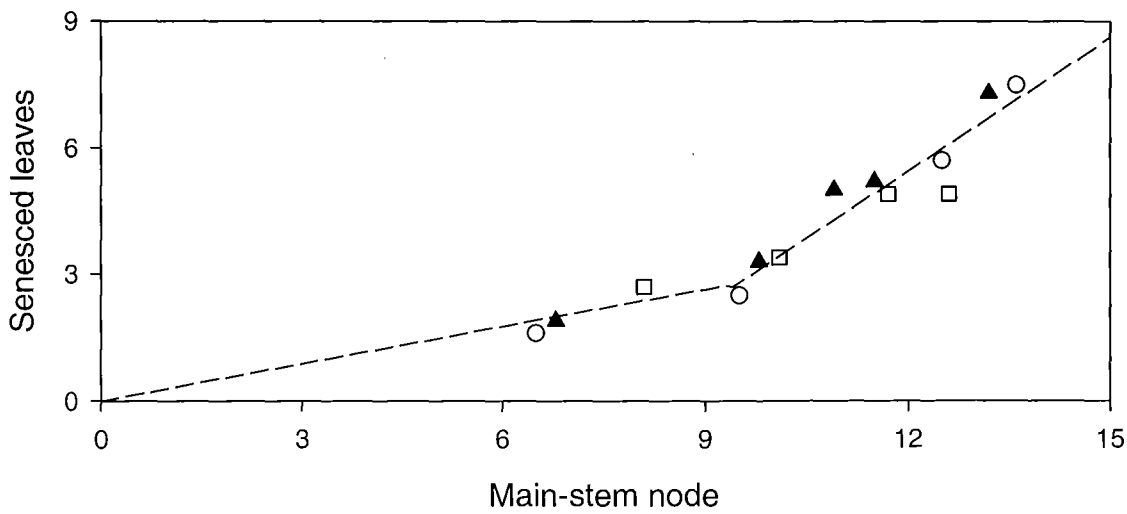
Figure 7.11 Number of senesced leaves as a function of main-stem node number for irrigated lucerne from three different regrowth cycles (see note) at Lincoln University, Canterbury, New Zealand.

Note: O = 14 November–27 December 2000.   = 1 January–9 February 2001. ▲ = 2 February–14 March 2001. Broken stick regression (——) y=-7.3*(x>9.3) + 0.3x*(1+2.6*(x>9.3)) R^2 = 0.93.

7.3.4.3   Canopy position of branching and senescence

Branching was initiated at an early stage of regrowth (Figure 7.12a) as indicated by the increase in net leaf number per node (above 1) four main-stem nodes behind the most recently expanded leaf (represented by the highest main-stem node value). As the regrowth cycle progressed (Figure 7.12b-d) branching was consistently expressed three to four nodes behind the most recently expanded leaf. Figure 7.12 also shows the point when maximum net leaf number per node increased its absolute value and position on the main-stem throughout a regrowth cycle. There was a decline in net leaf number per main-stem node two to three main-stem nodes behind the point of maximum leaf number per node. The increase in leaf number at the second main-stem node from third to the fourth (final) measurement period was due to the initiation of basal buds.
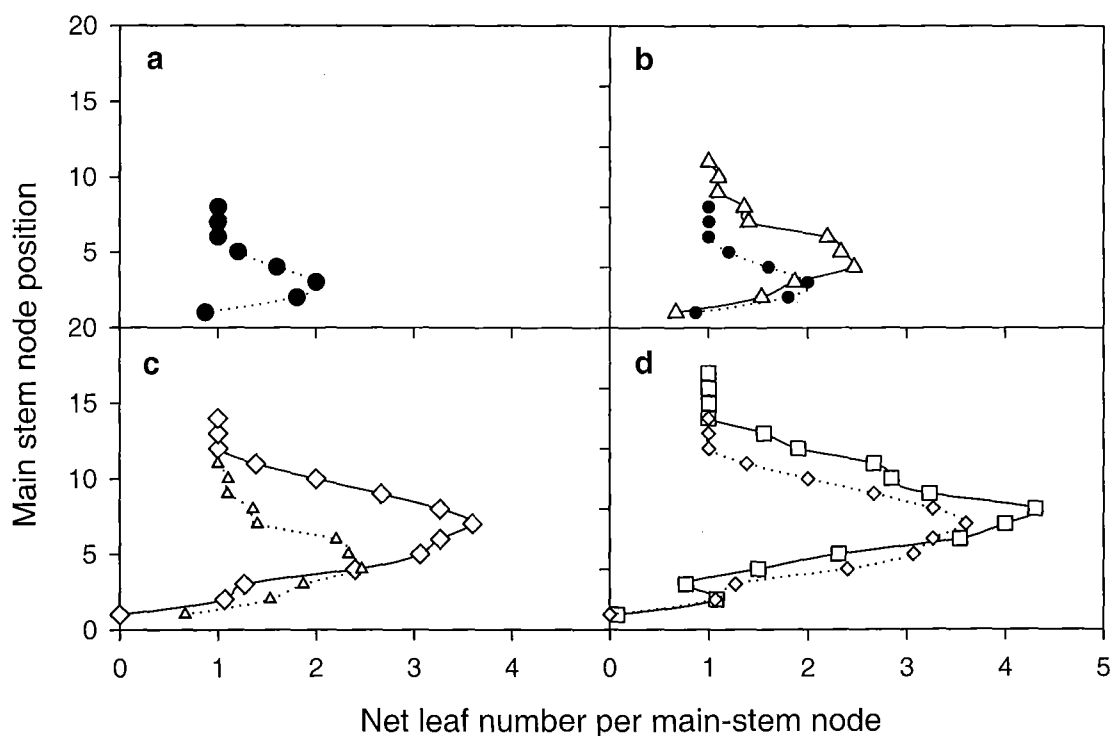
Figure 7.12 Net leaf number at each main-stem node for irrigated 'Kaituna' lucerne measured on four dates within a single regrowth cycle (beginning 30 January 2001) at Lincoln University, Canterbury, New Zealand. a) ● 21 February, b) △ 28 February, c) ◇ 6 March, d) ☐ 14 March 2001.

Note: Large symbols with solid lines display the data measured for that date and small symbols with dotted lines are a reference for comparison with the previous measurement date.

7.4 Discussion

7.4.1 Quantifying leaf area index

Canopy expansion could not be explained by a constant relationship between LAI and Tt accumulation (Figure 7.2). This demonstrated that expansion was not solely controlled by development as suggested by Ritchie (1991) when specifying the ideal model for predicting crop growth. These results indicate more detailed analyses of the environmental response of the components of LAI expansion are needed to quantify canopy expansion.

7.4.2 Main-stem node appearance

The use of main-stem node appearance as an input variable (Figure 7.3) reduced some of the variability in LAI expansion. This indicates that a quantification of the seasonal pattern of main-stem node appearance is required to explain changes in the LAI of lucerne.

7.4.2.1 Phyllochron

Main-stem node number showed a linear increase in response to accumulated Tt within each regrowth cycle (Figure 7.5). The implication was that a single phyllochron was suitable for describing morphological development of lucerne within a rotation. The slope ratio (Table 7.4) indicated the phyllochron decreased throughout each regrowth cycle but the high R^2 in all cases (Section 7.3.3.1) shows the use of a single phyllochron would only introduce small errors in the calculation of node appearance. The onset of flowering or the occurrence of a <0 °C air frost (Section 7.3.3.1) also reduced the phyllochron which will be important in some locations and management situations. However, the actual phyllochron differed between 30–60 °Cd throughout the season (Figure 7.6). There are a number of studies that have demonstrated the effect of temperature on main-stem node appearance in lucerne (2.4.2.2) but none have presented node accumulation in relation to Tt or calculated a phyllochron. Robertson et al. (2002) reanalysed some of these studies to calculate a phyllochron of 34 °Cd for regrowth

lucerne. Results in this chapter suggest a single phyllochron was not suitable for 'Kaituna' lucerne in a temperate environment.

7.4.2.2   *Temperature threshold*

Before examining relationships between the phyllochron and environmental factors a test was conducted to determine the most appropriate temperature threshold for calculating Tt. A broken stick temperature threshold between T_b and T_o was shown to be more suitable than a single linear response (Section 7.2.2.2, Table 7.1). This is consistent with Moot *et al.* (2001) who compared the $Tt_{b1/5}$ threshold with Tt_{b5} and showed an improvement in the accuracy of both morphological (node appearance) and phenological (time of flowering) development simulations at Lincoln University. Justification for the past use of the Tt_{b5} temperature threshold is obscure (Sharratt *et al.*, 1989) but recent simulation work still use this threshold (Probert *et al.*, 1998a; Robertson *et al.*, 2002). The error of using the wrong threshold will be small in warmer climates where temperature is usually above the inflection point of the relationship (Figure 7.1).

The zero slope of phyllochron ($Tt_{b1/5}$) in relation to temperature (Table 7.3) indicated that Tt calculations did not introduce systematic errors into phyllochron values so the seasonal variation in phyllochron (Figure 7.6) must be in response to some other environmental factor.

7.4.2.3   *Photoperiod response*

The most suitable means of describing the seasonal variation in phyllochron was by inducing a Pp response 150 °Cd prior to the appearance of the first main-stem node of a regrowth cycle (Figure 7.8). Induction at this point in the crops development probably coincides with the initiation of the axial buds that develop into regrowth shoots. Evidence of this is given by branches, which also develop from axial buds. The appearance of a branch node occurred four main-stem nodes behind the most recently expanded main-stem leaf (Figure 7.12). These four leaves represent the time from the initiation of the axial bud to the appearance of its first node, assuming axial buds are

initiated when the main-stem leaf reaches full expansion as is the case for wheat (Hay and Kirby, 1991). With a phyllochron of 37 °Cd (Figure 7.9) these four leaves correspond to initiation of the bud ~150 °Cd after the appearance of its first node.

Regrowth main-stems of 'Kaituna' lucerne developed from axial buds (above ground) at the base of the previous cohort of main-stems (Section 7.3.4.3). These buds were frequently visible at the time older shoots were removed. The initiation of these basal buds must occur in reduced light conditions at the bottom of the canopy. Therefore, the induction of a photoperiod response in buds at their time of induction must be sensed by the upper canopy and transmitted to the basal buds. This is consistent with the activity of signal compounds that are produced in the leaves in response to Pp and transferred throughout the crop (Hay and Kirby, 1991).

Inducing a photoperiod response at the time of basal bud initiation gave a seasonal pattern of phyllochron that was 37 ± 7 °Cd (Figure 7.9). However, phyllochron increased to 60 °Cd when photoperiod at the time of bud initiation decreased below 16 h (23 January). Phyllochron gradually decreased as photoperiod continued to decrease and returned to 37 °Cd when the Pp had decreased to 13.5 hours (15 March). The regrowth from crops with an increased phyllochron occurred in March and April. This seasonal pattern is similar to that of shoot RUE, which declined substantially during March/April due to increased partitioning to perennial organs (Section 6.3.3). It is possible that the potential phyllochron during this period was 37 °Cd but the higher assimilate demand for perennial storage limits its expression. This is consistent with other reports of growth limitations reducing development (Section 2.2.3.4). The alternative possibility is that shoot development was slowed to reduce assimilate demand and make more available for perennial storage.

A number of induction points (Section 7.3.3) and a daily response to Pp were all unsuccessful at removing the hysteresis type response to Pp (Figure 7.7). This contrasts the suggestion by Jamieson *et al.* (1998a) that hysteresis is a result of incorrect representation of Pp. These authors were able to remove hysteresis in their photoperiod response of final leaf number using Pp at the point of transition from vegetative to

reproductive growth (Brooking *et al.*, 1995). Jamieson *et al.* (1995b) were also able to remove Pp response of phyllochron using apex temperature instead of air temperature to calculate Tt. The relevance of this finding is uncertain for lucerne which has its apex in the air at the top of the stand at all times. Thus, air temperature would seem to be the most suitable measurement.

7.4.2.4   *Using seasonal phyllochron data to improve LAI quantifications*

Leaf area index showed a stronger relationship with main-stem node number (Figure 7.3) than it did with Tt (Figure 7.2). Main-stem node appearance controls the appearance of main-stem leaves and the potential for branching (axial bud appearance). The ability to account for this will improve the accuracy and robustness of LAI simulations. However, there was still systematic variation in the relationship between LAI and main-stem node indicating other components of LAI showed a different seasonal response to that of phyllochron. There are a number of legume models that simulate LAI as a direct function of main-stem node appearance (Boote *et al.*, 1998) assuming the other components of LAI expansion occur in proportion to main-stem node appearance. This simulation approach was developed for soy beans that do not display substantial branching (Sinclair, 1984). Pengelly *et al.* (1999) have also been successful using this approach to simulate the LAI of branching annual tropical legumes in Queensland, Australia where the photoperiod effect is small.

The variability in the relationship between main-stem node and LAI in the current research may be due to seasonal changes in branch expansion, and/or senescence affecting net leaf appearance and subsequent LAI expansion (Section 2.4.2). Thus, the next step in quantifying seasonal variation in LAI expansion was to examine these components.

7.4.3   Leaf appearance

7.4.3.1   Branching

Main-stem branching was expressed at the first node (Figure 7.12) when the fourth or fifth main-stem node reached full expansion (Figure 7.10). Branch expression remained about four nodes behind the most recently expanded leaf throughout each regrowth period (Figure 7.12) and 2.7–3.5 leaves were produced per main-stem node. This differs substantially to Robertson *et al.* (2002) who simulated lucerne LAI assuming only one leaf was produced at each main-stem node.

Total node accumulation was a linear function of main-stem node appearance once branching began (Figure 7.10). Total node accumulation remained linear because node appearance stopped at lower main-stem node positions once a substantial number of leaves appeared above them (Figure 7.12). This is most likely due to shading from overlying canopy layers as the size of leaves increase as the point of insertion increases (Section 2.4.2.5). In contrast, Black *et al.* (2002) showed an exponential increase in total leaf number for pot grown legume seedlings (i.e. little competition) that continued to produce leaves at each node.

The changed branching response at different times of the season (Figure 7.10) indicated branching responded differently to the environment than main-stem node appearance. This may be due to differences in temperature thresholds for these processes (Boote *et al.*, 1998), different Pp responses or growth factors that effect branch expression (Hesketh *et al.*, 1991). Controlled environment studies have shown lucerne branching increases with shorter Pp (Section 2.4.2.3) and this possibly explains why branching was least in the long days of summer (Figure 7.10). These data indicate separate environmental responses will be needed to simulate branching and more data is needed to accurately quantify these responses. It is also likely such responses are cultivar dependent (Evans and Peaden, 1984).

The increased branching at lower stem densities can partly compensate for the continued decline in lucerne plant density. However, branching was not expressed until the appearance of the fourth or fifth node and branch leaves are smaller than main-stem leaves (Section 2.4.2.5). Therefore, increased branching cannot be expected to fully compensate for less main-stems. This was demonstrated in Chapter 4 where substantial weed invasion occurred in the irrigated lucerne plots in the 2001/02 season when there were more gaps in the lucerne canopy due to lower stem density.

7.4.3.2   Senescence

Branching gives an explanation of total node appearance and information on senescence is needed to quantify net leaf appearance. Leaf senescence demonstrated a broken sick response to main-stem node accumulation (Figure 7.11). Figure 7.12 shows that senescence initially occurred from the lower order nodes in the canopy and progressed upward behind the point of maximum branching as the canopy developed. The initial senescence occurred at a rate of 0.3 leaves per main-stem node from main-stem nodes 1 to 9 (Figure 7.11), due to death of older leaves. This was consistent with Robertson *et al.* (2002) who scheduled the death of leaves at a main-stem node (they assume no branching) every 107 °Cd (~37 °Cd*1/0.3).

The rate of senescence increased to 1.08 leaves per main-stem node following the appearance of the ninth node. This was probably due to mutual shading from over lying canopy layers because LAI was ~3.5 with nine main-stem nodes (Figure 7.3). This corresponds to a R/R_o of ~0.90 (Section 2.4.1.1) indicating the radiation levels at the base of the canopy are low. At this point the situation changes from senescence affecting LAI formation to LAI formation affecting senescence. Robertson *et al.* (2002) deal with this occurrence by increasing senescence as a fraction of total leaf area above a LAI of 4.0. The increased senescence at high LAI values is of less importance because changes in LAI above the critical level (3.5) do not affect R/R_o calculations (Section 2.4.1.1)

7.4.4 Leaf size

Figure 7.4 demonstrated a linear relationship of LAI with net leaf number for summer regrowth cycles. However, the slope of this relationship was less in the spring indicating leaf size also displayed seasonal variability. Pearson and Hunt (1972a) have also reported a differing environmental response for leaf appearance and leaf expansion of lucerne. They showed lucerne plants grown in 15/10 and 20/15 °C (day/night) had fewer but larger leaves than plants grown at 30/25 °C. The reduction in leaf size is possibly due to high temperature limitations on growth and fits the common perception that growth is more sensitive to environment than leaf appearance which is a development process (Penning de Vries *et al.*, 1989). It is also possible that leaf expansion rates were responding to Pp. Hay and Heide (1983) demonstrated the leaves of *Poa pratensis* grew 2–4 times larger with a 24 hour Pp than with an 8 hour Pp (with similar radiant energy receipts) due to greater cell expansion. Another possibility is that the development of leaf expansion and leaf appearance have different temperature thresholds (Section 2.2.3.3).

7.5   Conclusions

This chapter has provided quantification of the environmental response of the components needed to describe LAI dynamics.

- Main-stem node appearance showed a linear relationship with accumulated Tt within regrowth cycles but phyllochron ranged from 30–60 °C within a season.

- The most suitable method of describing the seasonal changes in phyllochron was to induce a Pp response 150 °Cd prior to the appearance of the first node.

- The Pp response of lucerne was an increased phyllochron (40–60 °C) in crops that were induced with a decreasing Pp between 16 and 13.5 hours but phyllochron was 37 ± 7 °C for the remainder of the season.

- Branching of a main-stem was displayed at the appearance of the fifth main-stem node and between 3.7 and 2.7 leaves were produced per main-stem node beyond this point.

- Senescence of leaves proceeded at 0.3 leaves per main-stem node up to the ninth node then increased to 1.08 leaves per main-stem node beyond this point.

- Details of the effect of environmental factors on leaf expansion rates are needed to quantify seasonal change in LAI.

8 Water shortage influences on lucerne production

8.1 Introduction

The overall aim of this thesis was to explain the influence of water shortages on crop yield. To do this it is necessary to quantify the extent of water shortage and the influence of this shortage (water stress) on the processes that contribute to yield (Figure 6.1). Water stress can be quantified by the relative difference between water supply from soil water extraction by the roots and the E_T demand of the crops shoots (Section 2.5.3.1). The water supply can be quantified by measuring a crops transpiration (E_T) in a water limited situation (Section 2.5.2). The influence of soil water extraction on water supply was dealt with in Chapter 5. Therefore, to quantify the effects of water shortage on forage yield we need a suitable representation of the crops E_T demand to define the level of water stress. This can then be related to the yield forming processes quantified in Chapters 6 and 7.

Transpiration can be calculated from a soil water balance by calculating/removing evaporation losses from the soil surface (E_S) and the outer surfaces of the crop canopy (E_C). Transpiration demand is influenced by atmospheric conditions, which can be expressed in amounts of water (mm) using the calculation of potential evapotranspiration (EP; Section 2.5.1.1). A crops E_T demand is also affected by canopy characteristics, and multiplying EP by crop cover may give a suitable representation of E_T demand (Section 2.5.1.1). An alternative calculation of E_T demand is based on a constant E_T efficiency (E_T_eff). This approach requires less meteorological data than the physical approach (EP) but is dependant on more general assumptions (Section 2.5.1.3).

The objective of this chapter was to quantify water stress and the influence of this on yield forming processes. The quantification of water stress required a value of E_T to represent water supply. Evaporation losses (E_S and E_C) were calculated to estimate this value. It also required a calculation of E_T demand and the E_T of irrigated crops was related to EP to provide this. In addition the E_T_eff of lucerne was also assessed as a

predictor of E_T demand. Finally, E_T from dryland crops was related to E_T demand to represent water stress and this was related to yield forming processes.

8.2 Materials and methods

8.2.1 Treatments

This chapter uses data from all five perennial seasons from Experiment 1 ($I8_{97/98}$–$I8_{01/02}$) and the first sowing date from the two seasons recorded in Experiment 2 ($I9_{00/01}$–$I9_{01/02}$). Dryland treatments in $I9_{01/02}$ were rain-shelters from 16 August 2001–12 June 2002 (Section 3.2.5.2).

8.2.2 Measurements

Dry matter yields were measured at the end of every regrowth cycle (within 24 hours before grazing) and at 7–10 d intervals within all regrowth cycles in $I8_{00/01}$, $I8_{01/02}$, $I9_{00/01}$ and $I9_{01/02}$. Details of DM measurement were presented in Section 3.3.2 and DM results presented include production from the few weeds (<1%) that grew in the lucerne plots (Section 4.3.1.2).

Fractional radiation interception (R/R_o) measurements are described in Section 3.3.5. Briefly, radiation interception was recorded daily in $I8_{00/01}$ using solarimeters and recorded at 3–7 d intervals in $I8_{01/02}$, $I9_{00/01}$ and $I9_{01/02}$ using a canopy analyser.

Soil water measurements were made at 5–14 d intervals. This give 98 measurement points from July 1997–25 June 2002 in Iversen 8 and 68 measurement points from 1 November 2000–12 June 2002 in Iversen 9. Soil water measurements were described in Section 3.3.4 and the calculation of water use (WU) was detailed in Section 3.4.3.4.

8.2.3 **Calculations**

8.2.3.1 *Ground cover*

Ground cover was assumed to be analogous to R/R_o. The relationship between DM and R/R_o (Section 3.4.4.3) was used to extrapolate R/R_o in Iversen 8 from 1997–2000 where R/R_o was not measured directly. Ground cover was extrapolated to daily values by linear interpolation between successive measurement dates.

8.2.3.2 *Potential transpiration and evaporation*

The assumptions used to separate EP into potential evaporation from canopy (EP_C), soil (EP_S) and plant transpiration (EP_T) were; 1. that evaporation of water from external canopy surfaces (E_C) takes priority over other evaporation (Section 2.1.1.2), 2. any remaining EP is partitioned between soil evaporation (E_S) and transpiration (E_T) in proportion to R/R_o:

Equation 8.1
$$EP_C = EP$$
$$EP_S = (EP-E_C) * (1-R/R_o)$$
$$EP_T = (EP-E_C) * R/R_o$$

EP_C, EP_S and EP_T have lower limits of zero and $1-R/R_o$ represents the canopy gap fraction. Evaporation potentials were calculated daily for individual replicates of each treatment using measured and extrapolated R/R_o data (Section 8.2.3.1).

8.2.3.3 *Canopy evaporation*

Evaporation from the canopy (E_C) was calculated following the procedure used by Leuning, *et al.* (1994). It was assumed E_C occurred following each precipitation event (P_{R+I}) and was the minimum of EP and P_{R+I} (mm) that is intercepted by the canopy (IP_{R+I}):

Equation 8.2
$$E_C = min(EP, IP_{R+I})$$

Where IP_{R+I} was assumed to increase with ground cover and was calculated as a function of R/R_o and P_{R+I}:

Equation 8.3 $IP_{R+I} = P_{R+I} * R/R_o + (IP_{R+I\,i-1} - EP_{i-1})$

IP_{R+I} remained on the canopy from the previous days P_{R+I}, if $EP_{i-1} < IP_{R+I\,i-1}$ on that day. IP_{R+I} has a maximum value dependant on LAI and a canopy storage coefficient (CS):

Equation 8.4 $IP_{R+I\,max} = LAI * CS$

CS has a value of 0.7 mm (Section 8.4.1.1). Canopy evaporation was calculated daily for individual replicates of each treatment using R/R_o data (Section 8.2.3.1) and LAI was calculated from R/R_o using Equation 2.4 and an extinction coefficient of 0.8 (Section 2.4.1.1).

8.2.3.4   Infiltration

Infiltration (Inf_{R+I}) of P_{R+I} into the soil was estimated as precipitation reduced by IP_{R+I}

Equation 8.5 $Inf_{R+I} = P_{R+I} - IP_{R+I}$

8.2.3.5   Soil evaporation

Soil evaporation (E_S) was calculated for the dryland treatments in $I9_{01/02}$ using four methods, and these were then compared to select the most suitable.

The first method was adapted from Dunin *et al.* (2001) and is termed Dunin E_S. E_S is assumed to be a fraction of water use (WU) dependant on R/R_o:

Equation 8.6 $E_S = WU * (1 - R/R_o)$

The second method used was formulated by Ritchie (1972) and is referred to as Ritchie E_S. This method calculates E_S in two phases, Phase 1 (E_S1) is energy limited and Phase 2 (E_S2) is diffusion limited. E_S1 is dependant on EP and reduced by ground cover:

Equation 8.7 $\qquad E_S1 = EP * (1\text{-}R/R_o) \qquad$ when $\Sigma E_S \leq U$

E_S is summed daily and is switched from E_S1 to E_S2 when ΣE_S exceeds U (the point when E_S becomes diffusion limited):

Equation 8.8 $\qquad E_S2 = \alpha * t^{1/2} \qquad$ when $\Sigma E_S > U$

Where t is time in days, U and α are related to soil texture with values of 9 mm and 4.4 $mm/d^{-1/2}$ reported for a silt loam in Canterbury (Jamieson *et al.*, 1995a). On days of transition between E_S1 and E_S2, E_S is calculated as 0.6*EP and t = 1 on the first day that $\Sigma E_S > U$ and increases by 1 each subsequent day. Precipitation events are subtracted from ΣE_S and t declines (Equation 8.9) to account for the subsequent increase in soil evaporation (Equation 8.8):

Equation 8.9 $\qquad t = [(\Sigma E_S - U)/\alpha]^2$

On days where $E_S2 > E_S1$ soil evaporation is limited to E_S1. In this situation the soil is not dried to the same extent as in Equation 8.8 so E_S2 will be higher on the following day. This is accounted for by reducing t using Equation 8.9.

The third method was developed after critiquing the first two methods (Section 2.1.1.1) and is referred to as Method 3. E_S is calculated in two phases but E_S1 was calculated using EP_S, which also accounts for the influence of E_C:

Equation 8.10 $\qquad E_S1 = EP_S, \qquad$ where $\Sigma EP_S \leq U$

This assumes that E_C proceeds with preference to E_S because the sites of E_C are closer to turbulent air mass and E_C will reduce VPD, which will reduce the potential for other evaporation.

EP_S is summed daily (ΣEP_S) and for days of transition from E_S1 to E_S2, E_S is calculated as:

Equation 8.11 $\qquad E_S = (U - \Sigma EP_{S\,i-1}) + [EP - (U - \Sigma EP_{S\,i-1})]*0.6$

Where $\Sigma EP_{S\,i-1}$ is ΣEP_S for the previous day. On days where $\Sigma EP_S > 9$ mm (and $Inf_{R+I} = 0$), E_S is limited by diffusion but also EP_S (Boesten and Stroosnijder, 1986) and calculated as:

Equation 8.12 $\qquad E_S2 = (1-R/R_o) * \beta * \Sigma EP_S^{1/2}$

This differs from E_S2 in Ritchie E_S by the inclusion of the $1-R/R_o$ factor and the use of ΣEP_S instead of t. The β parameter (2.4 mm$^{1/2}$) is analogous to α in Equation 8.8 and was calculated from a tuning exercise using data of Jamieson *et al.* (1995a), who measured an α of 4.4 mm/d$^{-1/2}$ for a bare ($R/R_o = 0$) silt loam in Canterbury over a 9 day period. Firstly, E_S was calculated from Equation 8.8 (using $\alpha = 4.4$ mm/d$^{-1/2}$) and ΣE_S was graphed as a function of t to reproduce the evaporation data series that Jamieson *et al.* (1995a) calculated α from (Figure 8.1). The EP over this period was 3.3 mm/d ($\pm$ 0.3 mm/d). Secondly, E_S was calculated using Equation 8.12 (with $R/R_o = 0$), a daily EP of 3.3 mm and a starting β of 4.4 mm$^{1/2}$. This ΣE_S was plotted on the same figure as the reproduced data series and the value of β was progressively reduced until the two plots overlaid (Figure 8.1). This gave a value of 2.4 mm$^{1/2}$.
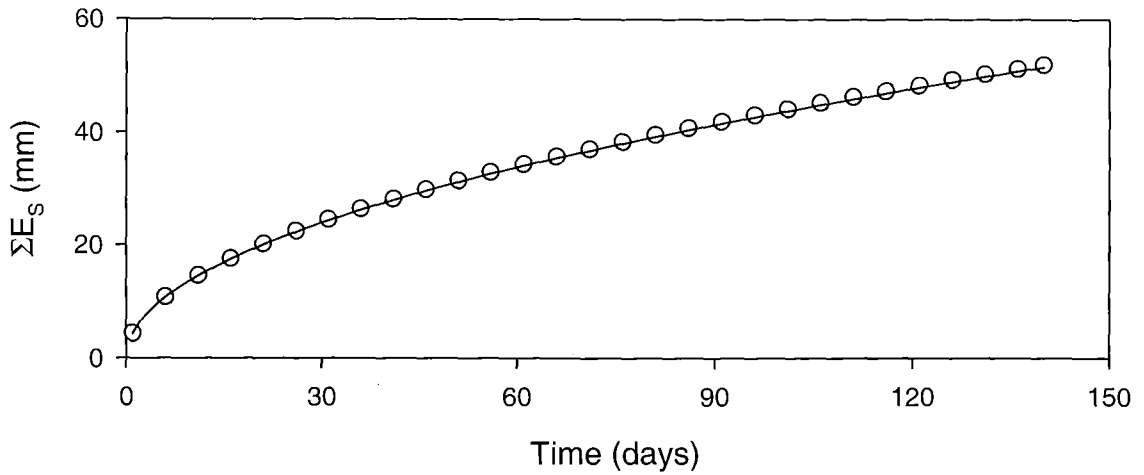
Figure 8.1 Bare soil evaporation (E_S) calculated using Equation 8.8 with $\alpha = 4.4$ mm/day$^{-1/2}$ ( ) and Equation 8.12 where $EP_S = t*3.3$ mm/d, $R/R_o = 1$ and $\beta = 2.4$ mm$^{1/2}$ (———).

Method 3 also differed from Ritchie E_S because amounts of $Inf_{R+I} <U$ were evaporated at EP_S (ΣEP_S remained unchanged while this evaporation occurred) rather than E_S2. The inclusion of $(1-R/R_o)$ in Equation 8.12 reduces E_S when water uptake by crop roots (E_T) speeds the drying of the soil and reduce E_S. This is based on the assumption that the fraction of soil drying caused by transpiration will increase and evaporation decrease in opposing proportions to increasing R/R_o. This is additional to the shading effects of R/R_o on E_S, which are already accounted for in ΣEP_S (Equation 8.12). To demonstrate the effect of the R/R_o factor in Equation 8.12 a fourth calculation (Method 4) was included, which excludes the R/R_o factor from E_S2 calculations (Equation 8.12).

The selected method was used to calculate E_S daily for each treatment using daily R/R_o (Section 8.2.3.1) and EP_S (Section 8.2.3.2) calculations.

8.2.3.6 Transpiration

Transpiration (E_T) was calculated using a water balance. Firstly, WU was calculated from the change in profile soil water content (Section 3.3.4) and the sum of infiltration (ΣInf_{R+I}) for that period:

Equation 8.13 $\Sigma WU = \Sigma Inf_{R+I} - \Delta SWC$

Then daily E_T was calculated for individual replicates of all treatments:

Equation 8.14 $E_T = (EP * \Sigma WU/\Sigma EP) - E_S$

Where ΣWU and ΣEP represent the sums for the measurement period in which the day of calculation occurs and EP and E_S are daily values. Transpiration was assumed to be zero and E_S equal to WU for the few early season periods when lucerne was dormant and Equation 8.14 gave negative values.

8.2.4 Selecting a soil evaporation calculation

The four methods of calculating E_S (Section 8.2.3.5) were assessed by comparing the estimated and measured soil water depletion (ΔSWC) in the top 0.2 and 0.4 m of soil from dryland treatment in $I9_{01/02}$. Rain-shelters excluded rainfall for 300 d, which provided an extended period where cumulative errors in evaporation calculations could be assessed. Although E_S was not measured directly it was assumed that all E_S would occur from the top 0.4 m of soil. Assuming that some of the drying in this layer was due to root extraction for transpiration an accumulation of $E_S \geq \Delta SWC$ indicated an overestimation in E_S. The E_S calculation that gave the most realistic estimation was selected and used for subsequent E_T calculations.

8.2.5   Validation of canopy and soil evaporation calculations

The E_C and E_S calculations were validated using E_T values from irrigated lucerne. Values of E_T were calculated from a water balance so errors in E_S or E_C calculations will be displayed as incorrect estimations of E_T. Irrigated treatments were used because E_T was not restricted by SWD and the frequent wetting produces the greatest E_S and E_C losses, which highlights any errors. Validations were made by separating data into three arbitrary groups:

1. Measurement periods where $R/R_o < 0.7$. E_S would make a high contribution to water balance.

2. Measurement periods where $IP_{R+I}/EP > 0.05$. E_C would make a higher contribution to the water balance.

3. Other measurement periods. E_S and E_C would have made a smaller contribution to the water balance.

Linear regressions were fitted to E_T as a function of EP_T for each group with the assumption that errors in the calculation of E_S will cause group 1 to differ from group 3 and errors in the calculation of E_C will cause group 2 to differ from group 3.

A single regression was fitted to all of the above groups and the slope of the relationship (b) was used as a coefficient to calibrate EP_T for local conditions (EP_{Tb}).

Equation 8.15 $EP_{Tb} = EP_T * b$

All values of EP_T were corrected by this coefficient and, following this calculation EP_T refers to calibrated values. A residual analysis was conducted to test the assumptions used in formulating EP_T. The assumption that E_T increases linearly with R/R_o (Equation 8.1) was tested by fitting a linear regression to residuals ($E_T–EP_T$) as a function of R/R_o, where a slope $\neq 0$ indicates this assumption produces a systematic error. Within this relationship a separate regression was fitted to points from periods of high E_C potential

($IP_{R+I}/EP > 0.1$) to test the assumption that E_C reduces E_T by an equal amount (Section 8.2.3.2). If this assumption was incorrect the residuals from periods of high E_C would have a higher y-axis intercept than the remaining periods.

In total, E_T was measured over 171 sample periods (5–15 d) from the seven paddock/season combinations (Table 3.3). Of these, 140 were used for analysis and 30 were omitted due to errors. For example large rainfall events (>20 mm) occurred in the spring when the SWD was close to zero for $I8_{99/00}$ and $I8_{00/01}$ causing drainage and overestimates of E_T in irrigated treatments. In some instances, uneven irrigation events occurred in short measurement periods and there were inaccuracies in quantifying irrigation (runoff and inaccuracies in rain-gauge measurements due to crosswinds).

8.2.6 Transpiration efficiency

Transpiration efficiencies were calculated in a number of regrowth cycles to assess stability and subsequent suitability as a predictor of E_T demand. The E_T_eff was calculated for dryland and irrigated treatments in each regrowth cycle from $I8_{00/01}$, $I8_{01/02}$ and $I9_{01/02}$ and the regrowth cycles from the first sowing date treatments in $I9_{00/01}$. For each of the 40 regrowth cycles DM was plotted against accumulated E_T (Section 8.2.3.6) and a linear regression was fitted. The slope of the linear regression represented E_T_eff. Regressions were fitted to the mean data from three replicates. Transpiration efficiency values were then normalised by multiplying by the mean VPD (Figure 3.4) for each cycle.

8.2.7 The effect of water shortages on transpiration

8.2.7.1 Quantifying water stress

Water stress was represented as a reduction in transpiration and quantified by E_T relative to transpiration demand (E_T/EP_T). A value of 1.0 shows E_T was equal to EP_T and indicated no water stress. When water supply becomes limiting E_T declined below EP_T and the greater the shortfall the greater the water stress and the closer to zero E_T/EP_T will become. E_T/EP_T was calculated for each regrowth cycle from values integrated from the date of first sample to the date of final sample.

8.2.7.2 The feedback of water stress on transpiration demand

Water stress may reduce crop cover (relative to an unstressed crop), which will reduce EP_T and influence subsequent E_T and water stress. The influence of this feedback on E_T was assessed by comparing the EP_T of irrigated crops to dryland crops (EP_{Tdry}/EP_{Tirr}).

8.2.7.3 Water stress effects on yield forming processes

The effect of water stress on the processes that contribute to yield was assessed by presenting dryland values (quantifying the process) as a fraction of the irrigated value ($f_{D/I}$) for the corresponding period of E_T/EP_T calculation (Section 8.2.7.1). The $f_{D/I}$ was then regressed against E_T/EP_T to demonstrate the sensitivity of each variable to water stress. Data was used from $I9_{01/02}$ and $I8_{00/01}$ because these were the situations where the greatest water deficits occurred (Section 5.3.1.1).

8.2.8 Statistics

Annual sums of E_T, E_S and E_C were compared using a split-plot ANOVA with paddock/season combination as main-plots and irrigation treatment as sub-plots. Probabilities and standard errors of the mean (SEM) are presented for the comparison of sub-plot means within and between main-plots. Detail on ANOVA, SEM and regression methods are given in Section 3.5.

8.3 Results

8.3.1.1 Dry matter production

Dry matter accumulation from the irrigated and dryland crops in Iversen 8 was presented in Figure 4.2. In Iversen 9 irrigated treatment produced more (P<0.05) DM than dryland in all but the final regrowth cycle of the 2000/01 season (Figure 8.2). There was no difference in DM yield in the first three regrowth cycles of the 2001/02 season but irrigated lucerne yields progressively increased above dryland yields (P<0.05) in the final three regrowth cycles.
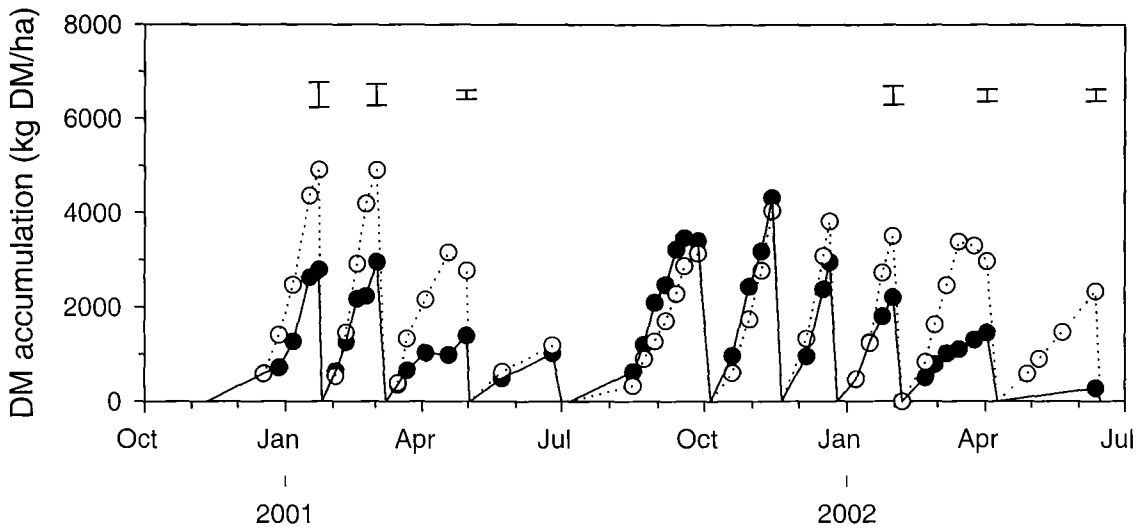
Figure 8.2 Dry matter (DM) accumulation of dryland (●) and irrigated (○) lucerne grown in Iversen 9 from 24 October 2000 (sowing date) to 1 July 2002 at Lincoln University, Canterbury, New Zealand.

Note: Bars represent one standard error of the mean for the final measurement of cycles where there was a difference (P<0.05) between dryland and irrigated treatments.

8.3.1.2   Leaf area index

The LAI of irrigated lucerne in $I8_{00/01}$ increased from zero immediately post grazing to ~4.0 prior to the next grazing (Figure 8.3a). These crops only produced a greater (P<0.05) LAI than dryland treatments during the last regrowth cycle of the season. Dryland lucerne in $I9_{01/02}$ developed a larger (P<0.05) LAI than the irrigated treatment in the first regrowth cycle with no difference in the second, but a smaller (P<0.05) LAI for the remaining four cycles (Figure 8.3b).
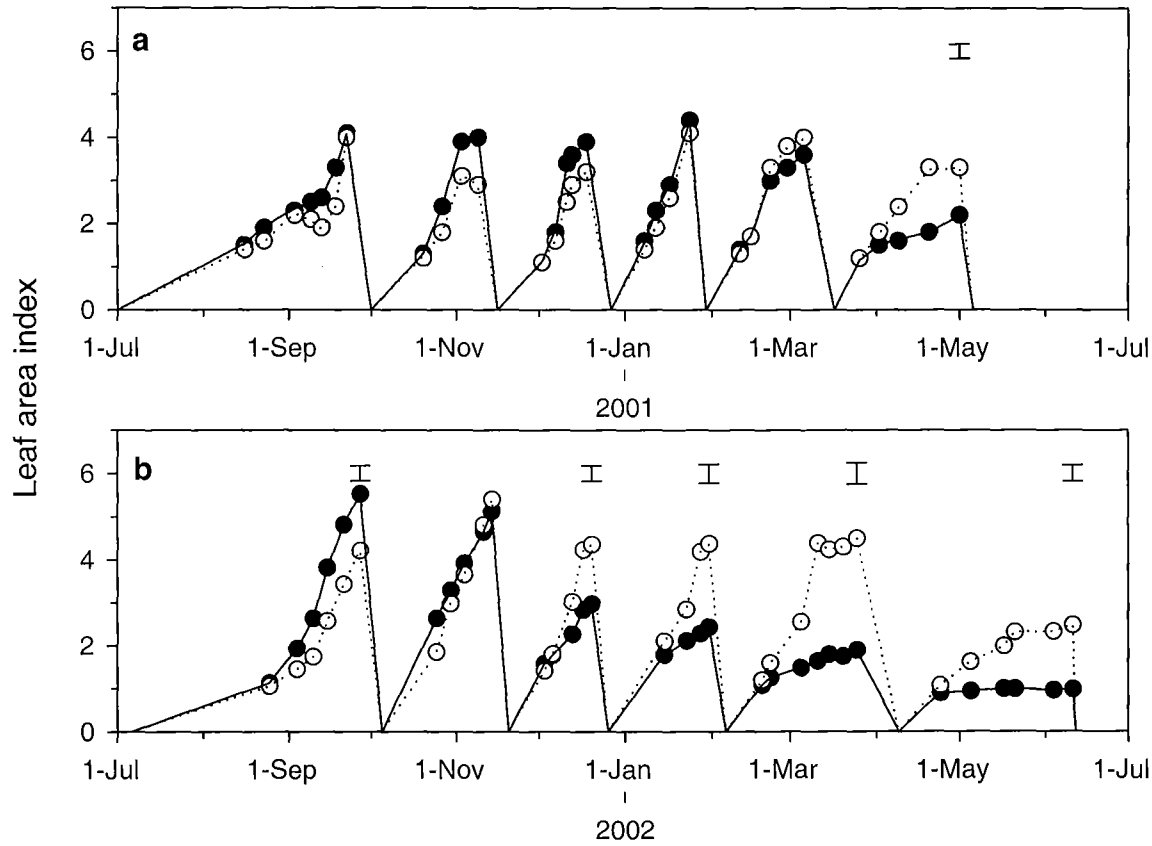
Figure 8.3 Leaf area index of dryland (●) and irrigated (○) lucerne grown in; a) $I8_{00/01}$ and b) $I9_{01/02}$ at Lincoln University, Canterbury, New Zealand.

Note: Bars represent standard error of the mean for the final measurement of periods when there was a difference (P<0.05) between dryland and irrigated treatments.

8.3.2   **Evaporation calculations**

8.3.2.1   *Selection of soil evaporation calculation*

Methods 3 and 4 gave the lowest predictions of E_S throughout the test period (Figure 8.4) and the inclusion of the R/R_o variable to account for soil drying by E_T (Method 3) reduced total E_S from 45 mm (Method 4) to 25 mm. During the first regrowth cycle (Period 1), the E_S calculated from Method 4 was slightly greater than Method 3 and the differences became more pronounced in Period 2 (30 September 2001–1 February 2002) where Method 4 E_S was similar to the ΔSWC in the top 0.2 m of soil. The ΔSWC was negligible during Period 3 (1 February 2001–12 June 2001) and Method 4 predicted 10 mm E_S compared with 5 mm for Method 3.

The 'Ritchie' and 'Dunin' methods for calculating E_S were similar during Period 1 and less than the ΔSWC in the top 0.4 m of soil. This was consistent with the low EP and high LAI at this time, indicating most of the ΔSWC was due to transpiration. 'Dunin' E_S accumulated more than the ΔSWC in the top 0.4 m of soil during Period 2 and the 'Ritchie' E_S accumulated at a similar rate, implied all the drying in this layer was due to E_S. This seems unlikely to be a true indication of what was happening as the crop was actively growing during this period. During Period 3 'Dunin' and 'Ritchie' E_S accumulated a further 20 and 30 mm (respectively) at a time when the ΔSWC was negligible, again indicating these two calculations overestimated the E_S.
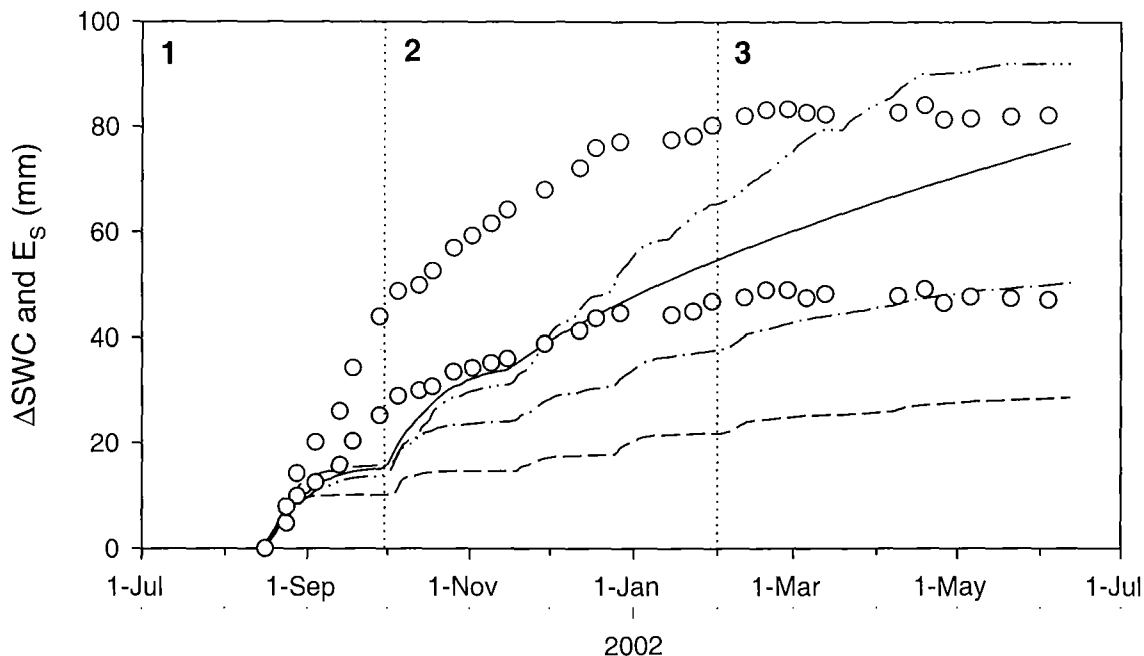
Figure 8.4 Cumulative 'Dunin' (—··—), 'Ritchie' (———), 'Method 3' (-----) and 'Method 4' (—·—) soil evaporation (E_S) and cumulative change in actual soil water content (ΔSWC) from the top 0.2 ( ) and 0.4 m (O) of the soil profile for dryland lucerne crops grown under rain-shelters ($I9_{01/02}$) at Lincoln University, Canterbury, New Zealand.

8.3.2.2   *Validation of evaporation calculations*

Regressions fitted to each of the three groups identified in Section 8.2.5 (Figure 8.5) had an $R^2 > 0.70$ (Table 8.1), the same (P<0.01) slopes (~0.86) and a y-axis intercept of zero (Table 8.1). This showed the use of E_C (Equation 8.2) and E_S (Equation 8.10–8.12) in the calculation of EP_T did not produce any systematic variation in its values relative to E_T and indicated the calculations were correct.
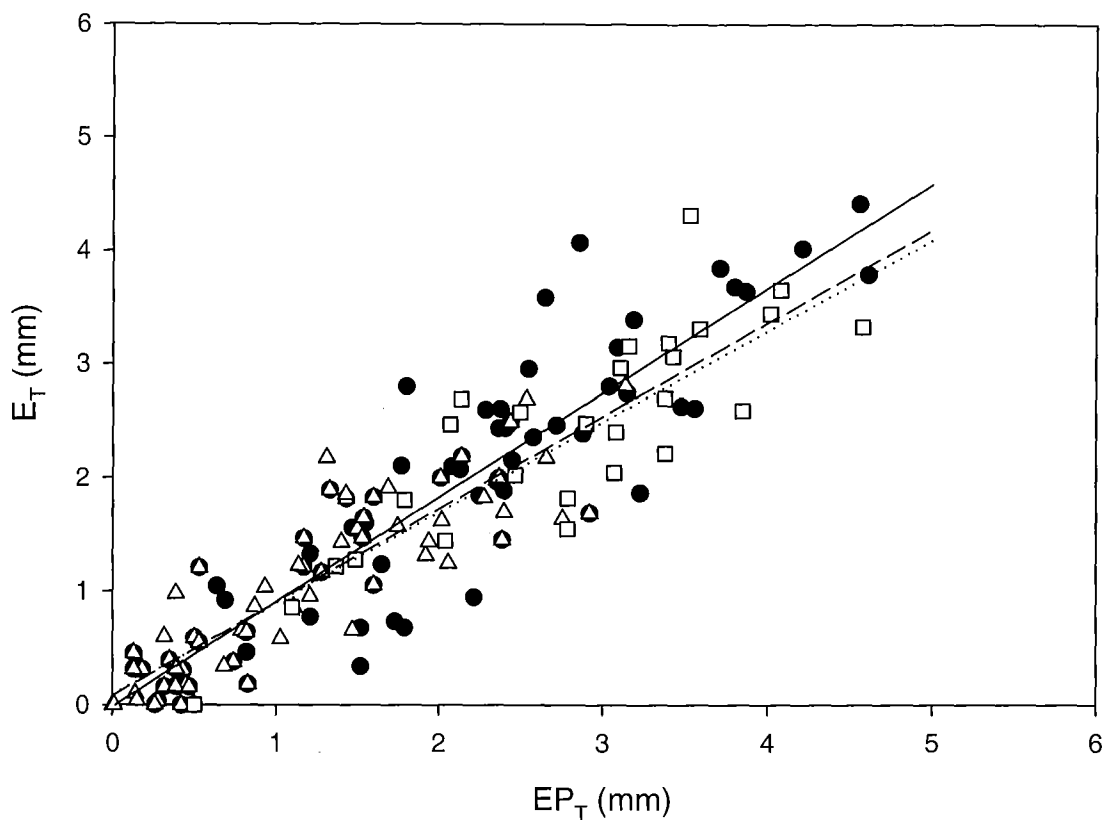
Figure 8.5 Mean daily transpiration (E_T) in relation to mean daily transpiration potential (EP_T) from 140 measurement periods for irrigated lucerne grown at Lincoln University, Canterbury, New Zealand from 1997/98–2000/02. Regressions are grouped in periods where $IP_{R+I}/EP > 0.05$ (●,--), $R/R_o < 0.7$ (△,····) and other periods (□,—). Coefficients for regressions are presented in Table 8.1

Table 8.1 Coefficients of regressions fitted to transpiration (y) as a function of transpiration potential (x) for irrigated lucerne grown from 1997/98–2001/02 at Lincoln University, Canterbury, New Zealand.

Grouping	a	b	R^2	P
$R/R_o < 0.7$	-0.09 (0.08)	0.81 (0.06)	0.77	0.27
$IP_{R+I}/EP > 0.05$	-0.02 (0.10)	0.92 (0.05)	0.82	0.88
Others	-0.09 (0.30)	0.82 (0.10)	0.72	0.78
All	-0.08 (0.08)	0.86 (0.03)	0.81	0.29

Note: a = y-axis intercept, b = slope, R^2 is the coefficient of variation and P is the probability of the hypothesis test a ≠ 0. Bracketed values are standard errors of coefficients. See Section 8.2.5 for rationale of groupings.

8.3.3   Transpiration demand

A regression fitted to all the data in Figure 8.5 had a R^2 of 0.81 and a y-axis intercept of zero (Table 8.1) showing the EP_T gave a good description of crop E_T and was a suitable predictor of E_T demand. The slope of 0.86 was different to 1.0 (P<0.001) and was used as a coefficient to calibrate EP_T (Section 8.2.5) and represent crop E_T demand. All values of EP_T presented in the remainder of this chapter are calibrated using this coefficient. The slope of the residual (E_T–EP_T) as a function of R/R_o (Figure 8.6) did not differ from zero (P<0.001). This shows the linear dependence of EP_T on R/R_o did not introduce any systematic variation into EP_T calculations and justified the assumption that E_T was linearly related to R/R_o. A regression fitted separately to the residuals for periods of high E_C ($IP_{R+I}/EP > 0.1$) did not differ (P<0.001) from the regression fitted to other points. This showed the assumption that EP_T was reduced by E_C did not introduce any systematic errors. This also indicated the occurrence of E_C reduced E_T and this assumption in Equation 8.1 was correct.
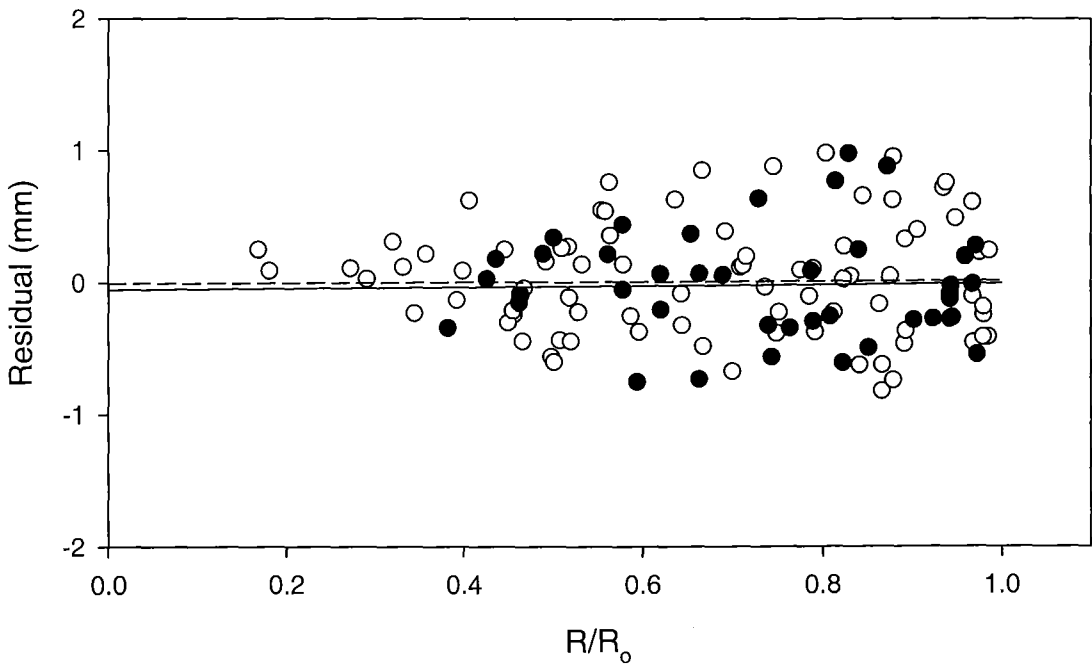
Figure 8.6 Residual (EP_T–E_T) from the linear regression of E_T against EP_T in relation fractional radiation interception (R/R_o) of irrigated lucerne grown at Lincoln University, Canterbury, New Zealand. Separate regressions were fitted to periods where $E_C>0.1*EP$ (●,‒‒) and the remaining data points (○,—).

Note: Linear regressions —) y = 0.06(0.13)-0.05(0.19)x, ‒‒) y = -0.01(0.27)+0.02(0.37)x. Bracketed values are standard errors of the coefficients.

8.3.4   Patterns of evaporation and transpiration

8.3.4.1   Canopy evaporation

The calculated annual E_C ranged from 8 mm in the dryland treatment of $I9_{01/02}$ (rain-shelter) to 107 mm in the irrigated treatment of $I8_{97/98}$ (Table 8.2). The percentage of total precipitation evaporated from the canopy ranged from 3% in the rain-shelter treatment ($I9_{01/02}$) to 17% in dryland $I8_{97/98}$. Dryland crops generally had a higher proportion of E_C than irrigated crops. An example of the seasonal accumulation of E_C is displayed for $I9_{01/02}$ (Figure 8.7) and periods of greatest E_C occurred during rainfall, when the crop had a LAI ≥ 2.0. The seasonal pattern of E_C accumulation is displayed for all other treatments in Appendix 14.

Table 8.2 Annual canopy evaporation (mm) from dryland and irrigated lucerne crops over five seasons in Iversen 8 and two seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand. Bracketed values represent the percent of total precipitation that was evaporated from the canopy.

Paddock	Season	Dryland mm *(%)*	Irrigated mm *(%)*
Iversen 8	1997/1998	79 *(17.0)*	107 *(12.7)*
	1998/1999	96 *(13.6)*	103 *(10.4)*
	1999/2000	97 *(11.4)*	88 *(9.4)*
	2000/2001	73 *(12.5)*	77 *(8.8)*
	2001/2002	86 *(11.0)*	77 *(9.0)*
Iversen 9	2000/2001	34 *(11.3)*	56 *(9.0)*
	2001/2002	8 *(3.0)*	84 *(8.3)*
Probability		< 0.001	
SEM		1.8	

Note: See Section 8.2.3.3 for details on calculation of E_C.
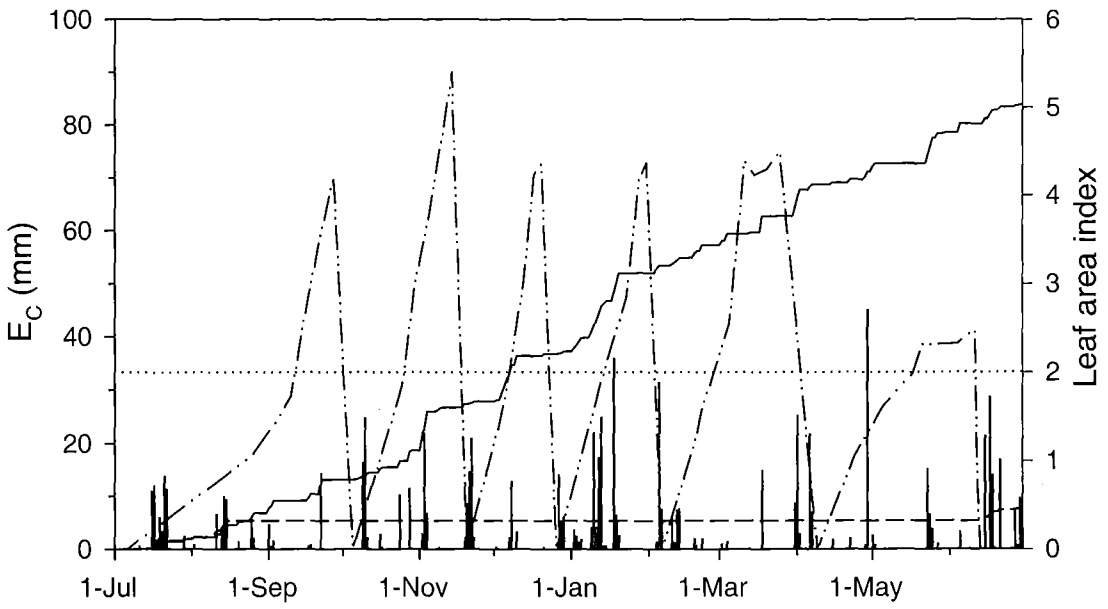
Figure 8.7 Cumulative canopy evaporation (E_C) from dryland (------) and irrigated (———) lucerne (treatment $I9_{01/02}$), rainfall (bars) and leaf area index ($\cdots-\cdots$) of irrigated lucerne crops from 1 July 2001–1 July 2002 at Lincoln University, Canterbury, New Zealand. ($\cdots\cdots$) marks a leaf area index of 2.

8.3.4.2   Soil evaporation

Annual totals E_S ranged from 36 mm for the rain-shelter treatment of $I9_{01/02}$ to 268 mm in the irrigated treatments of $I8_{99/00}$ (Table 8.3). Irrigated treatments displayed greater (P<0.001) E_S than dryland treatments except for $I9_{00/01}$ where the more frequent soil wetting in the irrigated treatments was offset by the higher LAI (relative to dryland treatments) reducing the potential for precipitation to evaporate from the soil. The E_S ranged from 26–34% of E_S+E_T in all treatments excluding the rain-sheltered treatment where E_S was 9% of E_S+E_T.

Table 8.3 Annual soil evaporation (E_S) from dryland and irrigated lucerne crops over five seasons in Iversen 8 and two seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand. Bracketed values represent soil evaporation as a percentage of total water use.

Paddock	Season	Dryland mm *(%)*	Irrigated mm *(%)*
Iversen 8	1997/1998	170 *(28)*	216 *(26)*
	1998/1999	170 *(28)*	255 *(30)*
	1999/2000	214 *(34)*	268 *(32)*
	2000/2001	195 *(28)*	255 *(32)*
	2001/2002	197 *(30)*	257 *(34)*
Iversen 9	2000/2001	153 *(33)*	149 *(22)*
	2001/2002	36 *(9)*	220 *(26)*
Probability		< 0.001	
SEM		6.0	

The seasonal pattern of E_S accumulation in $I9_{01/02}$ is displayed in Figure 8.8. The majority of E_S from irrigated lucerne occurred when $1\text{-}R/R_o > 0.5$, representing incomplete canopy closure. The E_S from dryland crops was only 36 mm during the same season and 15 mm occurred between 1 July–16 August 2001, prior to rain-sheltering. There was 30 mm evaporated from irrigated treatments during this period, because $1\text{-}R/R_o$ was lower in the dryland treatment in the first rotation (Figure 8.8). A further 20 mm evaporated from dryland crop during the period of rain-sheltering. The seasonal pattern of E_S accumulation for all other treatments is displayed in Appendix 15.
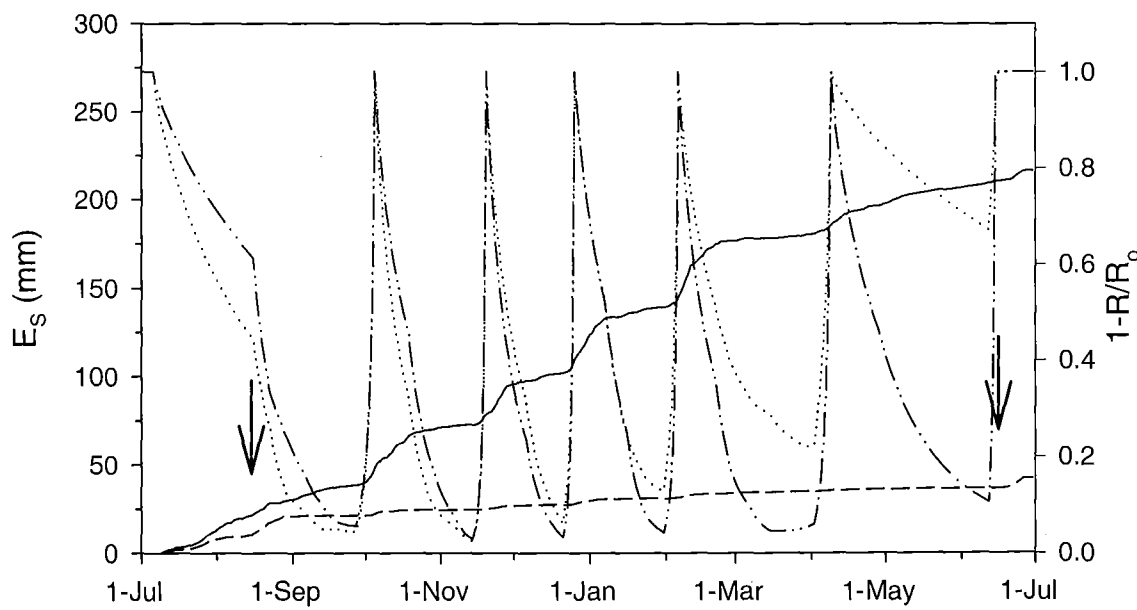
Figure 8.8 Cumulative soil evaporation (E_S) from dryland (------) and irrigated (———) lucerne and canopy gap fraction ($1\text{-}R/R_o$) of dryland (······) and irrigated (··–··) lucerne crops from 1 July 2001–1 July 2002 at Lincoln University, Canterbury, New Zealand. Arrows mark the beginning and end of rain-sheltering for the dryland treatments.

8.3.4.3   Transpiration

Annual E_T was ~550 mm for irrigated treatments (Table 8.4) and was $\geq 100\%$ of EP_T in all seasons except 1997/98. The E_T of dryland treatments was lower than irrigated treatments in dry seasons. For instance, E_T was 297 mm less than irrigated treatments (72% of EP_T) in $I9_{01/02}$ (30 mm rainfall) and 142 mm less (65% of EP_T) in $I8_{97/98}$ (488 mm rainfall). The 2000/01 season was also dry (587 mm rainfall) but the E_T of irrigated treatments in $I8_{00/01}$ was reduced relative to dryland by a decline in stem population and irrigation only increased E_T by 48 mm in this season. The 2001/02 season was wet (785 mm rainfall) and irrigation had no effect on E_T in $I8_{01/02}$. The E_T of irrigated treatments was 160 mm more than dryland crops in $I8_{99/00}$ despite it being the wettest of the five seasons (844 mm of rainfall). This difference was likely to be due to drainage because analysis of the seasonal pattern of E_T in 1999/00 (Appendix 16) showed irrigated crops had transpired ~100 mm before dryland crops had transpired any.

Table 8.4 Annual transpiration from dryland and irrigated lucerne crops over five growth seasons in Iversen 8 and two seasons in Iversen 9 at Lincoln University, Canterbury, New Zealand. Bracketed values represent E_T as a percent of EP_T.

Paddock	Season	Dryland mm *(%)*	Irrigated mm *(%)*
Iversen 8	1997/1998	427 *(65)*	596 *(90)*
	1998/1999	439 *(80)*	580 *(106)*
	1999/2000	420 *(90)*	582 *(127)*
	2000/2001	498 *(94)*	546 *(104)*
	2001/2002	459 *(92)*	498 *(112)*
Iversen 9	2000/2001	369 *(99)*	527 *(127)*
	2001/2002	347 *(72)*	644 *(130)*
Probability			< 0.001
SEM			16.5

8.3.5   Transpiration efficiency

8.3.5.1   *Dry matter production in relation to transpiration*

There was a strong linear relationship (R^2 0.80–0.99) between DM production and E_T in both irrigated and dryland treatments and examples of the relationship from $I9_{01/02}$ are displayed in Figure 8.9. There were no differences (P<0.05) in the slope of the regressions between irrigated and dryland treatments in each regrowth cycle but the lower E_T of the dryland crops coincided with lower DM production. It also appeared that the fifth regrowth cycle (March/April) had a lower slope than other regrowth cycles and this was consistent within all paddock/season combinations where E_T_eff was calculated.
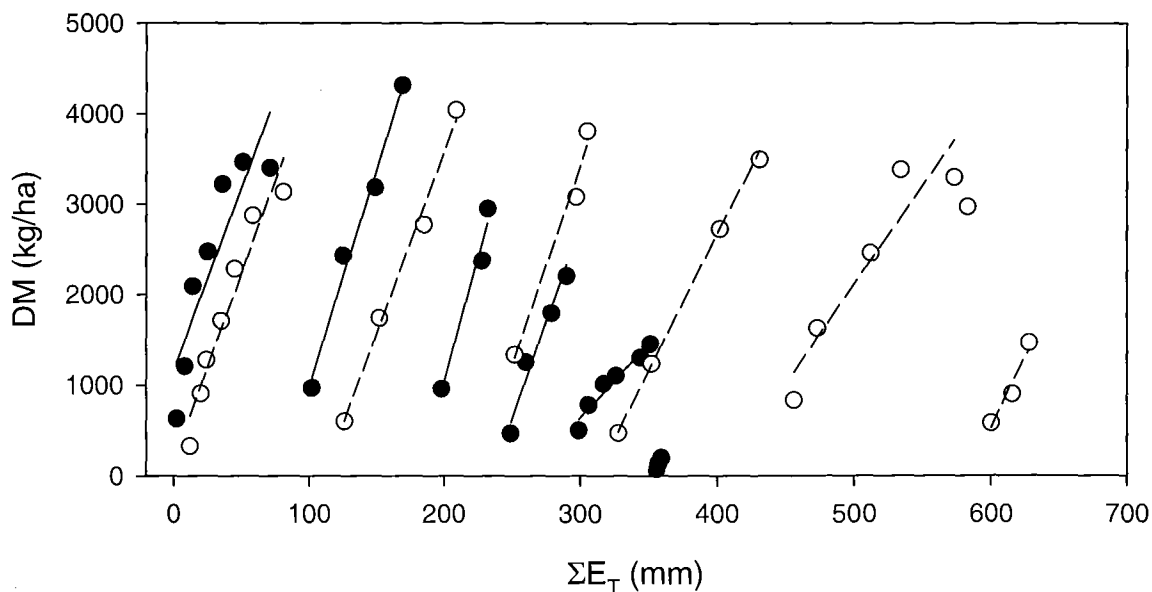
Figure 8.9 Dry matter (DM) production in relation to accumulated transpiration (ΣE_T) of dryland (●) and irrigated (○) lucerne crops grown from 1 July 2001–1 July 2002 at Lincoln University, Canterbury, New Zealand.

Note: E_T is accumulated from 1 July 2001–1 July 2002 and each individual data set represents consecutive regrowth cycles. The slope of the fitted lines represented transpiration efficiency.

8.3.5.2   *Seasonal pattern of normalised transpiration efficiency*

Normalised E_T_eff (Section 8.2.6) showed a seasonal pattern increasing from ~7 kg/ha/mm/kPa in September to ~11 kg/ha/mm/kPa in January and then decreasing abruptly between February and May (Figure 8.10a). Data points were plotted as a function of the mean temperature to explain the seasonal variation (Figure 8.10b). The relationship with temperature gave a good explanation ($R^2 = 0.73$) of the increase in normalised E_T_eff increased from ~4 kg/ha/mm/kPa at 7 °C to 13 kg/ha/mm/kPa at ~15 °C. However, data from regrowth cycles occurring as temperatures decreased during February–May were omitted from the regression because they had a lower E_T_eff compared with similar temperatures earlier in the growth season.
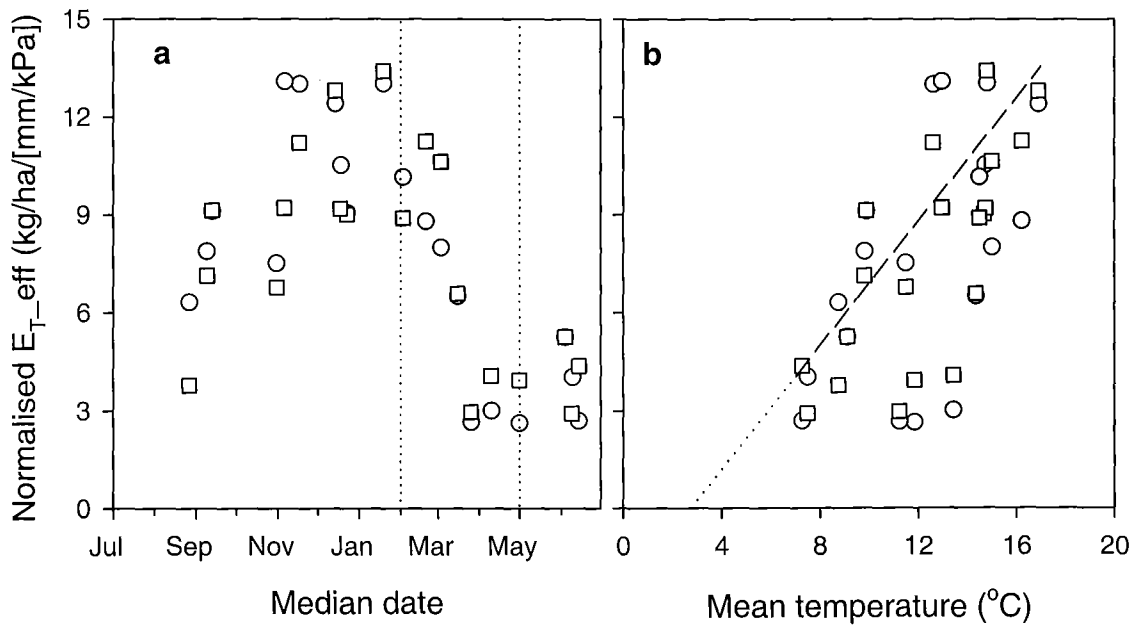
Figure 8.10 Transpiration efficiency (E_T_eff) normalised for VPD of dryland (◯) and irrigated (□) lucerne crops, a) throughout the season and, b) in relation to temperature.

Note: Each point is a value from a single regrowth cycle from paddock/season combinations $I8_{00/01}$, $I8_{01/02}$, $I9_{00/01}$ and $I9_{01/02}$ at Lincoln University, Canterbury, New Zealand. Linear regression, $y = -2.6(1.41) + 0.95(0.12)x$, $R^2 = 0.73$. Grey points are those that occurred during February–May and were omitted from the regression.

8.3.6   Water shortage responses

8.3.6.1   Seasonal transpiration under continual water shortage

The influence of water shortages on transpiration is displayed in Figure 8.11 where irrigated crops had an E_T of 644 mm and the SWD was always maintained below 200 mm. Rainfall was excluded from dryland treatments for the duration of the season and the continual drying of the soil was displayed by the increase in the SWD to 415 mm by the end of the season. There was no difference in E_T between dryland and irrigated crops during the first regrowth cycle with both crops using 90 mm by 30 September 2001. However, dryland E_T became progressively less than irrigated as the soil dried in each subsequent regrowth cycle and was 300 mm less than irrigated at the end of the season. The influence of crop cover can also be seen with E_T accumulating slowly immediately after defoliation and more rapidly toward the end of each regrowth cycle. The seasonal pattern of E_T accumulation for all other treatments is displayed in Appendix 16.
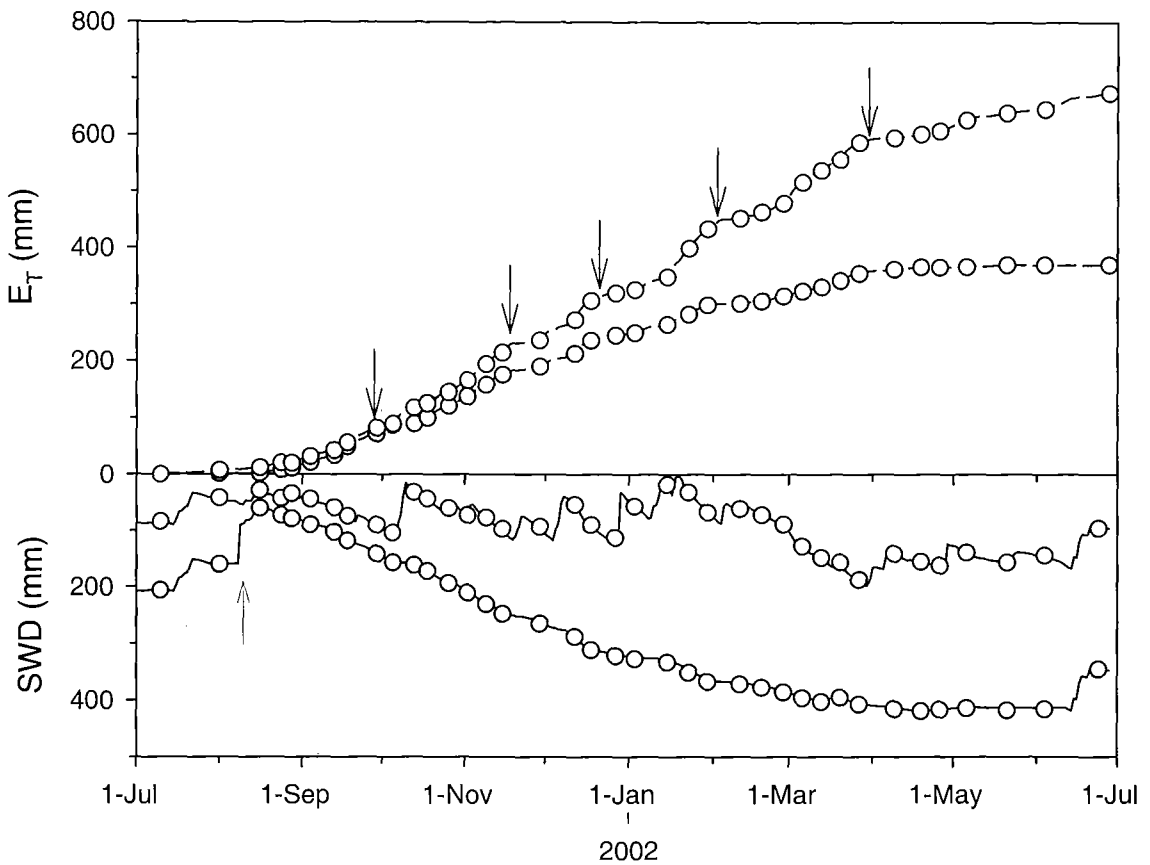
Figure 8.11 Transpiration (E_T) from dryland (-- --) and irrigated (--O--) lucerne and soil water deficit (SWD) of the same crops, dryland (-- --) and irrigated (-O-), from 1 July 2001–1 July 2002 in Iversen 9 at Lincoln University, Canterbury, New Zealand.

Note: Black arrows mark times of defoliation. Grey arrow marks the time of 70 mm pre-season irrigation in dryland treatments. Dryland treatments had rain excluded throughout this season and information on rainfall and irrigation receipts in irrigation treatments is displayed in Figure 3.2 and Appendix 1.

8.3.6.2   *Transpiration relative to demand (quantifying water stress)*

Water stress was quantified as E_T/EP_T and the influence of continual drought on water stress was appropriately displayed in $I9_{01/02}$ (Figure 8.12) when E_T/EP_T decreased from ~1.0 in the first regrowth cycle of the season to 0.22 in the final regrowth cycle (Table 8.5).

Table 8.5 Water stress (E$_T$/EP$_T$) and transpiration demand reduction (EP$_{Tdry}$/EP$_{Tirr}$) of lucerne grown under a rain-shelter from 16 August 2001–12 June 2002, at Lincoln University, Canterbury, New Zealand.

Regrowth cycle	1	2	3	4	5	6
E$_T$/EP$_T$	1.07	0.89	0.80	0.78	0.56	0.22
EP$_{Tdry}$/EP$_{Tirr}$	1.04	1.01	1.03	1.01	0.79	0.65
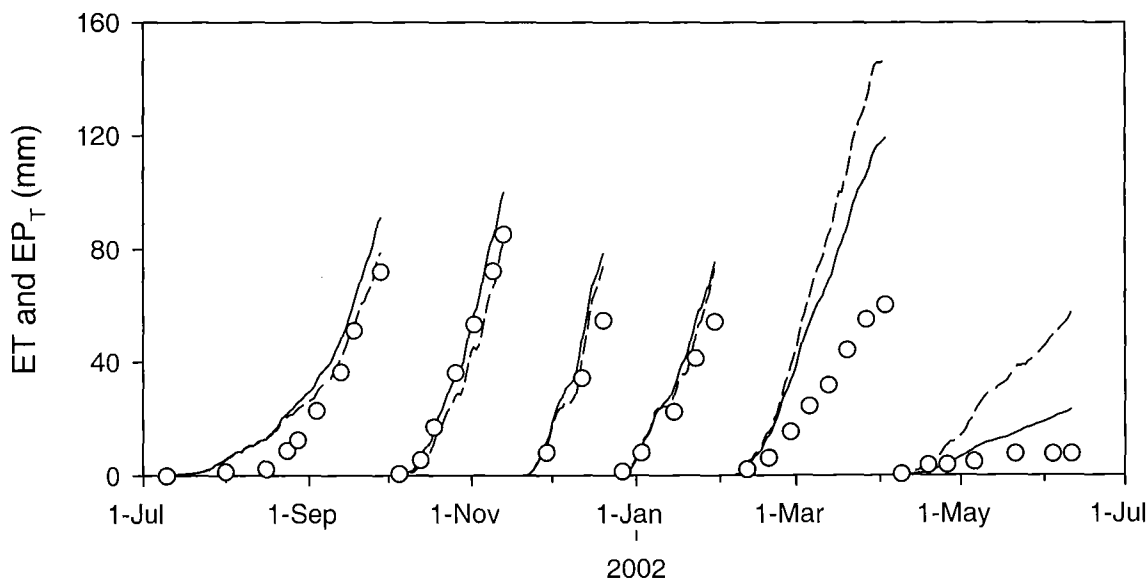
Figure 8.12 Transpiration (E$_T$) from dryland lucerne ( ) compared with transpiration potential (EP$_T$) of dryland (——) and irrigated (- - - -) lucerne grown in Iversen 9 at Lincoln University, Canterbury, New Zealand.

Note: Each line represents an individual regrowth cycle and dryland treatments were rain-sheltered throughout the season.

8.3.6.3   Transpiration demand feedback

The EP$_T$ of irrigated treatments is presented (Figure 8.12) to demonstrate the feedback of prior water stress on EP$_T$. The EP$_T$ of dryland crops was the same as irrigated so EP$_{Tdry}$/EP$_{Tirr}$ remained ~1.0 in the first four regrowth cycles but decreased in the final two regrowth periods to a value of 0.65 in the final regrowth cycle (Table 8.5).

8.3.6.4 *Water stress effects on yield components*

An increase in water stress (decrease in E_T/EP_T) caused a linear decrease in the values quantifying yield forming processes in dryland treatments relative to irrigated (Figure 8.13). Leaf area expansion was the most sensitive process decreasing from a $f_{D/I}$ of 1.0 at an E_T/EP_T of 0.97 to 0.10 with a E_T/EP_T of 0.20 (Figure 8.13a). Main-stem node appearance was the least sensitive component measured decreasing to a $f_{D/I}$ of 0.7 with a E_T/EP_T of 0.20 (Figure 8.13b). The $f_{D/I}$ of the crops RUE showed a 1:1 decrease in response to E_T/EP_T ($R^2 = 0.76$), decreasing to 0.25 with an E_T/EP_T of 0.25 (Figure 8.13c).
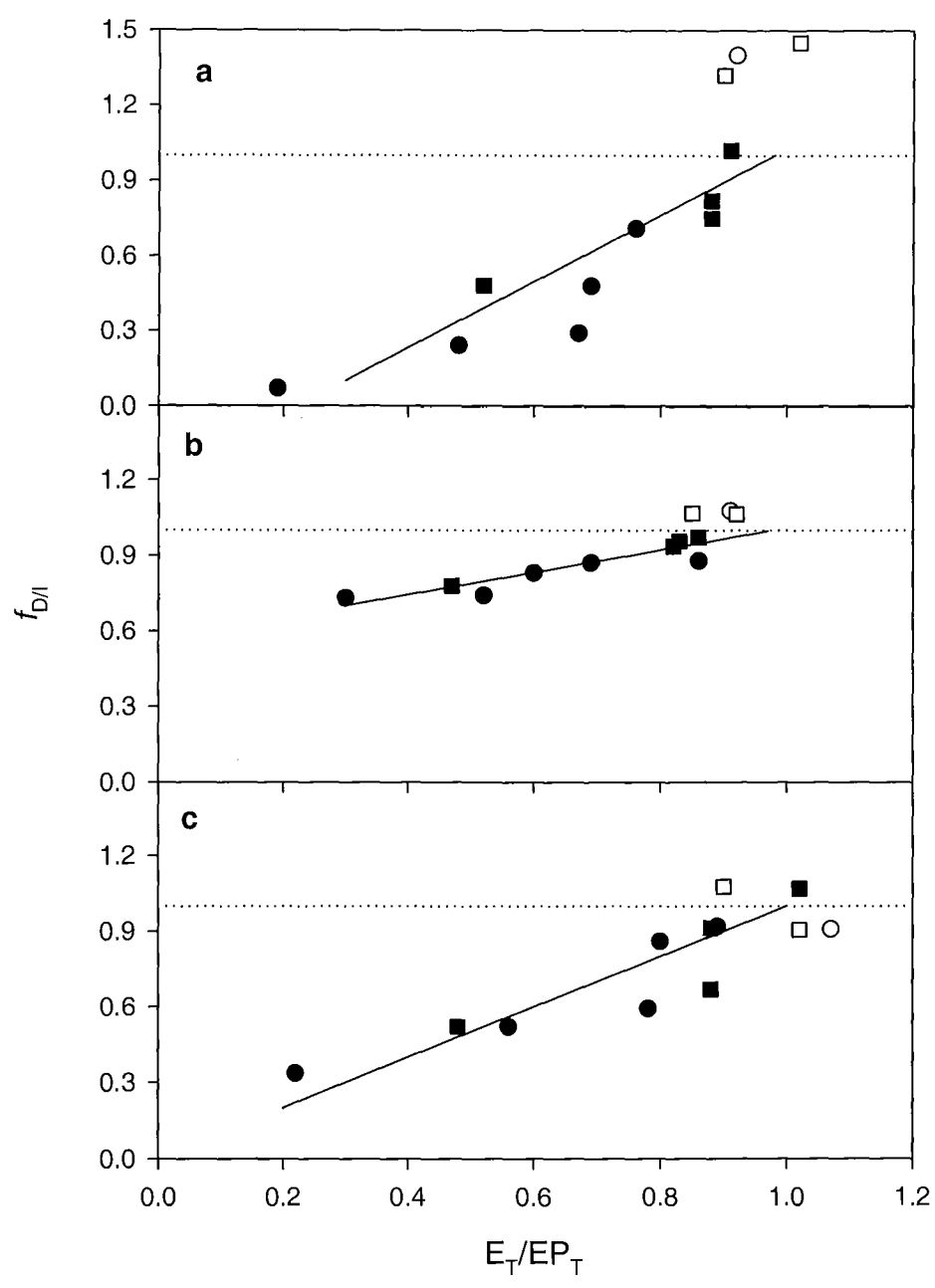
Figure 8.13 Dryland yield forming processes relative to irrigated ($f_{D/I}$) in relation to water stress (E_T/EP_T) for a) leaf area index expansion, b) node appearance rate and, c) radiation use efficiency for crops grown in $I8_{00/01}$ (■) and $I9_{01/02}$ (●) at Lincoln University, Canterbury, New Zealand. Fitted regression (———), a $f_{D/I}$ of 1.0 (······).

Note: Fitted regressions (and standard errors) a) y = -0.44(0.24) + 1.44(0.32)x, R^2 = 0.76. b) y = 0.53(0.06) + 0.49(0.09)x, R^2 = 0.83. c) y = 0(fixed) + 1.0(0.042), R^2 = 0.76. Grey values represent the first regrowth cycles from each season and were excluded from regressions a and b but included in c.

8.4 Discussion

Explaining the influence of water shortages on crop yield requires quantification of the effects of water stress on the processes that contribute to yield (Figure 6.1). Water stress was quantified as E_T relative to E_T demand and the calculation of E_T required the calculation of evaporation losses from the water balance.

8.4.1   Evaporation

8.4.1.1   Canopy evaporation

Precipitation evaporating directly from the canopy to the atmosphere accounted for ~10 and 13% of annual precipitation for irrigated and dryland treatments, respectively (Table 8.2). Validation of the size of this loss was provided by the relationship between measured (E_T) and potential transpiration (EP_T). This was the same during periods of increased ($P_{R+I}>0.05EP$) and decreased ($P_{R+I}<0.05EP$) E_C potential (Figure 8.5) indicating calculations were correct. The magnitude of E_C was controlled by the canopy storage coefficient (Equation 8.4) and the value of 0.7 mm was adjusted from a value of 0.55 mm from wheat (Leuning *et al.*, 1994). The increase was to account for two factors; 1) lucerne leaf angle is closer to horizontal than wheat (Hay and Walker, 1989) which will increase canopy water retention, 2) This study used LAI to calculate precipitation interception (Equation 8.4) whereas Leuning *et al.* (1994) used leaf and stem area.

The E_C losses from dryland treatments in Iversen 8 represented 73–107 mm per year and failure to account for this when calculating E_T from a water balance (Equation 8.14) may introduce substantial errors into E_T values. Evaporation of intercepted precipitation is considered to be an essential part of forest hydrology but is usually excluded from studies of crop water relations (Leuning *et al.*, 1994). Leuning *et al.* (1994) made a detailed analysis of E_C from a wheat crop in New South Wales, Australia (including measuring the canopy storage coefficient) and reported 33% of in-season precipitation was lost by E_C. A less detailed calculation from wheat in Brazil showed 5% of total precipitation was evaporated from the canopy, but these calculations were

based on an assumed canopy storage coefficient of 0.3 mm (de Faria and Madramootoo, 1996).

Seasonal variation of E_C (Table 8.2) was caused by the variation in the size and distribution of precipitation events. For instance E_C losses (relative to precipitation) from irrigated treatments were less than dryland treatments (Table 8.2) even though precipitation events were more frequent. This was because E_C has an upper limit set by LAI (Equation 8.2) and irrigation gave large precipitation events (>20 mm/day), which increased the proportion of precipitation that drips through the canopy and is then "safe" from E_C. The influence of crop cover on E_C is displayed in the annual distribution of E_C (Figure 8.7), where little E_C accumulates in periods of frequent precipitation if LAI is low (<2.0). This explains the higher E_C losses from the irrigated treatment in $I8_{97/98}$ and $I8_{98/99}$ when irrigation was applied during regrowth cycles in these seasons but only at the beginning of regrowth cycles (low cover) in the later seasons.

8.4.1.2   *Soil evaporation*

The other loss that was accounted for to calculate E_T from soil water measurements was evaporation from the soil. Annual E_S (1 July–1 July) ranged from 149–268 mm (Table 8.3) and accounted for ~30% of infiltration (Equation 8.5). Soil evaporation was also controlled by crop cover but in the opposite direction to E_C, with E_S accumulating faster when R/R_o was low (Figure 8.8). Jamieson *et al.* (1995a) reported 45–116 mm of E_S from barley crops in Canterbury (10 October–10 January, calculated using Ritchie E_S). It was argued that E_S is a small fraction of total water use in cereal crops because they maintain full cover for much of their duration so any errors in E_S calculations would have a small impact on E_T calculations (Jamieson *et al.*, 1995a; Jamieson *et al.*, 1998b). However, lucerne crops are repeatedly defoliated during the growth season, resulting in periods of 10–20 d per cycle with incomplete ground cover, ~100 d per year (Figure 8.8). This increases the potential for soil evaporation (Equation 8.1) making it more important to have accurate E_S estimates for the accurate calculation of E_T (Equation 8.14). A number of different methods for calculating E_S were evaluated in recognition of the importance of E_S for forage crops.

'Method 3' E_S (Section 8.2.3.5) gave the most realistic description of E_S based on comparisons with the drying of the top 0.4 m of soil (Figure 8.4). Method 3 E_S was validated by comparing the relationship between measured E_T and calculated EP_T in irrigated conditions (Figure 8.5). There was no difference in the relationship between periods of high ($R/R_o < 0.7$) and low ($R/R_o > 0.7$) E_S potential, which indicated the E_S calculations were correct.

The other methods tested overestimated E_S. Two reasons were identified for the overestimations by 'Ritchie' E_S. Firstly, 'Ritchie' Phase 2 evaporation is calculated in relation to time, and the shape of the relationship is dependant on soil texture with the assumption that diffusion is limiting E_S. Allowances are made in the 'Ritchie' calculation to restrict Phase 2 evaporation when it is higher than Phase 1 potential, but this did not seem to restrict E_S sufficiently in this study (Figure 8.4). This error can be corrected by calculating Phase 2 E_S as a function of EP (Boesten and Stroosnijder, 1986) and Method 4 was included in the analysis to demonstrate the improvement this correction makes (Figure 8.4).

The second error in 'Ritchie' E_S was the failure to account for drying of the topsoil by root extraction (Section 2.1.1.1). Method 3 E_S includes a factor to reduce E_S to account for transpiration drying the soil (Equation 8.12). The effect of this factor can be seen by comparing 'Method 4' Es with 'Method 3' (Figure 8.4). The R/R_o factor is an empirical adjustment that assumes soil drying by roots will increase in proportion to canopy cover. This is a reasonable assumption when crop cover is increasing (Eastham and Gregory, 2000), but takes no account of residual effects of soil drying when the canopy is removed by defoliation. Further improvements in predicting E_S are offered by including a soil dryness factor in the calculations (Section 2.1.1.1). The 'Dunin' methodology was adapted from wheat data to fit lucerne and uses crop cover to partition total water use between transpiration and evaporation. This may be suitable for shallow rooted species but it overestimated E_S for lucerne (Figure 8.4) when the soil surface was dry but the crop was still transpiring water from deeper in the soil profile (Section 5.3.3).

8.4.2   Transpiration efficiency

Transpiration efficiency was considered in this chapter because it offers a physiological method of calculating E_T demand when there is insufficient meteorological data to calculate transpiration demand using EP.

8.4.2.1   *Physiological prediction of transpiration demand*

There was a strong linear relationship between DM production and E_T (Figure 8.9). However, transpiration efficiency normalised to account for seasonal changes in VPD was not stable throughout the season (Figure 8.10a). This suggests it will give inaccurate estimations of E_T demand and subsequent water stress effects on crop production. The physiological approach of calculating transpiration demand has been adopted because it requires less meteorological data than the physical approach (Boote *et al.*, 1996; Hayes *et al.*, 1982; Ritchie, 1991). However, justification of its use is based on annual means (Section 2.5.1.3) and there has been little consideration of the stability of the E_T_eff throughout the season. The physiological approach facilitates the simulation of crop production in areas and or over long time periods where limited meteorological data is available (Carberry *et al.*, 2002), but the audience of such research must consider the potential to compromise simulation accuracy.

8.4.2.2   *Variation in transpiration efficiency*

Although variable, normalised E_T_eff followed a general seasonal pattern and some of this variation could be attributed to changes in temperature (Figure 8.12). There are a number of factors that may have caused the temperature response of E_T_eff. The first is a possible temperature effect on C_i/C_a (Section 2.1.1.4). There are two means by which C_i/C_a may increase with increasing temperature. Firstly an increase in temperature may decrease g_m and increase E_T_eff. The effects of temperature on g_m are recognised in the adjustment of RUE for temperature (Sands, 1996) and the link between RUE and E_T_eff has been recognised (Sadras *et al.*, 1991; Singh and Sri Rama, 1989). However, there is a lack of data on the relationship between temperature and E_T_eff. Secondly, the response of E_T_eff to VPD may not be linear, so the normalisation overestimates E_T_eff at higher temperatures. This possibility was demonstrated in Section 2.5.1.3, where an

increase in VPD caused stomatal closure which increased C_i/C_a and so E_T_eff did not decrease as much as expected.

Another possibility for the temperature effect on E_T_eff may be that an error in the normalisation of E_T_eff was correlated with temperature. Air temperature was used to calculate VPD in the absence of leaf temperature data, with the assumption that leaf and air temperature were the same. Jamieson (1999) reported boundary layer insulation and radiation load, cause leaf temperatures to rise above air temperature in temperate environments. However, Peri (2002) reported canopy temperatures of cocksfoot were less that air temperatures from 10–30 °C in Canterbury. Canopy temperature was not measured in the current experiment. An energy balance that accounts for boundary layer insulation, radiation heating and air temperature effects on leaf temperature needs to be conducted to resolve the magnitude of this error on $E_T\_eff*VPD$ values.

There was a period in the autumn where E_T_eff was lower than for similar temperatures at other times of the year. The likely cause of this is a change in the partitioning behaviour of the crop because this coincided with the period when the crop was allocating more of its DM production to perennial storage. The seasonal decline in E_T_eff is well documented for lucerne (Smeal et al., 1991; Undersander, 1987) and is another of the issues that needs to be considered when studying the physiology of perennial forages. Most transpiration efficiency studies are made on annual crops and use above ground DM because DM partitioned to roots is considered to be a small and constant fraction of total DM (Ashok et al., 1999; Campbell, 1991).

8.4.3 Quantifying water shortage

The expression of a crops actual E_T relative to its E_T demand was used to quantify the extent of water shortage. This method requires a suitable representation of the crops E_T demand.

8.4.3.1 *Transpiration demand*

The actual E_T of a crop is the minimum of E_T supply and demand (Carberry *et al.*, 2002) so E_T under non-water limited conditions represents the crops E_T demand. The strong relationship ($R^2 = 0.81$) between measured and potential E_T of irrigated lucerne (Figure 8.6) demonstrates the suitability of EP_T as a predictor of E_T demand, and validates the assumptions that are made in the formulation of EP_T (Equation 8.1).

The first assumption was that EP gives a good prediction of the E_T of a well-watered crop with full ground cover (Section 2.5.1.3). The suitability of EP for this purpose is well recognised (Heine, 1976), but annual transpiration was >100% of annual EP_T in some seasons (Table 8.4). The reason for this was the inclusion of a number of periods within annual totals where E_T was overestimated due to errors in the water balance (Section 8.2.5). The removal of these periods from the analysis reduced E_T to 86% of total EP_T (Table 8.1). Transpiration of irrigated crops often differs to EP due to crop specific resistances or local climatic/meteorological station effects (Doorenbos and Pruitt, 1977). To account for this overestimation the slope of the relationship between E_T and EP_T (0.86) was used as a correction factor to calibrate EP_T calculations. Meinke *et al.* (2002) also calibrated EP by this method with correction factors of 1.0 and 0.91 for wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*), respectively in Queensland (Australia) and 0.86 for wheat in Western Australia.

The next assumption in the calculation of EP_T was that E_T increased in direct proportion to crop cover. The influence of crop cover was demonstrated in Figure 8.11 where E_T was accumulated faster toward the end of each regrowth cycle. The zero slope of the residual (E_T–EP_T) versus R/R_o (Figure 8.6) indicates the assumed linear relationship was correct. Potential evapotranspiration is often multiplied by cover to represent a crops transpiration demand in studies of crop water relations (French and Legg, 1979;

Jamieson, 1999; Ritchie, 1972) but this assumption is not often validated. Canopy evaporation was removed from EP_T, with the assumption that drying of external canopy layers uses radiant and advective energy that will not be available for evaporating water from sub-stomatal cavities. Residual analysis (Figure 8.6) indicated this was correct and gave justification for the inclusion of E_C in the calculation of EP_T.

8.4.3.2 Transpiration

The influence of water shortage on E_T was best displayed in $I9_{01/02}$ where rain-shelters gave continual drying of the soil and E_T continually declined relative to that of irrigated treatments (Figure 8.11). Reduced E_T is caused by the inability of plants to extract sufficient water to meet E_T demand as the soil dries. The influence of soil water extraction on E_T was discussed in Chapter 5 and this reduction in E_T was expressed relative to EP_T to quantify water stress.

8.4.3.3 Water stress

The E_T/EP_T decreased from ~1.0 in the first regrowth cycle in $I9_{01/02}$ to 0.22 by the sixth cycle (Table 8.5) showing continual increase in water stress as the soil dried (Figure 8.12). The E_T/EP_T was ~1.0 in the first regrowth cycle (Table 8.5), which indicated the crops roots were able to provide sufficient water to meet E_T demand. However, the rate of soil water extraction reached its maximum at the end of the first regrowth cycle (Figure 5.9). This, combined with the exclusion of rainfall and increasing EP (Figure 3.2), meant water supply from the roots was unable to meet demand and E_T/EP_T declined to 0.89 in the second regrowth cycle. Water supply was then approximately constant from October until February, but EP continued to increase during this time reducing E_T/EP_T to 0.78 in the fourth regrowth cycle. After February water extraction reached its maximum depth, which decreased supply (Section 5.3.3.2) and E_T/EP_T decreased to 0.56 and 0.22 in the final two regrowth cycles. The influence of in-season rainfall on water stress was displayed by annual E_T values, which ranged from 65–94% of annual EP_T (Table 8.4) for dryland treatments and the lowest values were recorded in the driest seasons ($I8_{97/98}$ and $I9_{01/02}$).

Values of E_T/EP_T were integrated over each regrowth cycle to remove some of the day-to-day variability. The instantaneous effect of water shortage on E_T was displayed in regrowth cycles 3 and 4 (Figure 8.12) when E_T was similar to EP_T in the first part of the regrowth cycle, indicating water supply from the crops roots was able to meet demand. However, the increase in crop cover (Figure 8.3) increased EP_T and E_T decreased below EP_T at the end of these cycles.

8.4.3.4 *Water stress feedback*

The feedback effect of water stress on subsequent EP_T was quantified by EP_{Tdry}/EP_{Tirr} (Table 8.5), which was ~1.0 in regrowth cycles 1–4, and then decreased to 0.65 in the final regrowth cycle. This indicated water stress only caused feedback on EP_T following high levels of water stress (E_T/EP_T 0.56). However, it is possible the extent of EP_{Tdry}/EP_{Tirr} was underestimated and this is discussed further in Section 8.4.4.2. The dynamics of the feedback were displayed in regrowth cycles 5 and 6 where water supply was less than E_T demand for the duration of the cycle. Part way through each cycle EP_{Tdry} was reduced relative to EP_{Tirr}, which indicated the water stress at the beginning of the regrowth cycle reduced EP_T demand later in the cycle. This reduction in EP_T reduced ET/EP_T relative to a crop that had not decreased EP_T and results in a lower E_T/EP_T. This is a survival mechanism which keeps E_T/EP_T from declining to very low values that may be fatal to the crop (Sinclair, 2000). The reduction in EP_T also reduces water extraction so prolongs the utilisation of limited soil water aiding persistence of the crop (Section 5.4.2.4).

8.4.4 The influence of water stress on crop yield components

8.4.4.1 *RUE and R/R_o*

The influence of water shortages on yield forming processes can be quantified by the relationships of water stress with RUE and R/R_o (Figure 6.1). In this thesis it is assumed that R/R_o can be accurately calculated from LAI using an extinction coefficient (Section 2.4.1.1). The influence of environmental factors on R/R_o is then quantified indirectly by the influence on LAI. The LAI of lucerne was the most sensitive factor to water stress, showing a linear reduction in $f_{D/I}$ from 1.0–0.1 with the decrease in E_T/EP_T

from 0.97–0.2 (Figure 8.13a). Node appearance affected LAI expansion (Section 2.4.2) but showed low sensitivity to water stress (Figure 8.13b). Thus, the reduced LAI expansion was probably due to reduced leaf expansion (smaller leaves) rather than fewer leaves. This is consistent with Ritchie (1991) who classed development as having a low sensitivity to water stress and Ottman (1999) who reported that individual leaf expansion of lucerne is highly sensitive to water stress due to its dependence on cell water potential.

The RUE was also sensitive to water stress and showed a linear 1:1 decrease as E_T/EP_T decreased (Figure 8.13c). Other authors have presented a decrease in RUE under conditions of water limitation but few have quantified it relative to water stress (Section 2.5.3.2). This relationship has not been defined for lucerne before but Robertson *et al.* (2002) have assumed the same 1:1 reduction of RUE in their lucerne simulation model.

These results show that reductions in both RUE and LAI contributed to reduced yield under water shortages and the relationships provide parameters to quantify these reductions. The LAI was the most sensitive to water shortages but the impact of this on crop yields will be less (relatively) because LAI is converted to R/R_o by an exponential relationship. The results presented in this chapter may also be used to assess the relative impact of reduced RUE and LAI on crop yield.

8.4.4.2   Relative contribution of RUE and LAI reductions to forage yield

Yield was proportional to E_T within a regrowth period (Figure 8.10) so the contribution of RUE and R/R_o reductions to yield may be assessed using E_T/ET_P and EP_{Tdry}/EP_{Tirr} results. The E_T/EP_T was the more sensitive of these two parameters. It began to decline in the second regrowth cycle in $19_{01/02}$ and was 0.22 by the end of the growth season (Table 8.5). There was a 1:1 relationship between E_T/EP_T and RUE (Figure 8.13c) so this reduction in E_T/EP_T will be accompanied by an equivalent reduction in RUE. Assuming a reduction in E_T/EP_T coincides with stomatal closure, the reduced RUE would be mainly due to stomatal closure limiting CO_2 exchange and subsequent assimilation (Section 2.2.2).

The EP_{Tdry}/EP_{Tirr} remained at ~1.0 for the first four regrowth periods in $19_{01/02}$ but decreased in the fifth and sixth periods (Table 8.5). Values of EP_T were calculated from R/R_o data (Equation 8.2) therefore the reduction in EP_{Tdry}/EP_{Tirr} can be attributed to water stress reducing R/R_o. It appears the reduced E_T (and crop yield proportionally) can only be attributed to reduced R/R_o after prolonged water shortages so most of the reduction in yield must be due to reduced RUE. These results are consistent with Jamieson et al. (1995a) who also found stomatal closure had a greater influence on wheat E_T than a reduction in LAI under dryland conditions. However, there are two factors that possibly underestimate the influence of reduced LAI on EP_T presented in this chapter.

The first is the exclusion of rainfall, and subsequent E_C, from dryland treatments (Figure 8.12). Total E_C was 80 mm in irrigated crops (Figure 8.7), which reduced EP_T by ~13 mm per regrowth cycle (Section 8.2.3.2) and reduced the difference in EP_T between dryland and irrigated treatments. If E_C was excluded from EP_T calculations the values of EP_{Tdry}/EP_{Tirr} would decrease putting more emphasis on the influence of reduced R/R_o. The rational behind removing E_C from the EP_T calculation was that it would reduce E_T and so should be accounted for (Section 8.2.3.2). However, the influence of the reduced E_T on water stress may be offset by the cooling influences of the E_C.

The second factor is a possible overestimate of R/R_o in dryland treatments, which overestimates EP_T and reduces the apparent effect of actual reductions in R/R_o. The possibility of this overestimate is due to the solar tracking behaviour of lucerne leaves. Leaves arrange themselves perpendicular to incoming solar radiation when well watered and become more horizontal and cupped, reducing radiation interception (Brown and Blaser, 1968), when water stressed (Moran et al., 1989; Travis and Reed, 1983). This effect may not have been represented in measurements of R/R_o because they were conducted in diffuse radiation conditions (canopy analyser) when the effects of water stress are least evident (Rawson et al., 1978). A direct measurement of radiation interception may have increased the difference between irrigated and dryland EP_T further increasing the emphasis of reduced R/R_o on E_T and yield.

8.4.5   Conclusions

This chapter gives a description of the seasonal patterns of evaporation from the soil, the crop canopy and crop transpiration. It then used transpiration data to validate a calculation of crop transpiration demand, quantify water stress and relates water stress to yield forming factors. Specific conclusions are:

- The E_C of a lucerne crop (73–107 mm per year) could be calculated assuming precipitation interception was proportional to R/R_o and has a maximum value set by the crops LAI and a storage coefficient of 0.7 mm/LAI.

- The E_S (170–268 mm per year) could be calculated using EP and R/R_o to calculate EP_S. The EP_S was then decreased by empirical relationships to account for drying of the soil reducing actual E_S below EP_S.

- Transpiration from irrigated crops was ~550 mm per year and was closely related to EP_T, calculated from EP and R/R_o, demonstrating the suitability of EP_T to represent E_T demand. The EP_T was calibrated for lucerne with a coefficient of 0.86.

- Transpiration efficiency, normalised for VPD, was variable throughout the season and not a suitable predictor of transpiration demand.

- Water shortages reduced E_T and water stress can be quantified by E_T/EP_T.

- The E_T/EP_T decreased from ~1.0 in the first regrowth cycle to 0.22 in the final regrowth cycle of a season of continual drying and there was a 1:1 relationship between E_T/EP_T and RUE.

- The EP_{Tdry}/EP_{Tirr} was ~1.0 for the first four regrowth cycles then decreased to 0.65 in the final regrowth cycle, which indicated reduced leaf expansion had a lesser influence on yield under dryland conditions.

9 General discussion

This thesis aimed to improve the understanding of dryland forage yield. The results are of importance to those who use forage crops in their farming business and crop physiologists who study the influence of environment and management on forage crops.

9.1 Agronomic implications

9.1.1 Forage options

The primary aim of this thesis was to select the most suitable forage species for inclusion in New Zealand dryland farming systems. To be suitable a forage species must be able to support greater live weight gain/maintenance than the ryegrass/white clover alternative, maintain this production advantage as long as possible and have the least impact on cool season (June-August) stock feeding. The potential of lucerne to support greater dryland production that ryegrass/white clover is well known (Langer, 1967; Wynn-Williams, 1982). However, there was no information of either the relative production benefits or negative impacts of lucerne compared with alternative tap-rooted forage species, chicory and red clover.

This thesis showed lucerne was superior to chicory and red clover in many respects. Dryland lucerne had an annual yield 4–5 t DM/ha greater than chicory or red clover (Figure 4.1) over the 5-year duration of Experiment 1. This combined with herbage quality and utilisation (measured from grazing residuals) data to demonstrate the superior stock production potential of lucerne (Section 4.3.6). Specifically, stock consumed 180 GJ ME/ha/y and 4.3 t of crude protein per hectare per year from lucerne over the duration of Experiment 1 (Table 4.5). This was ~30% more than the energy and protein consumed from chicory and red clover. These calculations also included the production of weed species, which comprised 6% of the lucerne production compared with 39% of chicory and 100% of red clover in the final season of Experiment 1 (Table 4.1). This demonstrates the greater persistence of lucerne, but also suggests the production advantage of lucerne would increase on lighter soils, where the relative production from the shallow rooted volunteer species (mainly white clover) would be

less. Finally, lucerne provided more feed at the beginning and end of the growth season (Figure 4.3) so had the greatest contribution to cool season feed supply.

9.1.2 **The limited utilisation of lucerne by dryland farmers**

It is clear that lucerne was the superior species for improving dryland production and this potential has been known for many years. However, lucerne is not widely utilised on dryland farms in New Zealand. White (1982) reported 50% of a farms area should be in lucerne to achieve maximum lamb growth rates. A recent survey by Kirsopp (2001) showed lucerne made up <20% of farm area on most of the 67% of Canterbury and North Otago properties that used it. There are two main reasons for the apparent under-utilisation of lucerne by dryland farmers. Firstly, there is the perception of disease problems and poor persistence that reduced lucerne production during the 1970s (Purves and Wynn-Williams, 1989). Kirsopp (2001), reported 'Wairau' is still the most widely used cultivar (32% of current lucerne plantings). The use of new cultivars with multiple pest and disease resistance would solve many of the pest and disease problems than lucerne may encounter (Dunbier and Easton, 1982).

The other major problem with lucerne is its winter production is less than ryegrass/white clover and, and ideal management means early spring growth cannot be utilised until at least mid-September (in Canterbury). Grazing in the winter, or too early in spring will reduce subsequent production and increase weed invasion (Moot *et al.*, 2003). This is the factor that limits the possible utilisation of lucerne to 50% of a farms area, but current utilisation (<20%) is still well below this. Farmers who use a large (>15%) area of lucerne begin lambing two weeks later than non-users (Kirsopp, 2001). This is because reliable spring feed supply becomes later with increased areas of lucerne. Many farmers see this as a disadvantage because early lambs earn a premium at the meat processors. However, if all farmers produced early lambs there would not be an early premium so it is not a realistic target for all farmers. The advantage of later lambing is a higher lambing percentage (more lambs per ewe) and heavier lambs (Kirsopp, 2001).

There is a reluctance by farmers to use increased areas of lucerne because of uncertainties about the impact of such changes on the farming system. Simulation modelling offers a way of demonstrating the advantages and impacts of increasing lucerne use and determining the most profitable strategy for using lucerne (Hochman *et al.*, 2001a). However a simulation must be able to produce reliable predictions of yield in varying situations and this capability does not exist for lucerne yet. The reason for poor lucerne simulation performance is inadequate understanding of the physiology of lucerne at the field scale (Section 2.2.4.3). The aim of this thesis moved onto studying the influence of environment on dryland lucerne yield to improve understanding of its physiology.

9.1.3 **Water and forage yield**

The first part of this study was to explain the superior dryland production of lucerne by comparing its WU with chicory and red clover. This was done using the linear relationship between yield and WU (Figure 5.4). This relationship is a generalisation of a number of processes analysed in this thesis. However, it shows the greater lucerne yield came from greater WU as a result of a greater extraction depth (Figure 5.5). The linear relationship is also useful for discussing how results may change in situations of reduced WU. For instance, yield was 17–21 t DM/ha/y on a Wakanui silt loam (Figure 4.1) with an AWC of >300 mm. However, many dryland farms are located upon soils with a lower AWC (50 – 150 mm) and less potential water extraction. This results in a lower potential yield and is displayed by the annual 'Kaituna' lucerne yield of 10 t DM/ha measured on a Lismore stony loam (90 mm AWC) at Ashley Dene (K.M. Pollock, personal communication).

Although lucerne yields are reduced on light soils they are still 10–30% greater than the yield of shallow rooted pastures on the same soil types (Douglas, 1986). The advantage of lucerne over shallow rooted pastures increases with increased AWC (Hayman and McBride, 1984) and the 17–21 t DM/ha/y of lucerne on the Wakanui silt loam was at least twice the 8.5 t DM/ha/y from a dryland ryegrass/white clover pasture in the adjacent paddock (Black, 2004). This demonstrates the benefit of planting lucerne on free draining soil of higher AWC (rather than low AWC soils). Lucerne's deep roots

enable more effective utilisation the high AWC of these better soils than a shallow rooted alternative.

9.2 The physiology of lucerne yield

The aim of this thesis then moved on to improving the understanding of perennial forage physiology with a detailed study of lucerne yield in response to the environment. Improvements to understanding of lucerne physiology may be judged by comparing environmental responses quantified in this thesis to parameters and mechanisms used to simulate lucerne production. The lucerne module in the APSIM crop simulator (Robertson *et al.*, 2002) is one of the few lucerne simulation models that has been used beyond its development. It was adapted from annual crop models such as CERES and its parameters were based on published data (where available) so it gave a good representation of the current understanding of lucerne physiology. The improvements presented in this thesis may be incorporated into APSIM-lucerne and subsequent model validated will highlight areas where additional research and understanding are required.

9.2.1 Water extraction of perennials forages

An accurate simulation of water extraction is important for determining water stress and subsequent yield reductions. Seedling lucerne showed a continual progression of water extraction downward through the soil profile (Section 5.3.2) and this pattern can be explained by the newly established root system (Section 2.5.2.3). Perennial regrowth of lucerne displayed the same top down pattern. This contrasts the mechanism in APSIM-lucerne that assumes perennial water extraction will be constant across the profile depth that lucerne roots inhabit. It is likely the extraction pattern was due to the downward renewal of fine absorbing roots following their death during winter dormancy (Section 5.4.2.2). However, this theory needs to be tested by measuring seasonal fine root dynamics over the depth of a soil profile.

The EFV and –kl values (Section 5.3.2) may be used to quantify water extraction using the calculation in Section 5.2.3.5 and this approach is used in APSIM-lucerne. The EFV and –kl represent potential water extraction and actual water extraction may be

less if demand is lower than this potential supply. In practice the –kl and EFV values measured may be a measure of water demand rather that potential supply during cool periods and following defoliation (Section 5.4.2.4). It would be sensible to use the highest –kl and EFV values measured to represent potential water extraction as they are least likely to be limited by demand. However, the –kl and EFV values were empirical descriptions of measured water extraction. This water extraction would change on different soil types and in situations where fine root dynamics are different (Section 5.4.2.4).

An alternative simulation of water extraction is to characterise the hydraulic properties of each soil layer, quantify fine root dynamics and use a function that combines the two factors to give potential water extraction (Jones and Kiniry, 1986). Such an approach would allow for the influence of perennial root dynamics to be simulated including the downward progress of the extraction front and the possible feedback of water stress reducing root growth and water extraction (Section 5.4.2). However, a detailed study of the seasonal fine root dynamics is needed to give the understanding required to facilitate this level of simulation.

9.2.2 Forage yield of perennial lucerne

The first step to understanding forage yield was to study shoot DM production with adequate water supply. The shoot production of lucerne was different to that of annual crops because it could not be quantified with a constant RUE (Figure 6.2). The research in this thesis provided an improved mechanism for explaining seasonal DM production of lucerne using a temperature dependent RUE for total DM production that was multiplied by a linear factor, increased from zero and 0 °C to unity and 18 °C. This temperature response is an improvement on that used in APSIM-lucerne, which assumes RUE reaches an optimum at 10 °C, based on the temperature response of wheat (Section 2.3.1.2).

Total DM production can then be converted to shoot production by multiplying total RUE by the seasonal partitioning factor (Figure 6.6). This gave a shoot RUE that (assuming no temperature limitation) decreased from 1.3 g/MJ in September to a

constant 1.0 g/MJ in December/January and then abruptly decreased to 0.6 g/MJ in March/April (Figure 6.8). The seasonal partitioning pattern is also an improvement on the mechanism used in APSIM-lucerne that was based on results from Khaiti and Lemaire (1992). APSIM-lucerne uses a RUE of 1.0 g/MJ for spring and summer that switches to 0.6 in autumn. Assimilate partitioning in lucerne has been studied in detail at the individual plant level and within single regrowth periods (Section 2.3.2). However, few studies focus on the influence of this partitioning on production at the field scale. The results in this thesis provide field scale understanding of lucerne partitioning behaviour in spring and reinforce previous quantifications of summer and autumn partitioning (Khaiti and Lemaire, 1992).

It is possible the extent of partitioning will change with cultivar (non/dormant types) and latitude (photoperiod). The mechanism presented in this thesis can be incorporated into a simulation model such as APSIM-lucerne to account for seasonal variation in temperature and partitioning on seasonal lucerne production. Validating outputs against actual production of different cultivars at different sites will give an indication of the extent of variation in partitioning and mechanisms necessary to quantify variation.

The dynamics of perennial DM within a single regrowth cycle also creates issues for quantifying the production of lucerne. It was apparent the frequently defoliated treatments in Experiment 3 were less able to accumulate perennial reserves and initiated regrowth slower than the longer regrowth treatments (Section 6.4.2). This demonstrates an issue that may be studied to further improve the understanding of lucerne yield. The use of perennial DM to initiate regrowth will increase shoot RUE at early stages of the regrowth cycle and the extent of perennial DM utilisation will be influenced by defoliation management. This aspect of perennial DM dynamics requires further research to fully understand its influence of shoot production. This research may be carried out by measuring perennial DM production and shoot RUE under different management situations. Alternatively, validating model outputs against the shoot production of different defoliation treatments will help to determine the extent of the variation in shoot production.

9.2.3   Canopy development of lucerne

A quantification of canopy development is necessary to simulate radiation interception and combine with RUE to quantify yield and understand its variation. There are a number of mechanisms for quantifying the expansion of a crop canopy (Section 2.4.1.2) and the components of lucerne LAI expansion all respond differently to environmental changes throughout the season (Section 7.3.2). Thus, an accurate quantification of LAI dynamics will require environmental responses for main-stem node appearance, branching, leaf expansion and senescence (Equation 2.5). This is consistent with the mechanism used to simulate LAI expansion in APSIM-lucerne but the environmental responses differ to the parameters presented by Robertson *et al.* (2002). A phyllochron of 37 °Cd would be suitable for simulating main-stem node appearance during most of the season and this is similar to the constant phyllochron of 34 °C used by Robertson *et al.* (2002). However, the phyllochron increased to 60 °Cd in the autumn and gradually returned to 37 °Cd by the winter. This increase in phyllochron coincided with a period when APSIM-lucerne underestimated radiation interception (Figure 6.4) and needs to be accounted for to quantify lucerne yield in a varying environment. This change could be related to photoperiod and appeared to be set at the time regrowth shoots were initiated (150 °Cd before the first node appeared). The photoperiod response presented in Figure 7.9 may be used to simulate node appearance of 'Kaituna' lucerne at the same latitude. However, it is uncertain how different cultivars of lucerne will respond to photoperiod at a different latitudes and further research is needed to fully understand this response.

An additional improvement in the understanding of LAI expansion is the expression of branching, which gave an additional 1.7 – 2.5 leaves per main-stem node after the fifth node (Figure 7.10). This differs from APSIM-lucerne, which assumes branching does not occur. The results in this thesis also showed branching was occurring in response to thermal time, but had a different photoperiod response or temperature threshold to main-stem node appearance (Section 7.4.3.1). There was also evidence that leaf expansion rates changed relative to leaf appearance rates throughout the season and more research on the environmental response of branching and leaf expansion is needed to fully understand the LAI expansion of lucerne. Others may suggest this research is not needed because changes in the environmental response of these components will not have a large influence on R/R_o due to its exponential relationship with LAI. An

improved understanding of the influence of variation in branching and leaf expansion on R/R_o may be determined by running a sensitivity analysis of model outputs to changes in these parameters.

9.2.4 Water shortage and yield

The RUE and LAI expansion of lucerne could be related to water stress to simulate the influence of water shortage on lucerne yield (Section 8.4.4). Water stress could be quantified by expressing E_T relative to E_T demand (Section 8.4.2), which is consistent with the quantification of water stress used in APSIM-lucerne. The E_T of lucerne decreased as the soil dried (Figure 8.3.6) and this response may be quantified by simulations of water extraction (Section 9.2.1). However, APSIM-lucerne assumes a constant $E_{T\_eff}*VPD$ to quantify E_T demand. This thesis showed the E_{T_eff} of lucerne was not constant so should not be used to calculate E_{T_dem}. A better representation of E_T demand is $EP*R/R_o$. However, it is often necessary to use E_{T_eff} to calculate E_T demand when insufficient meteorological data is available to calculate EP. The E_{T_eff} followed the same seasonal pattern as RUE and the influences of temperature and partitioning on E_{T_eff} may also be accounted for to improve the predictions of E_T demand.

Evaporation losses were ~30% of total WU (Table 8.3) and this loss is important for calculating water available for crop extraction. The 'Ritchie' E_S equation (Ritchie, 1972) overestimated E_S from lucerne as did the methodology used by Dunin et al. (2001). It was possible to improve 'Ritchie' E_S calculations by relating E_S2 to ΣEP instead of time and further improvements could be gained by including a crop cover factor to account for soil drying by E_T (Section 2.1.1.1). Evaporation of P_{R+I} intercepted by the canopy was about 13% of annual P_{R+I} (Table 8.2). The need to quantify E_C may be questioned because the loss of potential E_T from the water balance (Figure 8.5) is offset by an equivalent reduction in E_T from the crop (Figure 8.6).

9.3 Conclusion

This thesis began with a comparison of three perennial forage species and showed lucerne was superior to chicory or red clover for increasing forage production in dryland conditions. However, the inclusion of lucerne into a farming system is limited by its cool season production. Simulation of different farm scenarios is a way of demonstrating the potential benefits of lucerne to farmers and determining the ideal area of lucerne for a farm system. However, additional understanding of lucerne physiology is required to improve the reliability of lucerne simulations. The subsequent research focused on improving this understanding and specific findings were:

- Water extraction of perennial forages displayed a top down pattern during regrowth seasons. Additional research is required on the seasonal dynamics of fine roots to fully understand this pattern.

- Lucerne shoot production could be quantified with a temperature dependent total RUE and a seasonal partitioning pattern between perennial DM and shoots. Additional research is required to determine the possible influences of defoliation management, latitude and cultivar on perennial DM dynamics and shoot production.

- The environmental response of individual components of LAI is needed to quantify seasonal changes in R/R_o. This thesis provided quantification of the seasonal pattern of main-stem node appearance but additional understanding of seasonal variation in branching and leaf expansion is required.

- The influence of water shortages could be quantified by representing crop E_T relative to E_T demand. The influence of this shortage on crop yield could be quantified by relating it to RUE and LAI.

The improved environmental responses quantified in this thesis can be incorporated into a crop model such as APSIM-lucerne. The validation of the improved model will highlight priorities for additional research to further improve the understanding of forage crop yield.

References

Acock, B. (1991). Modelling canopy photosynthetic response to carbon dioxide, light interception, temperature and leaf traits. In K.J. Boote & R.S. Loomis (Eds.), *Modelling crop photosynthesis - from biochemestry to canopy* (pp. 41-56). American Society of Agronomy: Madison, U.S.A.

Al-Hamdani, S. and Todd, G. (1990). Effect of temperature on photosynthate partitioning in alfalfa. *Canadian Journal of Plant Science, 70*(1), 203-208.

Allen, R.B., McDonald, I.R. and Cullen, N.A. (1976). Herbage production of pasture legumes at three sites in Otago. *Proceedings of the New Zealand Grassland Association, 37*(2), 182-195.

Anderson, L.B. (1973). Relative performance of the late-flowering tetraploid red clover 'Grasslands 4706', five diploid red clovers, and white clover. *New Zealand Journal of Experimental Agriculture, 1*(3), 233-237.

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, 3*(4), 365-378.

Antolin, M.C. and Sanchez-Diaz, M. (1993). Effects of temporary droughts on photosynthesis of alfalfa plants. *Journal of Experimental Botany, 44*(265), 1341-1349.

Arteca, R.N. (1996). *Plant growth substances: principles and applications.* Chapman & Hall: New York, U.S.A.

Ashok, Hussain, I.S.A., Prasad, T.G., Kumar, M.U., Rao, R.C.N. and Wright, G.C. (1999). Variation in transpiration efficiency and carbon isotope discrimination in cowpea. *Australian Journal of Plant Physiology, 26*(6), 503-510.

Asseng, S. and Hsiao, T. (2000). Canopy CO_2 assimilation, energy balance, and water use efficiency of an alfalfa crop before and after cutting. *Field Crops Research, 67*(3), 191-206.

Asseng, S., Keating, B., Fillery, I., Gregory, P., Bowden, J., Turner, N., Palta, J. and Abrecht, D. (1998). Performance of the APSIM-wheat model in Western Australia. *Field Crops Research, 57*(2), 163-179.

Asseng, S., Turner, N. and Keating, B. (2001). Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. *Plant and Soil, 233*(1), 127-143.

Austin, R.B. (1989). Maximising crop production in water limited environments. In F.W.G. Baker (Ed.), *Drought resistance in cereals* (pp. 13-26). C.A.B International: Exter, U.K.

Avice, J.C., Lemaire, G., Ourry, A. and Boucaud, J. (1997a). Effects of the previous shoot removal frequency on subsequent shoot regrowth in two *Medicago sativa* L. cultivars. *Plant and Soil, 188*(2), 189-198.

Avice, J.C., Ourry, A., Lemaire, G. and Boucaud, J. (1996a). Nitrogen and carbon flows estimated by ^{15}N and ^{13}C pulse-chase labelling during regrowth of alfalfa. *Plant Physiology, 112*(1), 281-290.

Avice, J.C., Ourry, A., Lemaire, G., Volenec, J.J. and Boucaud, J. (1997b). Root protein and vegetative storage protein are key organic nutrients for alfalfa shoot regrowth. *Crop Science, 37*(4), 1187-1193.

Avice, J.C., Ourry, A., Volenec, J.J., Lemaire, G. and Boucaud, J. (1996b). Defoliation-induced changes in abundance and immuno-localization of vegetative storage proteins in taproots of *Medicago sativa*. *Plant Physiology and Biochemistry Paris, 34*(4), 561-570.

Baars, J.A., Douglas, J.A., Knight, T. and Janson, C.G. (1990). Growth rates and relationships between weather and growth rates for lucerne (*Medicago sativa* L.) in Canterbury and the Rotorua - Taupo region. *Proceedings of the New Zealand Grassland Association, 52*, 45-49.

Baars, J.A., Radcliffe, J.E. and Brunswick, L. (1975). Seasonal distribution of pasture production in New Zealand. 6. Wairakei, pasture and lucerne production. *New Zealand Journal of Experimental Agriculture, 3*(3), 253-258.

Badaruddin, M. and Meyer, D.W. (1989). Water use by legumes and its effect on soil water status. *Crop Science, 29*(5), 1212-1216.

Bailey, H.P. (1979). Semi-arid climates: their definition and distribution. In A.E. Hall, G.H. Cannell & H.W. Lawton (Eds.), *Agriculture in Semi-arid Environments* (pp. 73 - 97). Springer-Verlag: Berlin, Germany.

Baker, C.K., Gallagher, J.N. and Monteith, J.L. (1980). Daylength change and leaf appearance in winter wheat. *Plant, Cell and Environment, 3*(4), 285-287.

Barnes, D.K., Pearce, R.B., Carlson, G.E., Hart, R.H. and Hanson, C.H. (1969). Specific leaf weight differences in alfalfa associated with variety and plant age. *Crop Science, 9*, 421-423.

Barry, T.N. (1998). The feeding value of chicory (*Cichorium intybus*) for ruminant livestock. *Journal of Agricultural Science, U.K, 131*(3), 251-257.

Black, A.D. (2004). *A comparison of the abiotic adapration of Causasian clover and white clover in New Zealand Pasture*. Ph.D. thesis, Lincoln University, Christchurch, New Zealand.

Black, A.D., Moot, D.J. and Lucas, R.J. (2002). Seedling development and growth of caucasion clover, white clover and perennial rye grass grown in field and controlled environments. *Proceedings of the New Zealand Grassland Association, 64*, 197-204.

Bland, W.L. and Dugas, W.A. (1989). Cotton root growth and soil water extraction. *Soil Science Society of America Journal, 53*(6), 1850-1855.

Boesten, J.J.T.I. and Stroosnijder, L. (1986). Simple model for daily evaporation from fallow tilled soil under spring conditions in a temperate climate. *Netherlands Journal of Agricultural Science, 34*(1), 75-90.

Bonhomme, R. (2000a). Bases and limits to using 'degree.day' units. *European Journal of Agronomy, 13*(1), 1-10.

Bonhomme, R. (2000b). Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. *Field Crops Research, 68*(3), 247-252.

Boote, K.J., Bennett, J.M., Sinclair, T.R. and Paulsen, G.M. (1994). *Physiology and determination of crop yield.* American Society of Agronomy: Madison, U.S.A.

Boote, K.J., Jones, J.W. and Hoogenboom, G. (1998). Simulation of crop growth: CROPGRO model. In R.M. Peart & R. Curry (Eds.), *Agricultural systems modelling and simulation* (pp. 651-692). Marcel Dekker, Inc: New York, U.S.A.

Boote, K.J., Jones, J.W. and Pickering, N.B. (1996). Potential uses and limitations of crop models. *Agronomy Journal, 88*(5), 704-716.

Bootsma, A. (1984). Forage crop maturity zonation in the Atlantic region using growing degree-days. *Canadian Journal of Plant Science, 64*(2), 329-338.

Bowley, S.R., Taylor, N.L. and Dougherty, C.T. (1984). Physiology and morphology of red clover. *Advances in Agronomy, 37,* 317-347.

Brash, D.W. (1985). Lucerne cultivar comparisons: herbage yields under irrigation and on dryland in Central Otago. *Proceedings of the New Zealand Agronomy Society, 15,* 121-125.

Briggs, L.J. and Shantz, H.L. (1914). Relative water requirement of plants. *Journal of Agricultural Research, 3,* 1-63.

Bristow, K.L., Campbell, G.S. and Calissendorff, C. (1984). The effects of texture on the resistance to water movement within the rhizosphere. *Soil Science Society of America Journal, 48*(2), 266-270.

Brooking, I.R., Jamieson, P.D. and Porter, J.R. (1995). The influence of daylength on final leaf number in spring wheat. *Field Crops Research, 41*(3), 155-165.

Brown, P.W. and Tanner, C.B. (1981). Alfalfa water potential measurement: a comparison of the pressure chamber and leaf dew-point hygrometers. *Crop Science, 21*(2), 240-244.

Brown, P.W. and Tanner, C.B. (1983). Alfalfa stem and leaf growth during water stress. *Agronomy Journal, 75*(5), 799-805.

Brown, R.H. and Blaser, R.E. (1968). Leaf area index in pasture growth. *Herbage Astracts, 38*(1), 1-9.

Burke, J.L., Waghorn, G.C. and Chaves, A.V. (2002). Improving animal performance using forage-based diets. *Proceedings of the New Zealand Society of Animal Production, 62,* 267-272.

Campbell, G.S. (1991). Simulation of water uptake by plant roots. In J. Hanks & J.T. Ritchie (Eds.), *Modeling plant and soil systems* (pp. 273-285). American Society of Agronomy: Madison, U.S.A.

Carberry, P.S., Meinke, H., Poulton, P.L., Hargreaves, J.N.G., Snell, A.J. and Sudmeyer, R.A. (2002). Modelling crop growth and yield under the environmental changes induced by windbreaks. 2. Simulation of potential benefits at selected sites in Australia. *Australian Journal of Experimental Agriculture, 42*(6), 887-900.

Carberry, P.S. and Muchow, R.C. (1992). A simulation model of kenaf for assisting fibre industry planning in Northern Australia. II. Leaf area development. *Australian Journal of Agricultural Research, 43*(7), 1515-1526.

Carlson, G.E. (1965). Photoperiodic control of adventitious stem initiation on roots. *Crop Science, 5*, 248-250.

Carter, P.R. and Sheaffer, C.C. (1983a). Alfalfa response to soil water deficits. I. Growth, forage quality, yield, water use, and water-use efficiency. *Crop Science, 23*(4), 669-675.

Carter, P.R. and Sheaffer, C.C. (1983b). Alfalfa response to soil water deficits. II. Plant water potential, leaf conductance, and canopy temperature relationships. *Crop Science, 23*(4), 676-680.

Caviglia, O.P. and Sadras, V.O. (2001). Effect of nitrogen supply on crop conductance, water- and radiation-use efficiency of wheat. *Field Crops Research, 69*(3), 259-266.

Chapman, S.C., Hammer, G.L. and Palta, J.A. (1993). Predicting leaf area development of sunflower. *Field Crops Research, 34*(1), 101-112.

Chen, W., Bellotti, B., Robertson, M.J., Biao Nan, Z. and Shen, Y. (2003). Performance of APSIM-Lucerne in Gansu, north-west China. *Proceedings of the 11th Australian Agronomy Conference*, Geelong, Victoria. www.regional.org.au/au/asa/2003/c/7/chen.htm

Christian, K.R. (1977). Effects of the environment on the growth of alfalfa. *Advances in Agronomy 29*, 183-227.

Clark, D.A., Anderson, C.B. and Berquist, T. (1990). Growth rates of 'Grasslands Puna' chicory (*Cichorium intybus* L.) at various cutting intervals and heights and rates of nitrogen. *New Zealand Journal of Agricultural Research, 33*(2), 213-217.

Clothier, B.E., Scotter, D.R. and Kerr, J.P. (1977). Drainage flux in permeable soil underlain by a coarse-textured layer. *Soil Science Society of America Journal, 41*(4), 671-676.

Collins, M. (1996). Management, utilization, quality and antiquality. In N.L. Taylor & K.H. Quesenberry (Eds.), *Red clover science* (pp. 57-79). Kluwer Academic Publishers: Dordrecht, The Netherlands.

Cox, J.E. (1978). *Soils and agriculture of part Paparua County, Canterbury*. New Zealand Soil Bureau bulletin No. 34. D.S.I.R: Wellington, New Zealand.

Crush, J.R. and Evans, J.P.M. (1990). Shoot growth and herbage element concentrations of 'Grasslands Puna' chicory (*Cichorium intybus* L.) under varying soil pH. *Proceedings of the New Zealand Grassland Association, 51*, 163-166.

Cunningham, S.M. and Volenec, J.J. (1998). Seasonal carbohydrate and nitrogen metabolism in roots of contrasting alfalfa (*Medicago sativa* L.) cultivars. *Journal of Plant Physiology, 153*(1-2), 220-225.

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*(1), 29-38.

de Faria, R.T. and Madramootoo, C.A. (1996). Simulation of soil moisture profiles for wheat in Brazil. *Agricultural Water Management, 31*(1-2), 35-49.

de Wit, C.T. (1986). Introduction. In H. van Keulen & J. Wolf (Eds.), *Modelling of agricultural production: weather, soils and crops* (pp. 3-10). Pudoc: Wageningen, Netherlands.

Dhont, C., Yves, C., Nadeau, P., Belanger, G. and Chalifour, F.P. (2003). Alfalfa root nitrogen reserves and regrowth potential in response to fall harvests. *Crop Science, 43*(1), 181-194.

Di, H.J. and Kemp, R.A. (1989). Variation in soil physical properties between and within morphologically defined series taxonomic units. *Australian Journal of Soil Research, 27*(2), 259-273.

Dirksen, C. and Raats, P.A.C. (1985). Water uptake and release by alfalfa roots. *Agronomy Journal, 77*(4), 621-626.

Doorenbos, J. and Pruitt, W.O. (1977). *Guidelines for predicting crop water requirements*. Irrigation and Drainage Paper. F.A.O: Rome, Italy.

Douglas, J.A. (1986). The production and utilization of lucerne in New Zealand. *Grass and Forage Science, 41*(2), 81-128.

Draper, N.R. and Smith, H. (1998). *Applied regression analysis* (3 ed.). John Wiley & Sons: New York, U.S.A.

Dunbier, M.W. and Easton, H.S. (1982). Longer stand life with new cultivars. In R.B. Wynn-Williams (Ed.), *Lucerne for the 80's* (pp. 121-126). Agronomy Society of New Zealand, Special publication No. 1: Christchurch, New Zealand.

Dunin, F.X., Smith, C.J., Zegelin, S.J., Leuning, R., Denmead, O.T. and Poss, R. (2001). Water balance changes in a crop sequence with lucerne. *Australian Journal of Agricultural Research, 52*(2), 247-261.

Eastham, J. and Gregory, P.J. (2000). Deriving empirical models of evaporation from soil beneath crops in a Mediterranean climate using microlysimetry. *Australian Journal of Agricultural Research, 51*(8), 1017-1022.

Evans, D.W. and Peaden, R.N. (1984). Branching as a factor in alfalfa yield. *Report of the twenty-ninth alfalfa improvement conference*, Lethbridge, Canada.

Evans, J.R. and von Caemmerer, S. (1996). Carbon dioxide diffusion inside leaves. *Plant Physiology, 110*(2), 339-346.

Evans, P.S. (1978). Plant root distribution and water use patterns of some pasture and crop species. *New Zealand Journal of Agricultural Research, 21*(2), 261-265.

Fageria, N.K., Baligar, V.C. and Jones, C.A. (1997). *Growth and mineral nutrition of field crops*. Marcel Dekker, Inc: New York, U.S.A.

Farquhar, G.D., Ehleringer, J.R. and Hubick, K.T. (1989). Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology, 40*, 503-537.

Fick, G.W., Holt, D.A. and Lugg, D.G. (1988). Environmental physiology and crop growth. In A.A. Hanson, D.K. Barnes & R.R.J. Hill (Eds.), *Alfalfa and alfalfa improvement* (pp. 163-194). American Society of Agronomy: Madison, U.S.A.

Field, T.R.O. and Hunt, L.A. (1974). The use of simulation techniques in the analysis of seasonal changes in the productivity of alfalfa (*Medicago sativa* L.) stands. *Proceedings of the 12th international grasslands congress*. Vol 1 pp. 357-365.

Fitter, A.H. and Hay, R.K.M. (2002a). Introduction. In *Environmental physiology of plants*. (pp. 1-17). Academic Press: London, U.K.

Fitter, A.H. and Hay, R.K.M. (2002b). Temperature. In *Environmental physiology of plants*. (pp. 193-239). Academic Press: London, U.K.

Fletcher, A., Moot, D.J. and Stone, P. (2003). Canopy development in phosphorus deficient sweet corn. *Proceedings of the 11th Australian Agronomy Conference*, Geelong, Victoria. www.regional.org.au/au/asa/2003/c/5/fletcher.htm

Fletcher, L.R. (1976). Effect of season and regrowth period on the in vitro digestibility of irrigated lucerne in Canterbury. *New Zealand Journal of Experimental Agriculture, 4*(4), 469-471.

Fosket, D.E. (1994). *Growth and development in plants: a molecular approach*. Academic Press, Inc: California, U.S.A.

Frame, J., Charlton, J.F.L. and Laidlaw, A.S. (1998a). Lucerne. In *Temperate forage legumes* (pp. 107-179). C.A.B International: Wallingford, U.K.

Frame, J., Charlton, J.F.L. and Laidlaw, A.S. (1998b). Red clover. In J. Frame, J.F.L. Charlton & A.S. Laidlaw (Eds.), *Temperate forage legumes* (pp. 180-195). C.A.B International: Wallingford, U.K.

French, B.K. and Legg, B.J. (1979). Rothamsted irrigation 1964-76. *Journal of Agricultural Science, U.K, 92*(1), 15-37.

Geenty, K.G. and Rattray, P.V. (1987). The energy requirements of grazing sheep and cattle. In A.M. Nicol (Ed.), *Feeding livestock on pasture*. New Zealand Society of Animal Production, Occasional Publication No. 10: Christchurch, New Zealand.

Goins, G.D. and Russelle, M.P. (1996). Fine root demography in alfalfa (*Medicago sativa* L.). *Plant and Soil, 185*(2), 281-291.

Good speed, M.J. (1975). *Computer routines for solar position, daylength and related qualities*. Technical Memorandum No. 75/11. CSIRO Division of Land Use Research: Canberra, Australia.

Gosse, G., Lemaire, G., Chartier, M. and Balfourier, F. (1988). Structure of a lucerne population (*Medicago sativa* L.) and dynamics of stem competition for light during regrowth. *Journal of Applied Ecology, 25*(2), 609-617.

Gramshaw, D., Lowe, K.F. and Lloyd, D.L. (1993). Effect of cutting interval and winter dormancy on yield, persistence, nitrogen concentration, and root reserves of irrigated lucerne in the Queensland subtropics. *Australian Journal of Experimental Agriculture, 33*(7), 847-854.

Halim, R.A., Buxton, D.R., Hattendorf, M.J. and Carlson, R.E. (1989). Water-stress effects on alfalfa forage quality after adjustment for maturity differences. *Agronomy Journal, 81*(2), 189-194.

Hall, A.E., Cannell, G.H. and Lawton, H.W. (1979). *Agriculture in semi-arid environments*. Springer-Verlag: Berlin, Germany.

Hammer, G.L., Sinclair, T.R., Boote, K.J., Wright, G.C., Meinke, H. and Bell, M.J. (1995). A peanut simulation model: I. Model development and testing. *Agronomy Journal, 87*(6), 1085-1093.

Hanson, A.A., Barnes, D.K. and Hill, R.R.J. (1988). *Alfalfa and alfalfa improvement.* American Society of Agronomy: Madison, U.S.A.

Hare, M.D., Rolston, M.P., Crush, J.R. and Fraser, T.J. (1987). Puna chicory - a perennial herb for New Zealand pastures. *Proceedings of the New Zealand Agronomy Society, 17,* 45-49.

Hatfield, J.L. (1990). Methods of estimating evapotranspiration. In A. Stewart & D.R. Nielsen (Eds.), *Irrigation of agricultural crops* (pp. 435-474). American Society of Agronomy: Madison, U.S.A.

Hay, R.J.M. and Ryan, D.L. (1983). An evaluation of 'Pawera' red clover with perennial grasses in a summer dry environment. *Proceedings of the New Zealand Grassland Association, 1983,* 91-97.

Hay, R.J.M. and Ryan, D.L. (1989). A review of 10 years research with red clovers under grazing in Southland. *Proceedings of the New Zealand Grassland Association, 50,* 181-187.

Hay, R.K.M. (1999). Physiological control of growth and yield in Wheat: analysis and synthesis. In D.L. Smith & C. Hamel (Eds.), *Crop yield: physiology and processes* (pp. 1-38). Springer: Heidel, Germany.

Hay, R.K.M. and Heide, O.M. (1983). Specific photoperiodic stimulation of dry matter production in a high-latitude cultivar of *Poa pratensis. Physiologia Plantarum, 57*(1), 135-142.

Hay, R.K.M. and Kemp, D.R. (1992). The prediction of leaf canopy expansion in the leek from a simple model dependent on primordial development. *Annals of Applied Biology, 120*(3), 537-545.

Hay, R.K.M. and Kirby, E.J.M. (1991). Convergence and synchrony-a review of the coordination of development in wheat. *Australian Journal of Agricultural Research, 42*(5), 661-700.

Hay, R.K.M. and Walker, A.J. (1989). *Introduction to the physiology of crop yield.* Longman: Harlow, U.K.

Hayes, J.T., O' Rourke, P.A., Terjung, W.H. and Todhunter, P.E. (1982). A feasible crop yield model for worldwide international food production. *International Journal of Biometeorology, 26*(3), 239-257.

Hayman, J., M and McBride, S.D. (1984). *The response of pasture and lucerne to irrigation.* MAF: Ashburton, New Zealand.

Hayman, J.M. (1985). The effect of irrigation interval and soil type on pasture and lucerne production. *Proceedings of the New Zealand Grassland Association, 46,* 15-23.

Heichel, G.H. (1983). Alfalfa. In I.D. Teare & M.M. Peet (Eds.), *Crop-water relations* (pp. 127-155). John Wiley & Sons: New York, U.S.A.

Heichel, G.H., Delaney, R.H. and Cralle, H.T. (1988). Carbon assimilation, partitioning and utilization. In A.A. Hanson, D.K. Barnes & R.R.J. Hill (Eds.), *Alfalfa and alfalfa improvement* (pp. 195-228). American Society of Agronomy: Madison, U.S.A.

Heine, R.W. (1976). Comparison of methods for estimating potential evapotranspiration in Canterbury. *New Zealand Journal of Science, 19*(3), 255-264.

Hendershot, K.L. and Volenec, J.J. (1992). Taproot nitrogen accumulation and use in overwintering alfalfa (*Medicago sativa* L.). *Journal of Plant Physiology, 141*(1), 68-74.

Hesketh, J.D., Wisiol, K., Pettigrew, W.T. and Alm, D.M. (1991). Stems: patterns and duration of development. In T. Hodges (Ed.), *Predicting crop phenology* (pp. 43-72). CRC Press: Boston, U.S.A.

Hickey, M.J. and Harris, A.J. (1989). Comparative performance on three early-flowering red clovers under sheep grazing in Southland. *New Zealand Journal of Agricultural Research, 32*(3), 327-332.

Hochman, Z., Carberry, P.S., McCown, R.L., Dalgliesh, N.P., Foale, M.A. and Brennan, L.E. (2001a). APSIM in the marketplace: a tale of kitchen tables, boardrooms and courtrooms. *Acta- Horticulturae, 566*, 21-33.

Hochman, Z., Dalgliesh, N. and Bell, K. (2001b). Contributions of soil and crop factors to plant available soil water capacity of annual crops on Black and Grey Vertosols. *Australian Journal of Agricultural Research, 52*(10), 955-961.

Hodges, T. (1991a). *Predicting crop phenology*. CRC Press: Boston, U.S.A.

Hodges, T. (1991b). Temperature and water stress effects on phenology. In T. Hodges (Ed.), *Predicting crop phenology* (pp. 7-14). CRC Press: Boston, U.S.A.

Hoffmann, J.D., Eberbach, L., Virgona, J.M. and Katupitiya, A. (2003). Conservative water use by lucerne. *Proceedings of the 11th Australian Agronomy Conference*, Geelong, Victoria. www.regional.org.au/au/asa/2003/c/10/hoffmann.htm

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*(1), 7-11.

Hoglund, J.H. and White, J.G.H. (1985). Cultivatable summer dry east coast: environmental and agronomic constraints in dryland pasture and choice of species. In R. Burgess & H. Brock (Eds.), *Using herbage cultivars* (pp. 39-44). New Zealand Grasslands Association, Research and Practice series No. 3: Palmerston North, New Zealand.

Holst, P.J., Kemp, D.R., Goodacre, M. and Hall, D.G. (1998). Summer lamb production from puna chicory (*Cichorium intybus*) and lucerne (*Medicago sativa*). *22nd Biennial Conference, Animal Production in Australia: Proceedings of the Australian Society of Animal Production*. Vol 22 pp. 145-148.

Holt, D.A., Bula, R.J., Miles, G.E., Schreiber, M.M. and Peart, R.M. (1975). *Environmental physiology, modeling and simulation of alfalfa growth. 1. Conceptual development of SIMED.* Research bulletin. Purdue University Agricultural Experiment Station.

Hopkins, W.G. (1999). *Introduction to plant physiology* (2nd ed.). John Wiley & Sons: New York; U.S.A.

Hume, D.E., Lyons, T.B. and Hay, R.J.M. (1995). Evaluation of 'Grasslands Puna' chicory (*Cichorium intybus* L.) in various grass mixtures under sheep grazing. *New Zealand Journal of Agricultural Research, 38*(3), 317-328.

Hunter, R.M., Knight, T.L., Hayes, G. and Allan, B.E. (1994). Evaluation of dryland forage species for lowland Marlborough and mid Canterbury. *Proceedings of the New Zealand Grassland Association, 56,* 149-153.

Irigoyen, J.J., Emerich, D.W. and Sanchez-Diaz, M. (1992). Alfalfa leaf senescence induced by drought stress: photosynthesis, hydrogen peroxide metabolism, lipid peroxidation and ethylene evolution. *Physiologia Plantarum, 84*(1), 67-72.

Iversen, C.E. (1967). Grazing management of lucerne. In R.H.M. Langer (Ed.), *The lucerne crop* (pp. 129-133). A.H & A.W Reed: Wellington, New Zealand.

Jagusch, K.T. (1982). Nutrition of ruminants grazing lucerne. In R.B. Wynn-Williams (Ed.), *Lucerne for the 80's.* (pp. 73-78). Agronomy Society of New Zealand, Special publication No. 1: Christchurch, New Zealand.

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*(3), 267-280.

Jamieson, P., Francis, G., Wilson, D. and Martin, R. (1995a). Effects of water deficits on evapotranspiration from barley. *Agricultural and Forest Meteorology, 76*(1), 41-58.

Jamieson, P.D. (1999). Crop responses to water shortages. In M. Kirkham (Ed.), *Water use in crop production* (pp. 71-83). Food Products Press: New York, U.S.A.

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*(1), 35-44.

Jamieson, P.D., Brooking, I.R., Semenov, M.A. and Porter, J.R. (1998a). Making sense of wheat development: a critique of methodology. *Field Crops Research, 55*(1-2), 117-127.

Jamieson, P.D., Porter, J.R., Goudriaan, J., Ritchie, J.T., van Keulen, H. and Stol, W. (1998b). A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Research, 55*(1-2), 23-44.

Jamieson, P.D., Semenov, M.A., Brooking, I.R. and Francis, G.S. (1998c). Sirius: a mechanistic model of wheat response to environmental variation. *European Journal of Agronomy, 8*(3-4), 161-179.

Jarvis, P.G. and Morison, J.I.L. (1981). The control of transpiration and photosynthesis by the stomata. In P.G. Jarvis & T.A. Mansfield (Eds.), *Stomatal physiology* (pp. 247-279). Cambridge University Press: Cambridge, U.K.

Jenson, M.E., Burman, R.D. and Allen, R.G. (1990). *Evapotranspiration and irrigation requirements: a manual.* American Society of Civil Engineers: New York, U.S.A.

Jodari-Karimi, F., Watson, V., Hodges, H. and Whisler, F. (1983). Root distribu
water use efficiency of alfalfa as influenced by depth of irrigation. *Ag
Journal, 75*(2), 207-211.

Johnson, R.C. and Tieszen, L.L. (1993). Carbon isotope discrimination, water relations,
and gas exchange in temperate grass species and accessions. In J.R. Ehleringer,
A.E. Hall & G.D. Farquhar (Eds.), *Stable isotopes and plant carbon-water
relations. 1993* (pp. 281-296). Academic Press: San Diago, USA.

Jones, C.A. and Kiniry, J.R. (1986). *CERES-Maize: a simulation model of maize growth
and development.* Texas A&M University Press: Texas, U.S.A.

Jones, F. (1943). Growth and decay of the transient (noncambial) roots of alfalfa.
Journal of the American Society of Agronomy, 35, 625-635.

Jones, H.G. (1998). Stomatal control of photosynthesis and transpiration. *Journal of
Experimental Botany, 49* (Special issue: Stomatal biology: papers presented at
the Annual Meeting of the Society for Experimental Biology, University of
Kent, 7-11 April 1997), 387-398.

Juan, N.A., Sheaffer, C.C. and Barnes, D.K. (1993). Temperature and photoperiod
effects on multifoliolate expression and morphology of alfalfa. *Crop Science,
33*(3), 573-578.

Justes, E., Thiebeau, P., Avice, J.C., Lemaire, G., Volenec, J.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(366), 111-121.

Kalu, B.A. and Fick, G.W. (1981). Quantifying morphological development of alfalfa
for studies of herbage quality. *Crop Science, 21*(2), 267-271.

Karageorgis, D., Tonkin, P.J. and Adams, J.A. (1984). Medium and short range
variability in textural layering in an Ochrept developed on an alluvial floodplain.
Australian Journal of Soil Research, 22(4), 471-474.

Kear, B.S., Gibbs, H.S. and Miller, R.B. (1967). *Soils of the downs and plains of
Canterbury and North Otago.* New Zealand Soil Bureau bulletin No. 14.
D.S.I.R: Wellington, New Zealand.

Kemp, P.D., Matthews, P.N.P. and Lucas, R.J. (1999). Pasture species and cultivars. In
J.G.H. White & J. Hodgson (Eds.), *New Zealand pasture and crop science* (pp.
83-100). Oxford University Press: Auckland, New Zealand.

Kendall, W.A., Shaffer, J.A. and Hill, R.R.J. (1994). Effect of temperature and water
variables on the juvenile growth of lucerne and red clover. *Grass and Forage
Science, 49*(3), 264-269.

Keoghan, J.M. (1991). *Future options for dryland pastures.* Invermay Agricultural
Centre: Mosgeil, New Zealand.

Khaiti, M. and Lemaire, G. (1992). Dynamics of shoot and root growth of lucerne after
seeding and after cutting. *European Journal of Agronomy, 1*(4), 241-247.

Kiesselbach, T.A., Anderson, A. and Russel, J.C. (1934). Subsoil moisture and crop
sequence in relation to alfalfa production. *Journal of the American Society of
Agronomy, 26*, 442-443.

Kim, T.H., Ourry, A., Boucaud, J. and Lemaire, G. (1991). Changes in source-sink relationship for nitrogen during regrowth of lucerne (*Medicago sativa* L.) following removal of shoots. *Australian Journal of Plant Physiology, 18*(6), 593-602.

Kim, T.H., Ourry, A., Boucaud, J. and Lemaire, G. (1993). Partitioning of nitrogen derived from N$_2$ fixation and reserves in nodulated *Medicago sativa* L. during regrowth. *Journal of Experimental Botany, 44*(260), 555-556.

Kiniry, J.R., Rosenthal, W.D., Jackson, B.S. and Hoogenboom, G. (1991). Predicting leaf development of crop plants. In T. Hodges (Ed.), *Predicting crop phenology* (pp. 29-42). CRC Press: Boston, U.S.A.

Kipnis, T., Vaisman, I. and Granoth, I. (1989). Drought stress and alfalfa production in a Mediterranean environment. *Irrigation Science, 10*(2), 113-125.

Kirsopp, S. (2001). *Management techniques to maximize legume production in dryland farming.* Masters of Applied Science thesis, Lincoln University, Canterbury, New Zealand.

Knight, T., Moss, R., Fraser, T., Rowarth, J. and Burton, R. (1996). Effect of pasture species on internal parasites of lambs. *Proceedings of the New Zealand Grassland Association, 58*, 59-62.

Koehler, P.G. (1973). The roles of cell division and cell expansion in the growth of alfalfa leaf mesophyll. *Annals of Botany, 37*, 65-68.

Kohl, R.A. and Kolar, J.J. (1976). Soil water uptake by alfalfa. *Agronomy Journal, 68*(3), 536-538.

Kolek, J. and Kozinka, V. (1992). *Physiology of the plant root system.* Kluwer Academic Publishers: Dordrecht, The Netherlands.

Komolong, M., Nicol, A.M., Poppi, D.P., Fraser, T.J. and Kirsopp, S. (1992). Nutrient supply for lamb growth from Grasslands Puna chicory (*Cichorium intybus*) and Wana cocksfoot (*Dactylis glomerata*). *Proceedings of the New Zealand Society of Animal Production, 52*, 85-97.

Kramer, P. and Boyer, J. (1995). *Water relations of plants and soils.* Academic Press, Inc: San Diego, USA.

Kubota, F., Matsuda, Y., Agata, W. and Nada, K. (1994). The relationship between canopy structure and high productivity in Napier grass, *Pennisetum purpureum* Schumach. *Field Crops Research, 38*(2), 105-110.

Kusmartono, Barry, T., Wilson, P., Kemp, P. and Stafford, K. (1996). Effects of grazing chicory (*Cichorium intybus*) and perennial ryegrass (*Lolium perenne*)/white clover (*Trifolium repens*) pasture upon the growth and voluntary feed intake of red and hybrid deer during lactation and post-weaning growth. *Journal of Agricultural Science, U.K, 127*(3), 387-401.

Kutschera, U. (1992). The role of the epidermis in the control of elongation growth in stems and coleoptiles. *Botanica Acta, 105*(4), 246-252.

Langer, R.H.M. (1967). *The lucerne crop.* A.H & A.W Reed: Wellington, New Zealand.

Langer, R.H.M. (1990). Pasture plants. In *Pastures: their ecology and management* (pp. 39-75). Oxford University Press: Auckland, New Zealand.

Latta, R., Blacklow, L. and Cocks, P. (2001). Comparative soil water, pasture production and crop yields in phase farming systems with lucerne and annual pasture in Western Australia. *Australian Journal of Agricultural Research, 52*(2), 295-303.

Latta, R., Cocks, P. and Matthews, C. (2002). Lucerne pastures to sustain agricultural production in southwestern Australia. *Agricultural Water Management, 53*(1), 99-109.

Lemaire, G., Khaity, M., Onillon, B., Allirand, J.M., Chartier, M. and Gosse, G. (1992). Dynamics of accumulation and partitioning of N in leaves, stems and roots of lucerne (*Medicago sativa* L.) in a dense canopy. *Annals of Botany, 70*(5), 429-435.

Leuning, R., Condon, A.G., Dunin, F.X., Zegelin, S. and Denmead, O.T. (1994). Rainfall interception and evaporation from soil below a wheat canopy. *Agricultural and Forest Meteorology, 67*(3-4), 221-238.

Li, G.D., Kemp, P.D. and Hodgson, J. (1994). Control of reproductive growth in Puna chicory by grazing management. *Proceedings of the New Zealand Grassland Association, 56*, 213-217.

Li, G.D., Kemp, P.D. and Hodgson, J. (1997a). Biomass allocation, regrowth and root carbohydrate reserves of chicory (*Cichorium intybus* L) in response to defoliation in glasshouse conditions. *Journal of Agricultural Science, U.K, 129*(4), 447-458.

Li, G.D., Kemp, P.D. and Hodgson, J. (1997b). Herbage production and persistence of Puna chicory (*Cichorium intybus* L.) under grazing management over 4 years. *New Zealand Journal of Agricultural Research, 40*(1), 51-56.

Li, G.D., Kemp, P.D. and Hodgson, J. (1997c). Regrowth, morphology and persistence of Grasslands Puna chicory (*Cichorium intybus* L.) in response to grazing frequency and intensity. *Grass and Forage Science, 52*(1), 33-41.

Li, G.D., Kemp, P.D. and Hodgson, J. (1998). Morphological development of forage chicory under defoliation in the field and glasshouse. *Australian Journal of Agricultural Research, 49*(1), 69-77.

Li, R., Volenec, J.J., Joern, B.C. and Cunningham, S.M. (1996). Seasonal changes in nonstructural carbohydrates, protein, and macronutrients in roots of alfalfa, red clover, sweetclover, and birdsfoot trefoil. *Crop Science, 36*(3), 617-623.

Little, T.M. and Jackson, F.H. (1978). *Agricultural Experimentation.* John Wiley & Sons: New York, U.S.A.

Littleboy, M., Silburn, D., Freebairn, D., Woodruff, D., Hammer, G. and Leslie, J. (1992). Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. *Australian Journal of Soil Research, 30*(5), 757-774.

Loomis, R.S. and Connor, D.J. (1992). *Crop ecology: productivity and management in agricultural systems.* Cambridge University Press: Cambridge, U.K.

Lu, Z., Chen, J., Percy, R.G., Sharifi, M.R., Rundel, P.W. and Zeiger, E. (1996). Genetic variation in carbon isotope discrimination and its relation to stomatal conductance in Pima cotton (*Gossypium barbadense*). *Australian Journal of Plant Physiology, 23*(2), 127-132.

Luo, Y., Meyerhoff, P.A. and Loomis, R.S. (1995). Seasonal patterns and vertical distributions of fine roots of alfalfa (*Medicago sativa* L.). *Field Crops Research, 40*(2), 119-127.

Lyons, A. and Latta, R. (2003). Benefits of a lucerne pasture-crop rotation in the south-east of WA. *Proceedings of the 11th Australian Agronomy Conference*, Geelong, Victoria. www.regional.org.au/au/asa/2003/p/8/lyons.htm

Major, D., Hanna, M. and Beasley, B. (1991). Photoperiod response characteristics of alfalfa (*Medicago sativa*). *Canadian Journal of Plant Science, 71*(1), 87-93.

Major, D.J. (1980). Photoperiod response characteristics controlling flowering of nine crop species. *Canadian Journal of Plant Science, 60*(3), 777-784.

Maruyama, J. and Fukunaga, K. (1991). Studies on branching in legumes. II. System of foliar emergence in alfalfa (*Medicago sativa* L.). *Journal of Japanese Society of Grassland Science, 37*(3), 371-375.

Masiunas, J.B. and Carpenter, P.L. (1984). Radicle growth of grasses and legumes in response to temperature. *Hort Science, 19*(2), 298-300; 218 ref.

Masle, J., Doussinault, G., Farquhar, G.D. and Sun, B. (1989). Foliar stage in wheat correlates better to photothermal time than to thermal time. *Plant, Cell and Environment, 12*(3), 235-247.

Matthews, P.N.P., Kemp, P.D. and Austin, G.M. (1990). The effect of grazing management on the growth and reproductive development of chicory. *Proceedings of the New Zealand Agronomy Society, 30*, 41-43.

Matthews, R.B. and Stephens, W. (2002). *Crop-soil simulation models: applications in developing countries*. C.A.B International: Wallingford, U.K.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. (1996). APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems, 50*, 255-271.

McKenzie, B. and Hill, G. (1989). Environmental control of lentil (*Lens culinaris*) crop development. *Journal of Agricultural Science, U.K, 113*, 67-72.

McKenzie, B.A., Gyamtsho, P. and Lucas, R.J. (1990). Productivity and water use of lucerne and two lucerne-grass mixtures in Canterbury. *Proceedings of the New Zealand Grassland Association, 52*, 35-39.

McLaren, R. and Cameron, K. (1990). *Soil science: an introduction to the properties of New Zealand soils*. Oxford University Press: Auckland, New Zealand.

McWilliam, J.R. (1989). The dimensions of drought. In F.W.G. Baker (Ed.), *Drought resistance in cereals* (pp. 1-12). C.A.B International: Exter, U.K.

Meinke, H., Carberry, P.S., Cleugh, H.A., Poulton, P.L. and Hargreaves, J.N.G. (2002). Modelling crop growth and yield under the environmental changes induced by windbreaks. 1. Model development and validation. *Australian Journal of Experimental Agriculture, 42*(6), 875-885.

Meinke, H., Hammer, G.L. and Want, P. (1993). Potential soil water extraction by sunflower on a range of soils. *Field Crops Research, 32*(1-2), 59-81.

Michaud, R., Lehman, W.R. and Rumbaugh, M.D. (1988). World distribution and historical development. In A.A. Hanson, D.K. Barnes & R.R.J. Hill (Eds.), *Alfalfa and alfalfa improvement* (pp. 26-82). American Society of Agronomy: Madison, U.S.A.

Moloney, S.C. and Milne, G.D. (1993). Establishment and management of Grasslands Puna chicory used as a specialist, high quality forage herb. *Proceedings of the New Zealand Grassland Association, 55*, 113-118.

Monteith, J.L. (1972). Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology, 9*(3), 747-766.

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. (1986). How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Society of London, A, 316*, 245-258.

Monteith, J.L. (1988). Does transpiration limit the growth of vegetation or vice versa? *Journal of Hydrology, Netherlands, 100*(1-3), 57-68.

Monteith, J.L. (1993). The exchange of water and carbon by crops in a mediterranean climate. *Irrigation Science, 14*(2), 85-91.

Monteith, J.L., Huda, A.K.S. and Midya, D. (1989). *RESCAP: A resource capture model of sorghum and pearl millet.* I.C.R.I.S.A.T: Patancheru, India.

Monteith, J.L. and Unsworth, M.H. (1990). *Principals of Environmental Physics* (2nd ed.). Arnold: London, U.K.

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. *Proceedings of the 10th Australian Agronomy Conference*, Hobart, Tasmania. http://www.regional.org.au/au/asa/2001/6/d/moot.htm

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* (pp. 201-208). New Zealand Grasslands Association, Research and Practice series No. 11: Palmerston North, New Zealand.

Moot, D.J., Scott, 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*(1), 15-25.

Moran, M.S., Pinter, P.J.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*(3), 251-261.

Morton, J., Roberts, A.H.C. and Edmeades, D.C. (1994). *Fertiliser use on sheep and beef farms: the principles and practice of soil fertility and fertiliser use on sheep and beef farms.* New Zealand Fertiliser Manufactures Research Association: Auckland, New Zealand.

Moss, R. and Vlassoff, A. (1993). Effect of herbage species on gastro-intestinal roundworm populations and their distribution. *New Zealand Journal of Agricultural Research, 36*(3), 371-375.

Muchow, R. and Bellamy, J. (1991). *Climatic risk in crop production: models and management for the semiarid tropics and subtropics. Proceedings of an international symposium.* C.A.B International: Wellingford, U.K.

Muchow, R.C. and Carberry, P.S. (1990). Phenology and leaf-area development in a tropical grain sorghum. *Field Crops Research, 23*(3-4), 221-237.

Niezen, J., Barry, T., Hodgson, J., Wilson, P., Ataja, A., Parker, W. and Holmes, C. (1993). Growth responses in red deer calves and hinds grazing red clover, chicory or perennial ryegrass/white clover swards during lactation. *Journal of Agricultural Science, U.K, 121*(2), 255-263.

Noquet, C., Avice, J., Ourry, A., Volenec, J., Cunningham, S. and Boucaud, J. (2001). Effects of environmental factors and endogenous signals on N uptake, N partitioning and taproot vegetative storage protein accumulation in *Medicago sativa. Australian Journal of Plant Physiology, 28*(4), 279-287.

Norman, J.M. and Arkebauer, T.J. (1991). Predicting Canopy photosynthesis and light use efficiency from leaf characteristics. In K.J. Boote & R.S. Loomis (Eds.), *Modelling crop photosynthesis - from biochemestry to canopy* (pp. 75-94). American Society of Agronomy: Madison, U.S.A.

Nouvellon, Y., Begue, A., Moran, M.S., Lo Seen, D., Rambal, S., Luquet, D., Chehbouni, G., Inoue, Y. and Lo, S. (2000). PAR extinction in shortgrass ecosystems: effects of clumping, sky conditions and soil albedo. *Agricultural and Forest Meteorology, 105,* 21-41.

Opik, H. (1980). *The respiration of higher plants.* Edward Arnold Ltd.: London; U.K.

Ottman, M.J. (1999). Water stress and alfalfa production. In M. Pessarakli (Ed.), *Handbook of plant and crop stress* (2nd edn., pp. 879-889). Marcel Dekker, Inc: New York; U.S.A.

Ourry, A., Kim, T.H. and Boucaud, J. (1994). Nitrogen reserve mobilization during regrowth of *Medicago sativa* L. Relationships between availability and regrowth yield. *Plant Physiology, 105*(3), 831-837.

Passioura, J.B. (1983). Roots and drought resistance. *Agricultural Water Management, 7*(1-3), 265-280.

Paton, J. and Fraser, W. (1992). *Securing the future of dryland pastoral farming in the east coast downlands.* AgResearch: Mosgeil, New Zealand.

Paton, R.J. (1992). Performance of dryland pasture options in the downlands. In R.J. Patton & W.J. Fraser (Eds.), *Securing the future of dryland farming in the east coast downlands.* AgResearch: Mosgeil, New Zealand.

Patterson, D.T. (1993). Effects of day and night temperature on goatsrue (*Galega officinalis*) and alfalfa (*Medicago sativa*) growth. *Weed Science, 41*(1), 38-45.

Peacock, J. (1975). Temperature and leaf growth in *Lolium perenne*. 1. The thermal microclimate: its measurement and relation to crop growth. *Journal of Applied Ecology, 12*(1), 99-114.

Pearson, C.J. and Hunt, L.A. (1972a). Effects of temperature on primary growth and regrowth of alfalfa. *Canadian Journal of Plant Science, 52*(6), 1017- 1027.

Pearson, C.J. and Hunt, L.A. (1972b). Effects of temperature on primary growth of alfalfa. *Canadian Journal of Plant Science, 52*(6), 1007-1015.

Pengelly, B.C., Muchow, R.C. and Blamey, F.P.C. (1999). Predicting leaf area development in response to temperature in three tropical annual forage legumes. *Australian Journal of Agricultural Research, 50*(2), 253-259.

Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London, A, 194*, 120 - 145.

Penning de Vries, F.W.T., Jansen, D.M., Bakema, A. and Ten Berge, H.F.M. (1989). *Simulation of ecophysiological processes of growth in several annual crops.* Pudoc: Wageningen, Netherlands.

Peri, P.L. (2002). *Leaf and canopy photosynthesis models for cocksfoot (Dactylis glometata L.) grown in a silvopastoral system.* Ph.D. thesis, Lincoln University, Christchurch.

Peri, P.L., Moot, D.J., McNeil, D.L., Varella, A.C. and Lucas, R.J. (2002). Modelling net photosynthetic rate of field-grown cocksfoot leaves under different nitrogen, water and temperature regimes. *Grass and Forage Science, 57*(1), 61-71.

Petit, H.V., Pesant, A.R., Barnett, G.M., Mason, W.N. and Dionne, J.L. (1992). Quality and morphological characteristics of alfalfa as affected by soil moisture, pH and phosphorus fertilization. *Canadian Journal of Plant Science, 72*(1), 147-162.

Pietola, L.M. and Smucker, A.J.M. (1995). Fine root dynamics of alfalfa after multiple cuttings and during a late invasion by weeds. *Agronomy Journal, 87*(6), 1161-1169.

Porter, J.R. (1984). A model of canopy development in winter wheat. *Journal of Agricultural Science, U.K, 102*(2), 383-392.

Porter, J.R. (1993). AFRCWHEAT2: a model of the growth and development of wheat incorporating responses to water and nitrogen. *European Journal of Agronomy, 2*(2), 69-82.

Porter, J.R., Jamieson, P.D. and Wilson, D.R. (1993). Comparison of the wheat simulation models AFRCWHEAT2, CERES-Wheat and SWHEAT for non-limiting conditions of crop growth. *Field Crops Research, 33*(1-2), 131-157.

Probert, M., Carberry, P., McCown, R. and Turpin, J. (1998a). Simulation of legume-cereal systems using APSIM. *Australian Journal of Agricultural Research, 49*(3), 317-327.

Probert, M., Dimes, J., Keating, B., Dalal, R. and Strong, W. (1998b). APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems, 56*(1), 1-28.

Probert, M., Keating, B., Thompson, J. and Parton, W. (1995). Modelling water, nitrogen, and crop yield for a long-term fallow management experiment. *Australian Journal of Experimental Agriculture, 35*(7), 941-950.

Probert, M.E., Robertson, M.J., Poulton, P.L., Carberry, P.S., Weston, E.J. and Lehane, K.J. (1998c). Modelling lucerne growth using APSIM. *Proceedings of the Australian Agronomy Conference, 9*, 247-250.

Pugnaire, F.I. (1999). Constraints by water stress on plant growth. In M. Pessarakli (Ed.), *Handbook of plant and crop stress* (2 edn., pp. 879-889). Marcel Dekker, Inc: New York; U.S.A.

Purves, R.G. and Wynn-Williams, R.B. (1989). Lucerne - a fresh look. *Proceedings of the New Zealand Agronomy Society, 19*, 95-102.

Radcliffe, J.E. and Baars, J.A. (1987). The productivity of temperate grasslands. In R.W. Snaydon (Ed.), *Ecosystems of the world: 17b managed grasslands* (pp. 7-17). Elsevier Science Publishers: Amsterdam, Netherlands.

Ranganathan, R., Chauhan, Y.S., Flower, D.J., Robertson, M.J., Sanetra, C. and Silim, S.N. (2001). Predicting growth and development of pigeonpea: leaf area development. *Field Crops Research, 69*(2), 163-172.

Ratliff, L.F., Ritchie, J.T. and Cassel, D.K. (1983). Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil Science Society of America Journal, 47*(3), 770-775.

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* (pp. 89-104). New Zealand Society of Animal Production, Occasional Publication No. 10: Christchurch, New Zealand.

Rawson, H.M., Begg, J.E. and Woodward, R.G. (1977). The effect of atmospheric humidity on photosynthesis, transpiration and water use efficiency of leaves of several plant species. *Planta, 134*(1), 5-10.

Rawson, H.M., Turner, N.C. and Begg, J.E. (1978). Agronomic and physiological responses of soybean and sorghum crops to water deficits IV. Photosynthesis, transpiration and water use efficiency of leaves. *Australian Journal of Plant Physiology, 5*(2), 195-209.

Ray, I.M., Townsend, M.S. and Henning, J.A. (1998). Variation for yield, water-use efficiency, and canopy morphology among nine alfalfa germplasms. *Crop Science, 38*(5), 1386-1390.

Reid, J.B., Hashim, O. and Gallagher, J.N. (1984). Relations between available and extractable soil water and evapotranspiration from a bean crop. *Agricultural Water Management, 9*(3), 193-209.

Rickard, D.S. and Radcliffe, J.E. (1976). Seasonal distribution of pasture production in New Zealand. 12. Winchmore, Canterbury Plains dryland and irrigated pastures. *New Zealand Journal of Experimental Agriculture, 4*(3), 329-335.

Ritchie, J.T. (1972). Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research, 8*(5), 1204-1213.

Ritchie, J.T. (1981). Soil water availability. *Plant and Soil, 58*(1-3), 327-338.

Ritchie, J.T. (1983). Efficient water use in crop production: discussion on the generality of relations between biomass production and evapotranspiration. In H.M. Taylor, W.R. Jordan & T.R. Sinclair (Eds.), *Limitations to efficient water use in crop production* (pp. 29-44). American Society of Agronomy: Madison, U.S.A.

Ritchie, J.T. (1991). Specifications of the ideal model for predicting crop yields. *Climatic risk in crop production: models and management for the semiarid tropics and subtropics. Proceedings of an international symposium*, Brisbane, Australia. pp. 97-122.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J. and Brinsmead, R.B. (2002). Simulation of growth and development of diverse legume species in APSIM. *Australian Journal of Agricultural Research, 53*, 429-446.

Robertson, M.J., Fukai, S., Hammer, G.L. and Ludlow, M.M. (1993a). Modelling root growth of grain sorghum using the CERES approach. *Field Crops Research, 33*(1-2), 113-130.

Robertson, M.J., Fukai, S., Ludlow, M.M. and Hammer, G.L. (1993b). Water extraction by grain sorghum in a sub-humid environment. I. Analysis of the water extraction pattern. *Field Crops Research, 33*(1-2), 81-97.

Robertson, M.J., Fukai, S., Ludlow, M.M. and Hammer, G.L. (1993c). Water extraction by grain sorghum in a sub-humid environment. II. Extraction in relation to root growth. *Field Crops Research, 33*(1-2), 99-112.

Rumball, W. (1986). 'Grasslands Puna' chicory (*Cichorium intybus* L.). *New Zealand Journal of Experimental Agriculture, 14*(1), 105-107.

Sadras, V.O., Whitfield, D.M. and Connor, D.J. (1991). Transpiration efficiency in crops of semi-dwarf and standard-height sunflower. *Irrigation Science, 12*(2), 87-91.

Sanderson, M.A., Karnezos, T.P. and Matches, A.G. (1994). Morphological development of alfalfa as a function of growing degree days. *Journal of Production Agriculture, 7*(2), 239-242.

Sands, P.J. (1996). Modelling canopy production. III. Canopy light-utilisation efficiency and its sensitivity to physiological and environmental variables. *Australian Journal of Plant Physiology, 23*(1), 103-114.

Scales, G.H., Knight, T.L. and Saville, D.J. (1995). Effect of herbage species and feeding level on internal parasites and production performance of grazing lambs. *New Zealand Journal of Agricultural Research, 38*(2), 237-247.

Scotter, D.R. (1977). Field capacity and available soil water. *Proceedings of Soil and Plant Water Symposium*, Palmerston North, New Zealand. pp. 3-11.

Seligman, N.G. (1990). The crop model record: promise or poor show? In R. Rabbinge, J. Goudriaan, H. van Keulen, F.T.W. Penning de Vries & H.H. van Laar (Eds.), *Theoretical Production Ecology: reflections and prospects* (pp. 249-255). Pudoc: Wageningen, Netherlands.

Shafiq Zahid, M., Bellotti, W., McNeill, A. and Robertson, M.J. (2003). Performance of APSIM-Lucerne in South Australia. *Proceedings of the 11th Australian Agronomy Conference.* www.regional.org.au/au/asa/2003/c/10/bellotti.htm

Sharratt, B.S., Reicosky, D.C., Idso, S.B. and Baker, D.G. (1983). Relationships between leaf water potential, canopy temperature, and evapotranspiration in irrigated and nonirrigated alfalfa. *Agronomy Journal, 75*(6), 891-894.

Sharratt, B.S., Sheaffer, C.C. and Baker, D.G. (1989). Base temperature for the application of the growing-degree-day model to field-grown alfalfa. *Field Crops Research, 21*(2), 95-102.

Sheaffer, C.C., Tanner, C.B. and Kirkham, M.B. (1988). Alfalfa water relations and irrigation. In A.A. Hanson, D.K. Barnes & R.R.J. Hill (Eds.), *Alfalfa and alfalfa improvement* (pp. 373-409). American Society of Agronomy: Madison, U.S.A.

Sheath, G.W., Galletly, W.S. and Greenwood, P. (1977). An evaluation of several grass and legume cultivars under dryland and irrigation in North Otago. *Proceedings of the New Zealand Grassland Association, 38*(1), 140-150.

Sheath, G.W. and Hay, R.J.M. (1989). Overview of legume persistence in New Zealand. *Persistence of forage legumes*, Honolulu, U.S.A. pp. 23-36.

Sinclair, T.R. (1984). Leaf area development in field-grown soybeans. *Agronomy Journal, 76*(1), 141-146.

Sinclair, T.R. (2000). Model analysis of plant traits leading to prolonged crop survival during severe drought. *Field Crops Research, 68*(3), 211-217.

Sinclair, T.R. and Horie, T. (1989). Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. *Crop Science, 29*(1), 90-98.

Sinclair, T.R. and Muchow, R.C. (1999). Radiation use efficiency. *Advances in Agronomy, 65*, 215-265.

Sinclair, T.R., Muchow, R.C., Ludlow, M.M., Leach, G.J., Lawn, R.J. and Foale, M.A. (1987). Field and model analysis of the effect of water deficits on carbon and nitrogen accumulation by soybean, cowpea and black gram. *Field Crops Research, 17*(2), 121-140.

Singh, P., Monteith, J.L., Lee, K.K., Rego, T.J. and Wani, S.P. (1998). Response to fertilizer nitrogen and water of post-rainy season sorghum on a vertisol. 2. Biomass and water extraction. *Journal of Agricultural Science, U.K, 131*(4), 429-438.

Singh, P. and Sri Rama, Y.V. (1989). Influence of water deficit on transpiration and radiation use efficiency of chickpea (*Cicer arietinum* L.). *Agricultural and Forest Meteorology, 48*, 317-330.

Skipp, R.A. and Christensen, M.J. (1990). Selection for persistence in red clover: influence of root disease and stem nematode. *New Zealand Journal of Agricultural Research, 33*(2), 319-333.

Smeal, D., Kallsen, C.E. and Sammis, T.W. (1991). Alfalfa yield as related to transpiration, growth stage and environment. *Irrigation Science, 12*(2), 79-86

Smil, V. (2000). *Feeding the world: A challenge for the twenty-first century*. The MIT Press: London, U.K.

Smith, D. (1970). Yield and chemical composition of leaves and stems of alfalfa at intervals up the shoots. *Journal of Agricultural Food Chemistry, 18*, 652-656.

Stanhill, G. (1986). Water use efficiency. *Advances in Agronomy, 39*, 53-85.

Stephen, R.C., Saville, D.J., Harvey, I.C. and Hedley, J. (1982). Herbage yields and persistence of lucerne (*Medicago sativa* L.) cultivars and the incidence of crown and root diseases. *New Zealand Journal of Experimental Agriculture, 10*(3), 323-332.

Stockle, C.O. and Kiniry, J.R. (1990). Variability in crop radiation-use efficiency associated with vapour-pressure deficit. *Field Crops Research, 25*(3-4), 171-181.

Ta, T.C., Macdowall, F.D.H. and Faris, M.A. (1990). Utilisation of carbon and nitrogen reserves of alfalfa roots in supporting N_2 fixation and shoot regrowth. *Plant and Soil, 127*(2), 231-236.

Tanner, C.B. and Sinclair, T.R. (1983). Efficient water use in crop production: research or re-search? In H. Taylor, W. Jordan & T. Sinclair (Eds.), *Limitations to efficient water use in crop production* (pp. 1-25). American Society of Agronomy: Madison, U.S.A.

Tardieu, F., Granier, C. and Muller, B. (1999). Modelling leaf expansion in a fluctuating environment: are changes in specific leaf area a consequence of changes in expansion rate? *New Phytologist, 143*(1, Special issue: Variation in leaf structure), 33-43.

Taylor, H., Jordan, W. and Sinclair, T. (1983). *Limitations to efficient water use in crop production.* American Society of Agronomy: Madison, U.S.A.

Taylor, N. and Quesenberry, K. (1996). *Red clover science.* Kluwer Academic Publishers: Dordrecht, The Netherlands.

Teuber, L.R. and Brick, M.A. (1988). Morphology and anatomy. In A.A. Hanson, D.K. Barnes & R.R.J. Hill (Eds.), *Alfalfa and alfalfa improvement* (pp. 125-162). American Society of Agronomy: Madison, U.S.A.

Theobald, P.W. and Ball, P.R. (1983). Performance of a stand of 'Wairau' lucerne and lucerne-annual ryegrass in the Manawatu. *New Zealand Journal of Experimental Agriculture, 11*(1), 21-26.

Thom, E.R. (1978). Effect of stage of growth and season on yield of lucerne (*Medicago sativa* L.) and on in vitro digestibility of the whole plant and its component parts. *Proceedings of the New Zealand Agronomy Society, 8*, 43-46.

Thomas, Fukai, S. and Hammer, G.L. (1995). Growth and yield response of barley and chickpea to water stress under three environments in southeast Queensland. II. Root growth and soil water extraction pattern. *Australian Journal of Agricultural Research, 46*(1), 35-48.

Thomson, N.A. (1977). Factors affecting animal production: intake and utilization by ewes grazing grass/clover and lucerne pastures. *Proceedings of the New Zealand Grassland Association, 9*(1), 86-97.

Thornley, J.H.M. (1998). Plant submodel. In J.H.M. Thornley (Ed.), *Grassland dynamics: an ecosystem simulation model.* (pp. 15-57). C.A.B International: Oxon, U.K.

Thornley, J.H.M. and Johnson, I.R. (2000). *Plant and crop modelling: a mathematical approach to plant and crop physiology.* (2nd ed.). The Blackburn Press: New Jersey, U.S.A.

Travis, R.L. and Reed, R. (1983). The solar tracking pattern in a closed alfalfa canopy. *Crop Science, 23*(4), 664-668.

Trenbath, B.R. and Angus, J.F. (1975). Leaf inclination and crop production. *Field Crop Abstracts, 28*(5), 231-244.

Truong, H.H. and Duthion, C. (1993). Time of flowering of pea (*Pisum sativum* L.) as a function of leaf appearance rate and node of first flower. *Annals of Botany, 72*(2), 133-142.

Ulyatt, M.J. (1978). Aspects of the feeding value of pastures. *Proceedings of the New Zealand Agronomy Society, 8*, 119-122.

Undersander, D.J. (1987). Alfalfa (*Medicago sativa* L.) growth response to water and temperature. *Irrigation Science, 8*(1), 23-33.

van Keulen, H. and Seligman, N.G. (1987). *Simulation of water use, nitrogen nutrition and growth of a spring wheat crop.* Pudoc: Wageningen, Netherlands.

Varella, A.C. (2002). *Lucerne crop responses to continuous and intermittent light under artificial and agroforestry regimes.* Ph.D. thesis, Lincoln University, Christchurch, New Zealand.

Vartha, E.W. and O'Connor, K.F. (1968). Prospects for high production from Canterbury Plains pastures. *Proceedings of the New Zealand Society of Animal Production, 28*, 65-73.

Virgona, J.M. and Farquhar, D.G. (1996). Genotypic variation in relative growth rate and carbon isotope discrimination in sunflower is related to photosynthetic capacity. *Australian Journal of Plant Physiology, 23*(2), 227-236.

Volenec, J.J., Cherney, J.H. and Johnson, K.D. (1987). Yield components, plant morphology, and forage quality of alfalfa as influenced by plant population. *Crop Science, 27*(2), 321-326.

Waghorn, G.C. and Barry, T.N. (1987). Pasture as a nutrient source. In A.M. Nicol (Ed.), *Feeding livestock on pasture* (pp. 21-38). New Zealand Society of Animal Production, Occasional Publication No. 10: Christchurch, New Zealand.

Warren Wilson, J. (1965). Stand structure and light penetration. I. Analysis by point quadrats. *Journal of Applied Ecology, 2*, 383-390.

Watt, J.P.C. and Brugham, S.J. (1992). *Physical properties of eight soils of the Lincoln area, Canterbury.* Land resources technical record No. 103. D.S.I.R: Christchurch, New Zealand.

Webb, T.H. (1989). Soil water measurements on four alluvial soils in Canterbury. 1. Soil water extraction patterns under spring-sown peas and barley, and pasture. *New Zealand Journal of Crop and Horticultural Science, 17*(2), 189-199.

Webb, T.H., Claydon, J.J. and Harris, S.R. (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*(6), 1115-1129.

Welles, J.M. and Cohen, S. (1996). Canopy structure measurement by gap fraction analysis using commercial instrumentation. *Journal of Experimental Botany, 47*(302), 1335-1342.

Welles, J.M. and Norman, J.M. (1991). Instrument for indirect measurement of canopy architecture. *Agronomy Journal, 83*(5), 818-825.

White, J.G.H. (1982). Lucerne grazing management for the 80's. In *Lucerne for the 80's* (pp. 111-114). Agronomy Society of New Zealand, Special publication No. 1: Christchurch; New Zealand.

White, J.G.H. (1999). The farmlands of New Zealand. In J.G.H. White & J. Hodgson (Eds.), *New Zealand pasture and crop science* (pp. 1-10). Oxford University Press: Auckland, New Zealand.

White, J.G.H. and Cosgrove, G.P. (1990). Lucerne grazing management. 2. Effect of grazing duration on defoliation pattern by ewes. *New Zealand Journal of Agricultural Research, 33*(4), 621-625.

Whitfield, D.M. (1990). Canopy conductance, carbon assimilation and water use in wheat. *Agricultural and Forest Meteorology, 53*(1-2), 1-18.

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*(1), 37-52.

Wilson, D.R. (1985). The value of water for crop production. *New Zealand Journal of Agricultural Science*, 174-178.

Wilson, D.R., Muchow, R.C. and Murgatroyd, C.J. (1995). Model analysis of temperature and solar radiation limitations to maize potential productivity in a cool climate. *Field Crops Research, 43*(1), 1-18.

Wolf, D.D. and Blaser, R.E. (1971). Leaf development of alfalfa at several temperatures. *Crop Science, 11*, 479-482.

Woolley, D.J., Karno and Nichols, M.A. (2002). Effects of daylength on dry matter partitioning in asparagus. *Acta Horticulturae, 589*(Proceedings of the 10th international asparagus symposium, Niigata, Japan), 243-247.

Wynn-Williams, R.B. (1982). *Lucerne for the 80's*. Agronomy Society of New Zealand, Special publication No. 1: Christchurch, New Zealand.

Young, H. (1989). What are the implications for farmers? *Farming through drought: working with climate change*, Lincoln College, New Zealand. pp. 43-51.

Yunusa, I.A.M., Mead, D.J., Lucas, R.J. and Pollock, K.M. (1995). Process studies in a *Pinus radiata*-pasture agroforestry system in a subhumid temperature environment. II. Analysis of dry matter yields in the third year. *Agroforestry Systems, 32*(2), 185-204.

Yunusa, I.A.M., Sedgley, R.H., Tennant, D. and Belford, R.K. (1993). Dynamics of water use in a dry mediterranean environment. II. A test of four evaporation models using microlysimetry under spring wheat. *Agricultural Water Management, 24*(3), 225-238.

Zhang, H.H. and Nobel, P.S. (1996). Dependency of C_i/C_a and leaf transpiration efficiency on the vapour pressure deficit. *Australian Journal of Plant Physiology, 23*(5), 561-568.

Appendices

Appendix 1a Amount and timing of irrigation applied over six growth seasons to chicory, lucerne and red clover crops grown Iversen 8 at Lincoln University, Canterbury, New Zealand from 1 November 1996–24 June 2002.

Season	Regrowth	Application date	Amount (mm)
1996/97		20–22 Oct	40
		3–5 Dec	40
		Total	**80**
1997/98	2	30–31 Oct	30
	3	1–4 Dec	50
	3	16–17 Dec	40
	4	7 Jan	14
	4	15–16 Jan	30
	4	23 Jan	26
	5	17–21 Feb	62
	5	6 Mar	23
	6	30–31 Mar	31
		Total	**306**
1998/99	1	9–14 Sep	90
	3	12–19 Nov	150
	5	20–25 Jan	127
	6	25–29 Feb	70
		Total	**437**
1999/00	3	11–12 Dec	30
	5	22–24 Jan	50
		Total	**80**
2000/01	4	27–30 Dec	75
	5	1–4 Feb	95
	6	20–22 Mar	65
	6	26–27 Apr	45
		Total	**280**
2001/02	3	19–23 Dec	65
Dryland* 1998/99	1	11–18 Sep	150

Note: * means irrigation applied to dryland treatments to reduce soil water deficit at the start of the 1998/99 growing season.

Appendix 1b Amount and timing of irrigation applied over two growth seasons to lucerne crops grown in Iversen 9 at Lincoln University, Canterbury, New Zealand from 24 October 2000–24 June 2002.

Season	Regrowth	Application date	Amount (mm)
2000/01	1#	19–20 Dec	25
	1#	28–29 Dec	30
	2	27–28 Jan	36
	2	15 –17 Feb	45
	2	5 –7 Mar	55
	3	27–30 Mar	80
	3	27 –29 Apr	52
		Total	**323**
2000/01	2	6–9 Oct	70
	3	4–6 Dec	70
	4	26–29 Dec	80
		Total	**220**
Dryland* 2001/02	1	8–11 Aug	70

Note: # is initial seedling growth not regrowth. * means irrigation applied to dryland treatments to reduce soil water deficit at the start of the 1998/99 growing season.

Appendix 2a   Regrowth cycle start date, grazing date and regrowth and grazing durations (days) of chicory, lucerne and red clover crops grown at Lincoln University, Canterbury, New Zealand over six seasons from 1 November 1996–24 June 2002.

Season	Regrowth	Start date	Grazing date	Regrowth days	Grazing days
1996/97	1	1-Nov	21-Feb	112	9
	2	2-Mar	5-Jun	95	5
1997/98	1	10-Jun	6-Oct	118	7
	2	13-Oct	19-Nov	37	5
	3	24-Nov	23-Dec	29	7
	4	30-Dec	3-Feb	35	14
	5	17-Feb	12-Mar	23	3
	6	15-Mar	29-May	75	7
1998/99	1	5-Jun	29-Sep	116	10
	2	9-Oct	11-Nov	33	5
	3	16-Nov	15-Dec	29	7
	4	22-Dec	11-Jan	20	0
	5	11-Jan	17-Feb	37	7
	6	24-Feb	9-Apr	44	13
	7	22-Apr	24-Jun	63	3
1999/00	1	27-Jun	29-Sep	94	7
	2	6-Oct	9-Nov	34	8
	3	17-Nov	20-Dec	33	6
	4	26-Dec	21-Jan	26	5
	5	26-Jan	13-Mar	47	5
	6	18-Mar	25-May	68	4
2000/01	1	29-May	22-Sep	116	9
	2	1-Oct	10-Nov	40	6
	3	16-Nov	19-Dec	33	8
	4	27-Dec	24-Jan	28	6
	5	30-Jan	11-Mar	40	6
	6	17-Mar	2-May	46	4
	7	6-May	24-Jun	49	10
2001/02	1	4-Jul	3-Oct	91	7
	2	10-Oct	21-Nov	42	5
	3	26-Nov	22-Dec	26	8
	4	30-Dec	6-Feb	38	9
	5	15-Feb	3-Apr	47	14
	6	17-Apr	24-Jun	68	11

269

Appendix 2b Regrowth and grazing start dates and durations for lucerne crops grown in Iversen 9 at Lincoln University, Canterbury, New Zealand from 24 October 2000–12 June 2002.

Growth season	Sowing date	Regrowth cycle	Start date	Defoliation date	Regrowth duration	Grazing duration
		1*	24-Oct-00	24-Jan-01	92*	-
	1	2	25-Jan-01	7-Mar-01	41	-
		3	8-Mar-01	30-Apr-01	53	2
		4	2-May-01	4-Jul-01	63	2
		1*	15-Nov 00	13 Feb 01	90*	-
	2	2	14 Feb 01	30 Apr 01	75	2
2000/01		3	1 May 01	4 Jul 01	64	2
		1*	5 Dec 00	7 Mar 01	92*	-
	3	2	8 Mar 01	30 Apr 01	53	2
		3	1 May 01	4 Jul 01	64	2
		1*	27 Dec 01	27 Mar 01	90*	-
	4	2	28 Mar 01	30 Apr 01	33	2
		3	1 May 01	4 Jul 01	64	2
		1	6-Jul-01	29-Sep-01	85	6
		2	5-Oct-01	14-Nov-01	40	6
2001/02		3	20-Nov-01	21-Dec-01	31	5
		4	26-Dec-01	31-Jan-02	36	6
		5	6-Feb-02	4-Apr-02	57	5
		6	9-Apr-02	12-Jun-02	64	6

Note: * is initial seedling growth not regrowth; - shows crops were defoliated by mowing rather than grazing.

Appendix 3. Calculating LAI from indirect green area index measurements.

Calculations of LAI was a two step process involving the calibration of the indirect GAI measurements then a conversion of these to LAI.

Calibrating the LI-COR LAI-2000 values of GAI

Calibration of GAI measurements was carried out by marking three 2.0 m^2 areas of uniform canopy on four occasions throughout a single regrowth cycle (8 March–30 April 2001) in I9$_{00/01}$. A single area was marked in an earlier regrowth cycle (25 January–7 March 2001) giving 13 data points of GAI ranging from 0.95–5.0. Measurements of GAI (LAI-2000) were taken from one point at the side of the marked area at dusk. One reference measurement was made above canopy and five below the canopy using the ¼ lens cap to confine measurements to a 90 ° sector within the marked area. The following morning a sample was cut at ground level from a round 0.5 m^2 quadrant placed adjacent to the point of GAI measurements (i.e. the main zone of the LAI-2000 measurement area). Samples were immediately placed into the refrigerator and GAI was manually measured as follows.

Each sample was weighed, thoroughly mixed by hand on a table top and divided into eight sub-samples. A random selection of four of these sub-samples were discarded and the other four were returned to the refrigerator. A LI-COR 3100 area meter was used to measure GAI of samples. This instrument consists of two rotating belts that converge on each other, pushing leaves flat as they travel through the instrument. The instrument has a light source and sensor which measures the area of light interruption by passing leaves. For each sub-sample all leaves were plucked from each stem and passed through the belt meter. Area sums were recorded regularly and summed at the end to give total leaf area of and total stem area of that sub-sample.

There was some concern about the magnitude of errors from transmission of light through and bending of light around the edge of the thin, small lucerne leaves. To account for this error the belt metre was also calibrated. This involved picking 10 stems of lucerne (> 40 cm high), plucking and arranging stems and leaves (not touching) on a

sheet of white A3 with a clean sheet of glass placed on top to hold leaves flat. Leaves and stems were arranged within a rectangular area (marked by a dot in each corner) of known dimensions and each of the 10 stems was photographed with a digital camera. A threshold function in Corel Photopaint was used to convert any dark pixels (i.e. leaves and stems) to black leaving all other areas (paper background) white. The image was then cropped to the edge of the marked area and Corel Photopaint gave statistics of the number of black and white pixels in the image. The fraction of black to white pixels multiplied by the area of the rectangle gave the GAI of that stem (and its leaves). The stem was then stored in the refrigerator and passed across the LI-COR belt meter later that morning. The belt meter under-estimated leaf by 10% and stem area by 22% compared with the digital images so stem and leaf areas calculated from belt metre measurements were multiplied by 1.11 and 1.29 (respectively) to correct for this. The area (leaves and stems) of the sub-samples was then multiplied by their weight fraction of the total sample to give the GAI of the 0.5 m^2 area.

The 10 measurements of GAI > 2.0 were well correlated (R^2 = 0.95) with LAI 2000 measurements and the regression was not different (P<0.05) from y = x (Figure 0.1a). The LAI 2000 gave an under prediction of GAI for GAI < 2.0 and this was described by line with an x intercept of 0.71 (y = 1.65x–1.30) that intercepted the regression fitted to GAI > 2.0 at 2.0. Any GAI values < 2.0 where adjusted to account for this underestimation using Equation 0.1.

Equation 0.1   Adjusted GAI = (GAI+1.3)/1.65   where GAI < 2.0

Adjusted GAI was then used to calculate LAI.
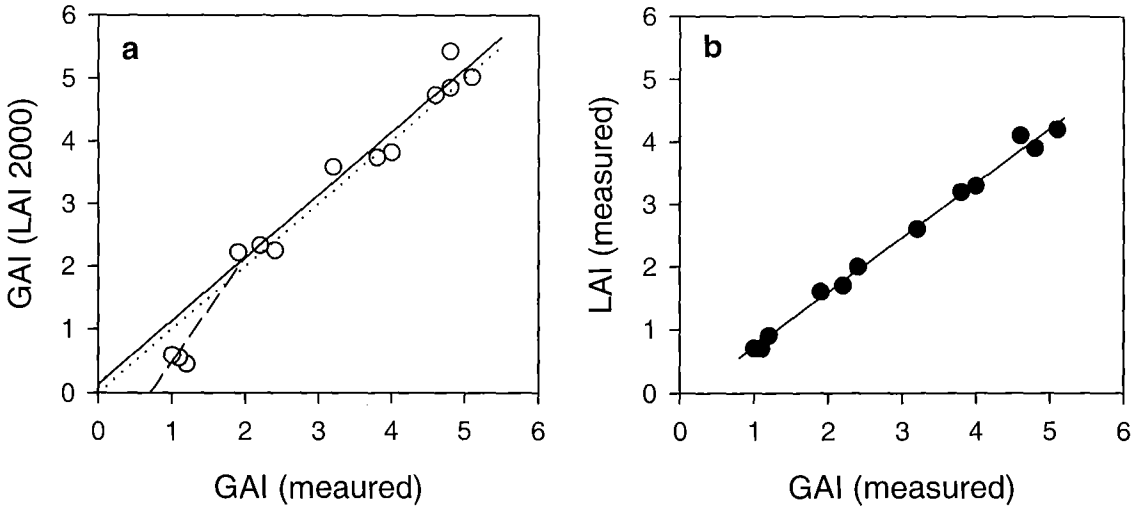
Figure 0.1 a) Green area index (GAI) measured with the LAI 2000 in relation to GAI measured via calibrated belt meter. b) leaf area index (LAI) in relation to GAI measured with a calibrated belt meter.

Note Coefficients (and standard errors) for fitted regressions. a) when GAI > 2 (———) y=0.13(0.32)+0.99(0.09)*x (R^2 = 0.95), when GAI < 2 y=-1.3+1.6*x. b) y=-0.15(0.07)+0.86(0.02)*x (R^2 = 0.99).

Converting GAI to LAI

Leaf area index from belt meter measurements was regressed as a function of GAI (Figure 0.1b) and the slope of the regression (0.86) was used as a coefficient to convert GAI from LAI-2000 measurements to LAI. All GAI measurements from the LAI-2000 were calibrated for underestimates at values < 2.0 and converted to LAI using this method.

Appendix 4 Botanical composition (% sown species) of chicory, lucerne and red clover crops (established in November 1996) under dryland and (Dry) and irrigated (Irr) conditions over six growth seasons in Canterbury New Zealand.

Season	Regrowth	Chicory		Lucerne		Red clover	
		Dry	Irr	Dry	Irr	Dry	Irr
	1	100	100	100	100	100	100
1996/97	2	100	100	100	100	100	100
	Average	**100**	**100**	**100**	**100**	**100**	**100**
	1	100	100	100	100	100	100
	2	100	100	100	100	100	100
	3	100	100	100	100	100	100
1997/98	4	100	100	100	100	100	100
	5	100	100	100	100	100	100
	6	100	100	100	100	100	100
	Average	**100**	**100**	**100**	**100**	**100**	**100**
	1	100	100	100	100	100	100
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
	4	-	-	-	-	-	-
1998/99	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	7	-	-	-	-	-	-
	Average	**100**	**100**	**100**	**100**	**100**	**100**
	1	82	90	97	93	54	26
	2	80	90	99	92	55	26
	3	89	81	99	91	79	34
1999/00	4	93	90	98	82	68	44
	5	91	75	100	100	37	21
	6	91	75	100	100	33	9
	Average	**88**	**84**	**99**	**93**	**54**	**27**
	1	69	78	97	85	11	0
	2	92	80	-	-	24	3
	3	68	58	-	-	14	1
2000/01	4	77	59	-	-	24	4
	5	71	82	-	-	44	12
	6	100	89	-	-	0	0
	7	100	74	-	-	0	0
	Average	**83**	**74**	**97**	**85**	**17**	**3**
	1	72	60	99	77	0	1
	2	69	46	98	51	0	0
	3	59	60	90	55	0	1
2001/02	4	59	60	90	55	0	1
	5	82	74	97	73	0	1
	6	22	31	90	82	0	0
	Average	**61**	**55**	**94**	**65**	**0**	**0**

Note: - means botanical composition was not determined because crops were observed to be monocultures of at least 85% sown species.

Appendix 5 Herbage utilisation (% of DM at final harvest removed by stock) for chicory, lucerne and red clover crops established in November 1996 and grown under dryland and (Dry) and irrigated (Irr) conditions until 24 June 2002 at Lincoln University, Canterbury New Zealand.

Season	Regrowth	Chicory		Lucerne		Red clover	
		Dry	Irr	Dry	Irr	Dry	Irr
	1	-	-	-	-	-	-
	2	67	62	73	69	86	87
	3	59	60	81	68	98	91
1997/98	4	32	52	71	72	100	95
	5	95	100	94	91	100	100
	6	100	100	100	100	100	100
	Average	**71**	**75**	**84**	**80**	**97**	**95**
	1	72	79	85	88	61	70
	2	48	90	51	54	82	75
	3	68	64	87	90	90	83
1998/99	4	70	69	78	75	100	100
	5	41	68	80	87	100	100
	6	82	94	85	92	93	100
	7	100	100	100	100	100	100
	Average	**69**	**81**	**81**	**84**	**89**	**90**
	1	-	-	-	-	-	-
	2	81	71	61	61	77	66
	3	-	-	-	-	-	-
1999/00	4	69	54	88	83	87	85
	5	82	84	84	88	100	100
	6	-	-	-	-	-	-
	Average	**77**	**70**	**78**	**77**	**88**	**84**
	1	62	72	77	76	77	80
	2	-	-	-	-	-	-
	3	71	77	63	73	73	75
2000/01	4	65	67	76	73	74	66
	5	37	55	44	71	26	57
	6	-	-	-	-	-	-
	7	-	-	-	-	-	-
	Average	**59**	**68**	**65**	**73**	**62**	**70**
	1	80	73	75	69	50	62
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
2001/02	4	-	-	-	-	-	-
	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	Average	**80**	**73**	**75**	**69**	**50**	**62**

Appendix 6 Crude protein (% DM) of leaf, stem, weed and post grazing residual fractions from chicory, lucerne and red clover under dryland (Dry) and irrigated (Irr) conditions at Lincoln University, Canterbury, New Zealand.

Season	Regrowth	Fraction	Chicory		Lucerne		Red clover	
			Dry	Irr	Dry	Irr	Dry	Irr
1997/98	4	Leaf	17.1	18.3	29.1	31.4	24.5	28.5
		Stem	4.0	-	10.5	12.8	-	-
	5	Leaf	17.2	18.0	29.7	31.1	24.4	28.7
		Stem	-	-	10.7	12.5	-	-
1998/99	2	Leaf	12.1	11.0	33.1	34.6	24.5	23.0
		Stem	-	-	18.9	14.3	-	-
		Residual	12.7	13.9	19.4	15.8	20.1	22.1
	5	Leaf	12.8	14.5	21.9	26.8	20.9	25.3
		Stem	-	-	7.9	7.9	-	-
		Residual	6.5	6.1	7.9	7.9	-	-
	6	Leaf	13.4	15.6	28.2	27.8	23.2	22.8
		Stem	-	-	12.7	11.1	-	-
		Residual	8.8	11.7	10.3	10.7	18.8	20.5
2000/01	1	Leaf	25.5	24.9	30.7	28.5	-	-
		Stem	-	-	16.9	13.0	-	-
		Weed	26.1	24.9	-	-	-	-
		Residual	13.9	12.7	15.0	16.4	-	-
	2	Leaf	17.7	15.2	29.5	27.5	-	-
		Stem	8.9	7.8	13.9	12.7	-	-
		Weed	26.1	24.9	-	-	-	-
	3	Leaf	16.9	21.4	29.8	28.7	-	-
		Stem	7.4	9.3	10.3	10.6	-	-
		Weed	25.3	26.9	-	-	-	-
		Residual	7.6	7.9	12.5	11.2	-	-
	4	Leaf	16.9	19.0	29.3	28.1	-	-
		Stem	-	-	9.7	10.2	-	-
		Weed	22.3	27.2	-	-	-	-
		Residual	7.1	10.0	9.4	10.1	-	-
	5	Leaf	13.7	18.1	25.3	26.2	-	-
		Stem	3.4	4.2	8.2	8.8	-	-
		Weed	17.3	27.5	-	-	-	-
		Residual	11.8	11.4	10.1	11.8	-	-
	6	Leaf	18.0	21.2	28.1	29.9	-	-
		Stem	-	-	11.3	10.8	-	-
		Weed	-	23.4	-	-	-	-
	7	Leaf	20.8	20.0	31.7	32.5	-	-
		Weed	-	23.7	-	-	-	-
Average		Leaf	16.8	18.1	28.9	29.4	23.5	25.6
		Stem	5.9	7.1	11.9	11.3	-	-
		Weed	9.8	14.9	-	-	-	-
		Residual	9.8	10.5	12.1	12.0	19.5	21.3

Appendix 7 Energy concentration (MJME/kg DM) of leaf, stem, weed and post grazing residual fractions from chicory, lucerne and red clover crops under dryland and (Dry) and irrigated (Irr) conditions at Lincoln University, Canterbury, New Zealand.

Season	Regrowth	Fraction	Chicory		Lucerne		Red clover	
			Dry	Irr	Dry	Irr	Dry	Irr
1997/98	4	Leaf	10.2	10.3	11.4	11.3	10.8	10.4
		Stem	6.2	7.1	6.1	6.7	-	-
	5	Leaf	10.6	10.4	12.1	11.6	11.5	11.2
		Stem	-	-	8.0	7.5	-	-
1998/99	2	Leaf	11.2	11.8	11.6	11.7	11.0	10.9
		Stem	-	-	8.6	7.5	-	-
		Residual	11.3	11.2	9.4	8.1	9.9	9.9
	5	Leaf	10.2	11.0	10.5	10.7	10.3	11.0
		Stem	-	-	4.4	4.7	-	-
		Residual	7.2	7.0	4.4	4.7	-	-
	6	Leaf	11.5	11.0	11.2	11.9	10.6	11.5
		Stem	-	-	8.1	7.7	-	-
		Residual	9.1	10.4	6.3	6.1	10.2	10.0
2000/01	1	Leaf	11.3	11.4	11.6	11.8	-	-
		Stem	-	-	9.9	9.5	-	-
		Weed	11.8	12.5	-	-	-	-
		Residual	9.1	9.1	8.1	8.5	-	-
	2	Leaf	12.7	12.6	11.5	12.3	-	-
		Stem	12.9	12.1	8.3	8.7	-	-
		Weed	11.8	12.5	-	-	-	-
	3	Leaf	11.4	11.8	11.6	11.6	-	-
		Stem	10.6	11.8	8.1	8.4	-	-
		Weed	11.5	11.6	-	-	-	-
		Residual	7.0	6.4	6.9	6.5	-	-
	4	Leaf	10.8	11.4	11.7	11.8	-	-
		Stem	-	-	7.3	7.3	-	-
		Weed	10.5	10.9	-	-	-	-
		Residual	6.2	7.5	5.9	5.9	-	-
	5	Leaf	12.1	11.9	11.5	11.1	-	-
		Stem	7.2	6.4	8.0	8.4	-	-
		Weed	11.9	11.6	-	-	-	-
		Residual	9.5	9.7	7.4	8.0	-	-
	6	Leaf	11.9	11.7	11.4	12.1	-	-
		Stem	-	-	9.4	9.1	-	-
		Weed	-	10.7	-	-	-	-
	7	Leaf	11.4	11.6	12.2	11.7	-	-
		Weed	-	9.8	-	-	-	-
Average		Leaf	11.3	11.4	11.5	11.6	10.8	11.0
		Stem	9.2	9.4	7.8	7.8	-	-
		Weed	11.5	11.4	-	-	-	-
		Residual	8.5	8.8	6.9	6.8	10.1	10.0

Appendix 8 Total dry matter (t DM/ha) yield of chicory, lucerne and red clover crops (established in November 1996) under dryland and (Dry) and irrigated (Irr) conditions over six growing seasons at Lincoln University, Canterbury, New Zealand.

Season	Regrowth	Chicory		Lucerne		Red clover	
		Dry	Irr	Dry	Irr	Dry	Irr
	1	2.13	2.13	2.70	2.70	3.80	3.69
1996/97	2	4.30	4.00	3.63	3.63	4.80	4.93
	Total	**6.43**	**6.13**	**6.34**	**6.34**	**8.60**	**8.62**
	1	2.51	2.47	5.50	6.06	4.81	5.15
	2	5.88	4.69	5.58	6.26	5.28	4.30
	3	2.55	3.43	3.40	4.46	3.36	4.11
1997/98	4	2.55	4.91	3.65	5.64	2.44	4.62
	5	1.02	1.68	1.64	3.98	0.48	1.20
	6	1.16	1.55	1.57	1.92	0.50	1.58
	Total	**15.7**	**18.7**	**21.3**	**28.3**	**16.9**	**21.0**
	1	1.97	2.20	5.37	5.35	2.22	2.73
	2	3.52	3.84	4.32	3.60	3.13	3.90
	3	2.08	2.09	2.76	2.39	2.77	2.69
1998/99	4	1.89	2.90	2.31	2.55	1.95	2.06
	5	1.16	1.67	2.46	3.09	1.65	1.21
	6	1.92	2.72	2.54	3.35	2.13	1.83
	7	0.81	1.02	1.54	1.51	1.21	1.00
	Total	**13.4**	**16.4**	**21.3**	**21.8**	**15.1**	**15.4**
	1	3.11	2.25	4.09	3.46	1.11	0.60
	2	3.80	3.45	3.50	2.79	3.07	2.56
	3	2.75	1.92	3.43	2.97	3.28	2.79
1999/00	4	2.12	2.31	3.03	3.14	1.48	1.76
	5	2.99	3.93	4.45	4.23	1.82	2.32
	6	1.61	1.87	1.86	1.58	0.93	1.33
	Total	**16.4**	**15.7**	**20.3**	**18.2**	**11.7**	**11.4**
	1	2.47	2.19	3.35	2.69	1.93	3.39
	2	3.78	2.81	3.23	3.28	3.72	3.63
	3	2.85	2.88	4.32	3.67	3.14	3.04
2000/01	4	1.85	2.33	3.67	3.40	1.82	2.64
	5	1.18	2.33	2.91	3.62	0.37	1.90
	6	0.50	1.67	1.20	2.83	0.00	0.00
	7	0.20	0.44	0.59	0.70	0.00	0.00
	Total	**12.8**	**14.6**	**19.3**	**20.2**	**11.0**	**14.6**
	1	2.53	2.41	4.38	3.27	2.29	2.46
	2	3.06	4.49	4.07	3.58	3.86	3.68
	3	1.83	2.52	2.88	2.65	1.88	2.22
2001/02	4	1.83	2.52	2.88	2.65	1.88	2.22
	5	0.82	1.07	1.90	2.73	0.70	0.74
	6	0.80	0.45	1.43	1.27	0.90	1.02
	Total	**10.9**	**13.4**	**17.5**	**16.2**	**11.5**	**12.3**

Appendix 9 Dry matter yield (t DM/ha) of sown species for chicory, lucerne and red clover crops (established in November 1996) under dryland and (Dry) and irrigated (Irr) conditions over six growing seasons at Lincoln University, Canterbury, New Zealand.

Season	Rotation	Chicory Dry	Chicory Irr	Lucerne Dry	Lucerne Irr	Red clover Dry	Red clover Irr	Probability Irr	Probability Spe	Probability Int
	1	4.27	5.41	7.59	4.27	5.41	7.37	na	***	na
1996/97	2	4.30	3.63	4.80	4.00	3.63	4.93	na	***	na
	Total	**8.57**	**9.04**	**12.39**	**8.27**	**9.04**	**12.30**			
	1	2.51	5.50	4.81	2.47	6.06	5.15		***	
	2	5.88	5.58	5.28	4.69	6.26	4.30		*	
	3	2.55	3.40	3.36	3.43	4.46	4.11	***		
1997/98	4	2.55	3.65	2.44	4.91	5.64	4.62	**		
	5	1.02	1.64	0.48	1.68	3.98	1.20	***	***	*
	6	1.16	1.57	0.50	1.55	1.92	1.58	**	**	
	Total	**15.66**	**21.33**	**16.87**	**18.73**	**28.31**	**20.96**			
	1	1.97	5.37	2.22	2.20	5.35	2.73		***	
	2	3.52	4.32	3.13	3.84	3.60	3.90			
	3	2.08	2.76	2.77	2.09	2.39	2.69			
1998/99	4	1.89	2.31	1.95	2.90	2.55	2.06	*		
	5	1.16	2.46	1.65	1.67	3.09	1.21		***	**
	6	1.92	2.54	2.13	2.72	3.35	1.83	**	***	**
	7	0.81	1.54	1.21	1.02	1.51	1.00		**	
	Total	**13.36**	**21.30**	**15.06**	**16.43**	**21.84**	**15.42**			
	1	2.55	3.96	0.60	2.03	3.22	0.15	*	***	
	2	3.07	3.46	1.70	3.12	2.57	0.66	*	***	
	3	2.45	3.40	2.64	1.58	2.72	0.93	**	*	
1999/2000	4	1.97	2.98	0.99	2.07	2.58	0.79	*	***	
	5	2.70	4.45	0.63	3.02	4.23	0.50		***	
	6	1.48	1.86	0.31	1.43	1.58	0.11		**	
	Total	**14.21**	**20.11**	**6.87**	**13.25**	**16.89**	**3.14**			
	1	1.81	3.25	0.21	1.69	2.28	0.00	*	***	
	2	3.47	3.14	0.89	2.28	2.80	0.12	*	***	
	3	1.95	4.19	0.45	1.67	3.13	0.03	*	***	
	4	1.34	3.56	0.41	1.35	2.90	0.10	*	***	
2000/01	5	0.79	2.82	0.16	1.90	3.09	0.25		***	
	6	0.50	1.17	0.00	1.49	2.41	0.00	***	***	***
	7	0.20	0.58	0.00	0.32	0.60	0.00		***	
	Total	**10.06**	**18.70**	**2.12**	**10.69**	**17.21**	**0.49**			
	1	1.80	4.33	0.01	1.41	2.56	0.01	*	**	*
	2	2.11	4.00	0.00	2.25	1.83	0.00	**	***	**
	3	1.11	2.60	0.00	1.54	1.41	0.01		***	*
2001/02	4	1.11	2.60	0.00	1.54	1.41	0.01		***	*
	5	0.66	1.85	0.00	0.77	2.02	0.01		**	
	6	0.13	1.30	0.00	0.14	1.06	0.00		***	
	Total	**6.91**	**16.68**	**0.01**	**7.65**	**10.29**	**0.05**			

Note: * = P<0.05, ** = P<0.01, *** = P<0.001, na = not applicable, ns = not significant.

Appendix 10 Linear growth rates of chicory, lucerne and red clover crops grown under dryland and (Dry) and irrigated (Irr) conditions over six growing seasons at Lincoln University, Canterbury, New Zealand.

Season	Regrowth	Chicory Dry		Irr		Lucerne Dry		Irr		Red clover Dry		Irr	
1996/97	1	38	*	38	*	48	*	48	*	68	*	66	*
	2	45	*	42	*	38	*	38	*	51	*	52	*
	Mean	**42**		**40**		**43**		**43**		**59**		**59**	
1997/98	1	21	*	21	*	47	*	51	*	41	*	44	*
	2	116		82		120		137		102		78	
	3	73		94		99		138		88		102	
	4	55		116		84		145		60		114	
	5	25		60		39		132		16		44	
	6	9		19		16		21		4		14	
	Mean	**50**		**65**		**67**		**104**		**52**		**66**	
1998/99	1	12		14		32		32		5		10	
	2	69		77		95		83		60		83	
	3	38		38		63		48		49		47	
	4	94	*	145	*	116	*	128	*	97	*	103	*
	5	7		3		36		52		31		18	
	6	35		52		33		57		40		35	
	7	7		11		14		16		9		4	
	Mean	**37**		**49**		**56**		**59**		**42**		**43**	
1999/00	1	29		20		33		29		9		4	
	2	57		54		56		48		44		39	
	3	67		40		89		73		72		62	
	4	45		53		84		80		38		39	
	5	23		36		44		32		14		8	
	6	18	*	19	*	29	*	23	*	0	*	0	*
	Mean	**40**		**37**		**56**		**48**		**30**		**25**	
2000/01	1	17		15		14		12		10		23	
	2	45		44		68		68		52		51	
	3	72		72		113		98		37		41	
	4	45		55		92		97		39		37	
	5	29	*	58	*	73	*	91	*	9	*	47	*
	6	11	*	36	*	26	*	61	*	0	*	0	*
	7	4	*	9	*	12	*	14	*	0	*	0	*
	Mean	**32**		**41**		**57**		**63**		**21**		**29**	
2001/02	1	24		22		37		29		21		21	
	2	33		64		47		44		38		51	
	3	71	*	97	*	111	*	102	*	72	*	85	*
	4	48	*	66	*	76	*	70	*	50	*	58	*
	5	17	*	23	*	40	*	58	*	15	*	16	*
	6	12	*	7	*	21	*	19	*	13	*	15	*
	Mean	**34**		**46**		**55**		**54**		**35**		**41**	
Mean		39		47		57		64		37		42	

Note: * LGR was calculated over the entire regrowth rather that linear growth phase.

Appendix 11 Stem percentage (% of sown species DM yield) of chicory and lucerne crops, established in November, 1996 under dryland and (Dry) and irrigated (Irr) conditions at Lincoln University, Canterbury, New Zealand.

Season	Regrowth	Date	Chicory		Lucerne	
			Dry	Irr	dry	Irr
1998/99	2	30-Oct-98	-	-	18	17
		03-Nov-98	-	-	26	25
		11-Nov-98	-	-	32	32
	3	04-Dec-98			43	44
	4	15-Dec-98	-	-	44	47
		02-Jan-99	-	-	45	42
1999/00	2	09-Nov-99	14	7	-	-
	3	20-Dec-99	13	11	-	-
	4	21-Jan-00	8	12	-	-
	5	13-Mar-00	23	18	-	-
2000/01	1	22-Sep-00	-	-	27	29
		01-Oct-00	-	-	24	28
	2	28-Oct-00	-	-	7	5
		10-Nov-00	13	13	23	25
	3	08-Dec-00	-	-	8	10
		13-Dec-00	-	-	19	15
		19-Dec-00	16	18	34	30
	4	13-Jan-01	-	-	19	17
		18-Jan-01	-	-	23	29
		24-Jan-01	14	9	36	33
	5	23-Feb-01	14	3	23	28
		01-Mar-01	-	-	28	27
		07-Mar-01	-	-	28	32
		11-Mar-01	9	11	30	30
	6	12-Apr-01	-	-	6	7
		23-Apr-01	8	-	15	14
		02-May-01	-	-	21	29
	7	24-Jun-01	0	0	0	0
Means	1		0	1	27	29
	2		14	10	27	29
	3		15	14	38	37
	4		11	10	41	37
	5		16	15	30	30
	6		8	0	21	29
	7		0	0	0	0
Mean			9	7	26	27

Note: - = measurements were not taken
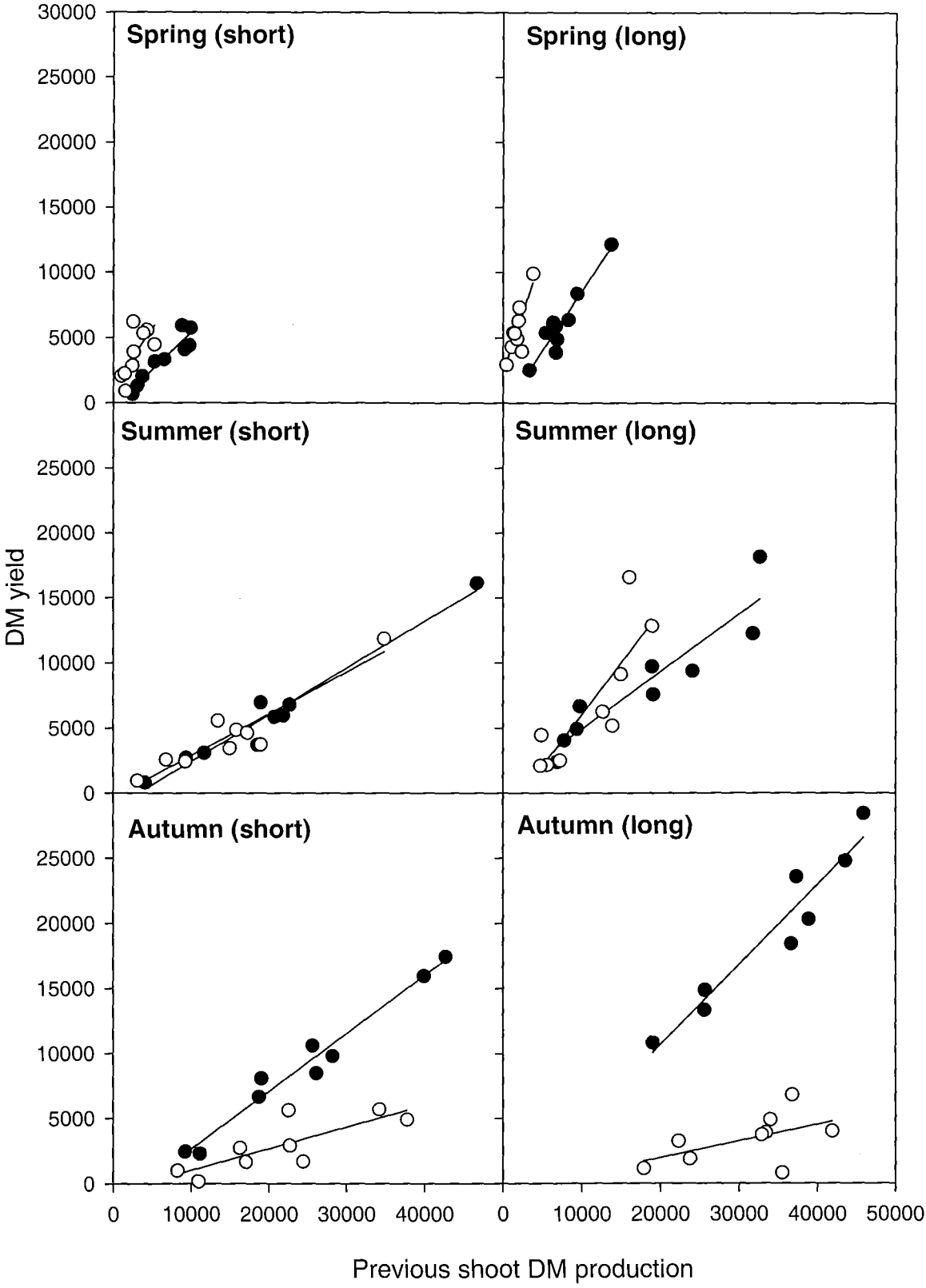
Appendix 12 Shoot (O) and perennial (●) DM yields relation to accumulated previous shoot production for lucerne grown in columns at Lincoln University, Canterbury, New Zealand.
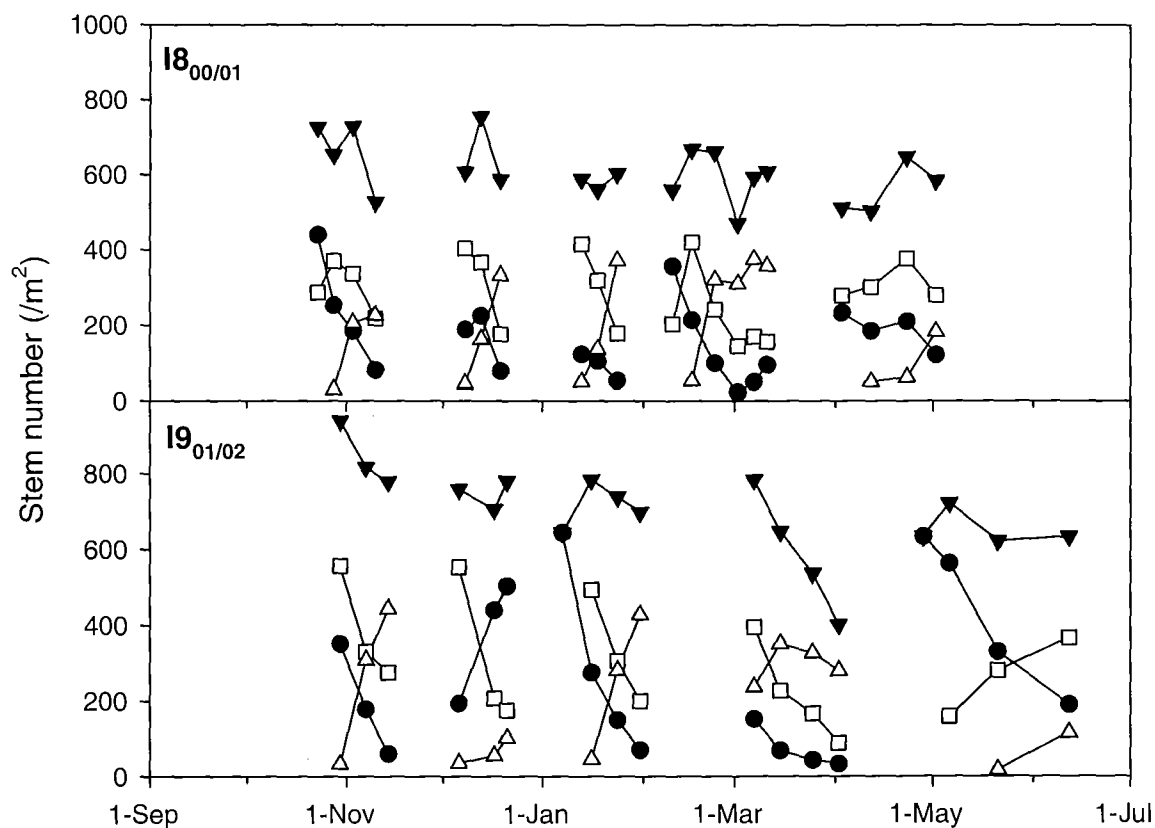
Appendix 13 Stem population of irrigated lucerne I8$_{00/01}$ and I9$_{01/02}$ at Lincoln University, Canterbury, New Zealand. ● = short (<0.1 m), □ = medium (0.1><0.3 m), = long (> 0.3 m), and ▼ = total stem number.
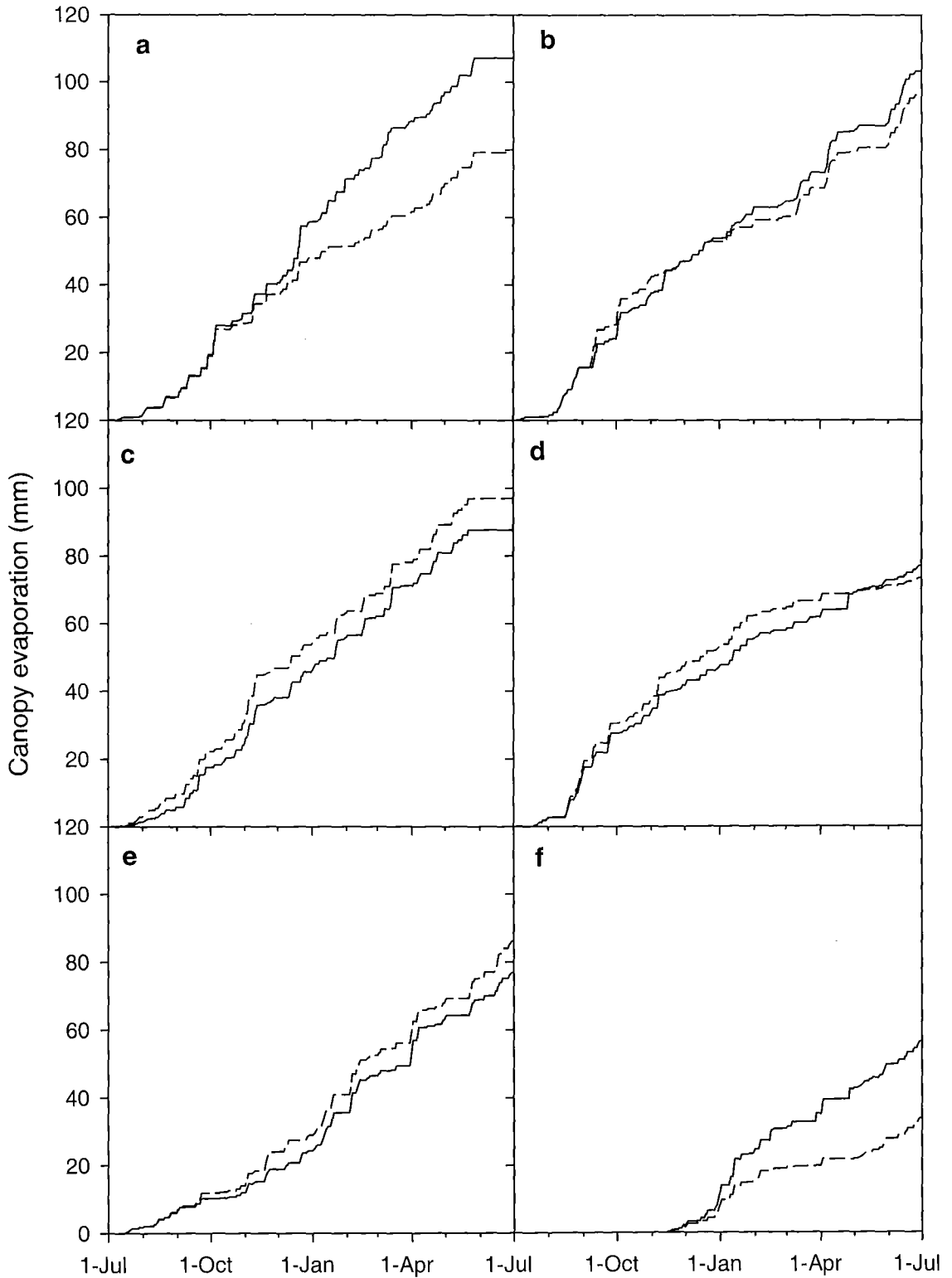
Appendix 14 Evaporation of canopy intercepted rainfall (E_C) from dryland (– –) and irrigated (——) lucerne grown in $I8_{97/98}$ – $I8_{01/02}$ (a–e respectively) and $I9_{00/01}$ (f) at Lincoln University, Canterbury, New Zealand.
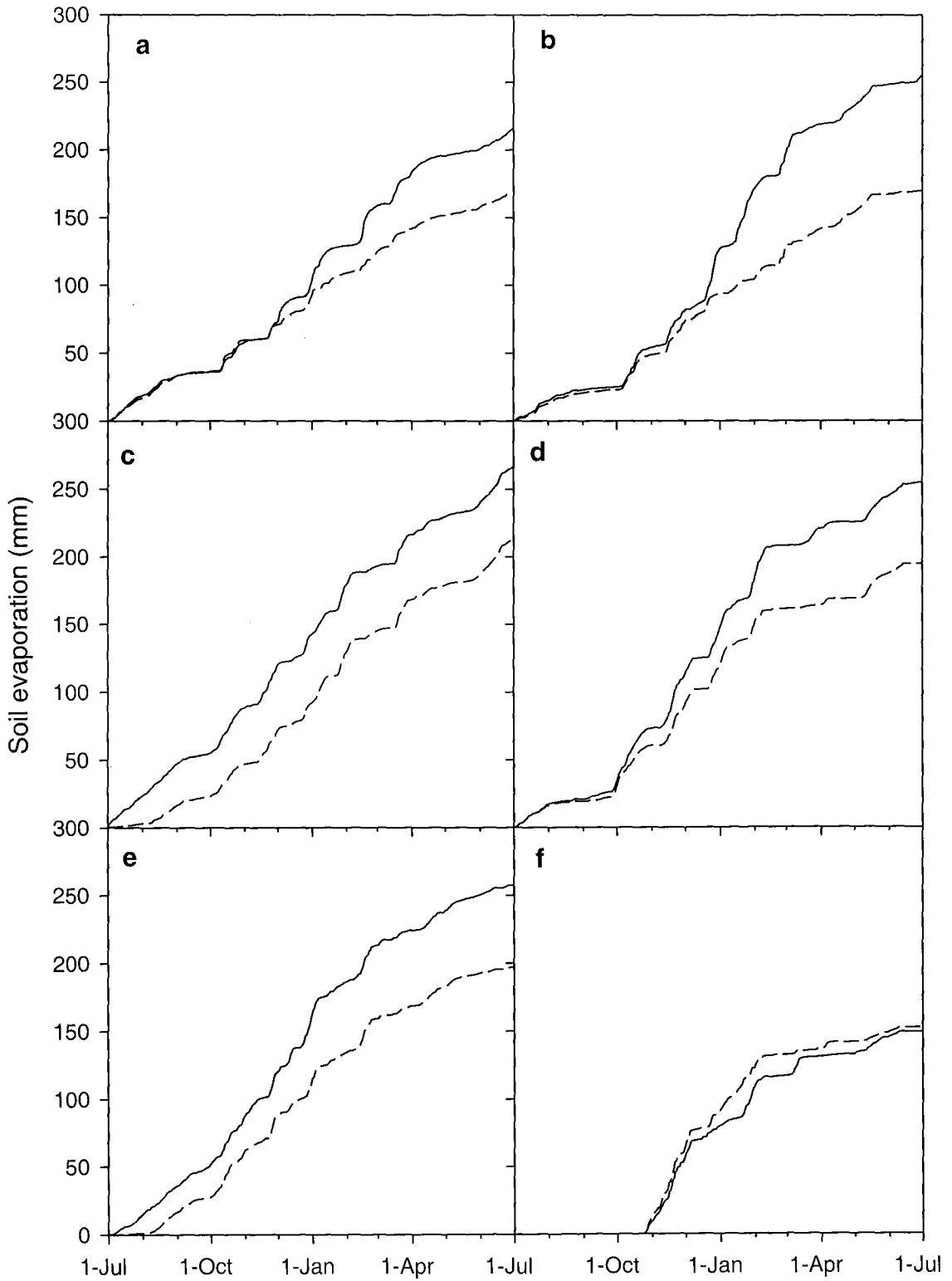
Appendix 15 Evaporation from the soil (E_S) of dryland (− −) and irrigated (——) lucerne grown in $18_{97/98}$ − $18_{01/02}$ (a–e respectively) and $19_{00/01}$ (f) at Lincoln University, Canterbury, New Zealand.
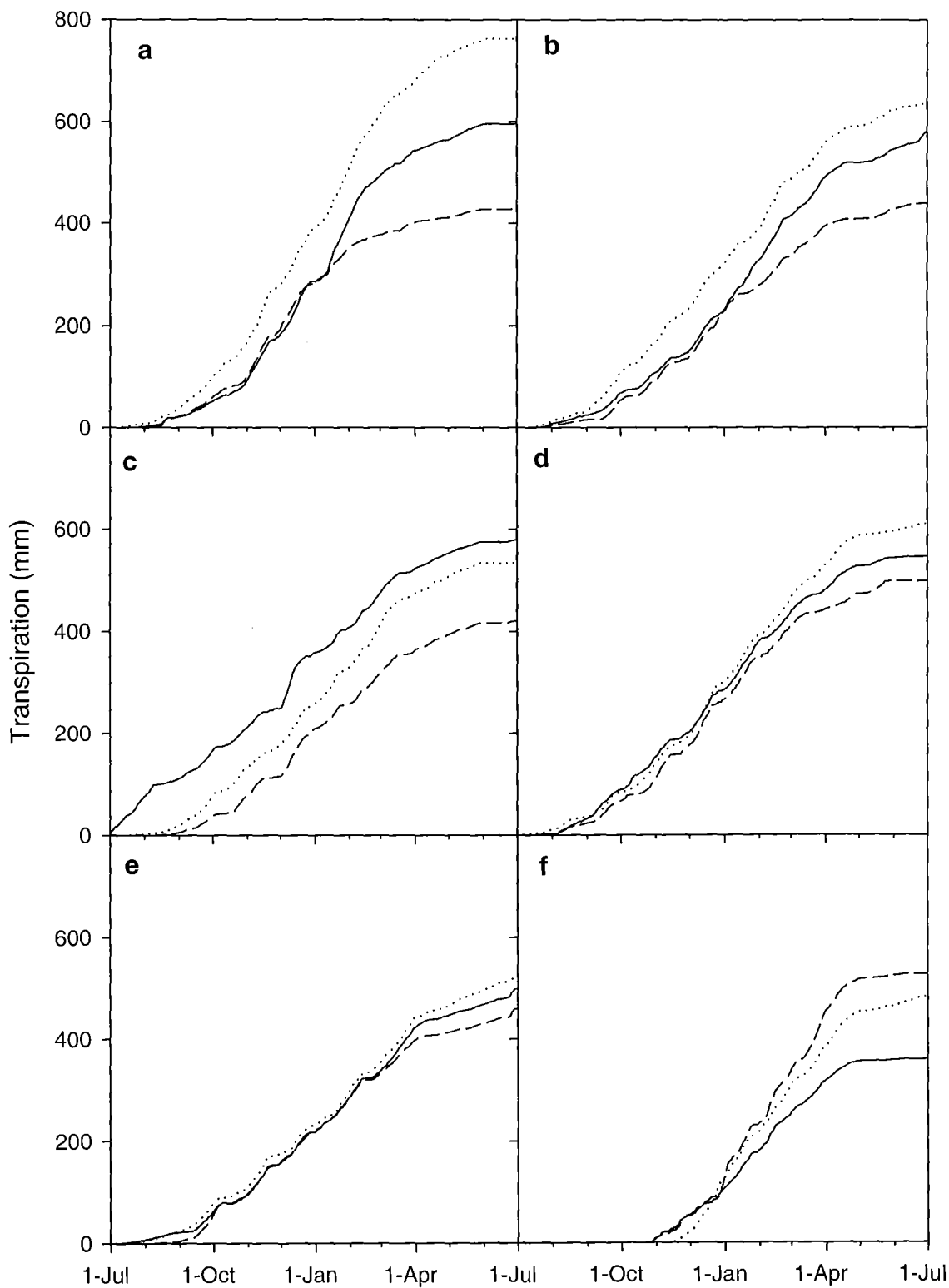
Appendix 16 Transpiration (E_T) of dryland (— —) and irrigated (——) lucerne and transpiration potential (······) for irrigated lucerne grown in $I8_{97/98}$ – $I8_{01/02}$ (a–e respectively) and $I9_{00/01}$ (f) at Lincoln University, Canterbury, New Zealand.

List of publications

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 New Zealand Agronomy Society, 30*, 129-137.

Brown, H.E., and Moot, D.J. (2002). Leaf appearance in seedling lucerne crops. *Proceedings of the 11th Australian Agronomy Conference*, Geelong, Victoria. www.regional.org.au/au/asa/2003/p/8/brown.htm

Brown, H.E., Moot, D.J., and Pollock, K.M. (2003). Long term growth rates and water extraction patterns of dryland lucerne, chicory and red clover. In D.J. Moot (Ed.), *Legumes for dryland pastures* (pp. 201-208). New Zealand Grasslands Association, Research and Practice series No. 11: Palmerston North, New Zealand.

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* (pp. 201-208). New Zealand Grasslands Association, Research and Practice series No. 11: Palmerston North, New Zealand.

Acknowledgments

This thesis only has one name on the front but was the result of many peoples contributions. The final pages are reserved for you and I hope this is due thanks.

To my family; Mum and Dad, Doug and Allannah. Without your love, nurturing and support I would never have made it to this point. Although I have been away from home during the course of my Ph.D studies it was always comforting to know you were there for me and happy to see me when ever I arrived home. Now I will go off into the world but my soul will always remain at Locharburn.

To my beloved Mika. The crossing of our paths was an unanticipated outcome of my time at Lincoln, but is the outcome I am most grateful for. Coming home to your love each night has made the most difficult times of completing my Ph.D possible and I look forward to the rest of our lives together.

To my dear friends. I won't list you because the list is large and you are all more important than any order may imply. I am sure you all know who you are and I am grateful for our friendship until now. I know this friendship will remain strong through whatever lies ahead.

To my Ph.D. colleagues who I was lucky enough to study with at the Field Service Centre. Pablo and Alex, who I was also lived with for some time, Al Black, Edmar, Ayaz, Fletch, Anwar, Anna and Anthony. I will always cherish the social and academic experiences we shared and know they have left a lasting impression on the person I have become. I eagerly await our future reunions as colleagues and friends.

To the technical team at the Field Service Centre, Don, Dave, Christina, Peter, Bruce and Murve. None of my research would have been possible without your assistance. I am forever grateful for the help you have provided and the interactions we had. I hope the students that follow after me are as ably assisted as I was, and as appreciative as I always shall be.