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

A thesis submitted

by

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Abstract

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

Soil water dynamics under both rainfed and surface irrigated treatments were adequately simulated by the Agricultural Production System Simulator (APSIM) with RMSD < 10% of the observed means and $R^2 > 0.80$ for the total soil profile (0-2000 mm). Simulation of growth and development was less satisfactory. For example, the RMSD was ~50% of observed mean for shoot biomass ($R^2 = 0.68$) in the rainfed treatment, and 36% ($R^2 = 0.77$) in the irrigated treatment. Overall, simulation of shoot DM production was close to observed values during the growing season (Apr-Nov), however the model was unable to capture the observed shoot yield in response to summer irrigation, with simulated shoot DM 40% less than the observed value in 2000 and 35% less in 2001. N dynamics were poorly simulated under these soil and climate conditions. Amounts of soil mineral nitrogen (kg NO^{-}_{3} -N ha^{-1}) were adequately simulated in rainfed conditions but consistently over-predicted under irrigated conditions. This evaluation of APSIM highlights both good and poor model performance and the analysis indicates the need for caution when applying the model in situations where observed data is scarce. Areas requiring improvements to the model are identified.

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

Declaration

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

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

Muhammad Shafiq Zahid

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List of Abbreviations

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

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Chapter 1

1 General introduction

Traditional euro-centric farming practices involving replacement of perennial native vegetation by shallow-rooted annuals have led to inefficient use of incident rainfall in many agro-ecological zones of Australia, resulting in low productivity and land degradation (Bolger and Turner 1999). Dryland salinity, the consequence of clearing of native deep rooted vegetation, trees and bushes since European settlement 200 years ago is now estimated to be costing approximately $A270 million per year in terms of effects on agriculture, infrastructure and the environment (Marten and Metcalf, 1998). When recharge of groundwater systems exceeds discharge through natural conditions (Barnett *et al*. 1996) the resulting rise in water table brings salts stored deep in the soil profile to the surface where they affect the structure of the surface soil and the vegetation growing on the soil (Nulsen 1993, Ridley *et al*. 1997). Since water use of native trees and grasses is significantly greater than that of annual shallow rooted crops and pastures currently in use in agricultural systems (Nott 1992) the risk of deep drainage is much higher, and with associated leaching of nitrate in conjunction with drainage the rate of soil acidification is also increasing (Helyar and Porter 1989). Furthermore, this contamination of groundwater has major environmental and human health implications (Mathers *et al*. 1975, Robbins and Carter 1980).

A major successful strategy suggested to increase water use (or dewater the landscape), recently introduced into farming systems in eastern and southern agricultural regions of Australia, is the use of deep-rooting perennial pasture species such as lucerne (Ridley *et al*. 1997, Lolicato 2000, McCallum *et al*. 2000, Latta *et al*. 2001, Peoples *et al*. 2001). Lucerne (*Medicago sativa* L.) is one of the oldest and most widely cultivated forage crops in the world due to its morphology, physiological traits and cultivar diversity (Grimes *et al*. 1988, Michaud *et al*. 1988). Lucerne's deep rooted nature and high water use potential provide an opportunity for profitable agriculture in association with reduced land degradation due to substantial reductions in recharge (Loane 1993, Crawford and Macfarlane 1995, Campbell *et al*. 1996, Ridley *et al*. 2001, Ward 2006). Lucerne pastures may be considered the key to sustainable cropping systems for many soils because they optimise soil water use, input nitrogen (N) to the soil, minimise disruption to soil aggregates, reduce the risk of rising water tables, salinity and acidity, increase soil organic matter and improve soil structure (Vance *et al.* 1988, Crawford and Macfarlane 1995, Williams 1998). Inclusion of lucerne in ley farming systems can provide a high yield of good quality forage for all types of livestock as well as improving productivity and quality of subsequent wheat (Holford 1980). Indeed, lucerne based pastures have been shown to increase overall farm profitability (Egan *et al.* 1998).

Lucerne, a native of semi-arid environments (Bolton, 1962), has the potential to be grown economically under dryland conditions in many regions of Australia (Stanley and Christinat 1994). Research has shown that the productivity of lucerne pastures can exceed that of annual medic pastures in areas of WA and Victoria with Mediterranean type climate (Lyons 2001, McCallum 2000, Latta *et al.* 2001). There is however relatively little information concerning the performance of lucerne pastures in dryland farming systems of South Australia. The climate of these Mediterranean agro-ecological zones is typified by mild wet winters and hot dry summers with annual rainfall ranging from 300–600 mm (Rovira 1992), and approximately 60-70% of this annual rainfall occurring in the winter months (Cawood and McDonald 1996). Summer rainfall is characteristically low, unpredictable, variable in temporal distribution, and generally less than potential evapotranspiration (Cawood and McDonald 1996, Stolte *et al.* 1997, Ridley *et al.* 1997)

Clearly, under conditions of such low summer rainfall, lucerne growth will be reliant during summer periods upon stored soil moisture. However, a large proportion of the area where lucerne can potentially be grown in southern Australia is known to have duplex (texture contrast) soils with physical or chemical constraints in the sub-soil (Rovira 1992, Coventry 1998, Adcock *et al.* 2007), which are likely to inhibit development of lucerne roots. Therefore, the advantage of lucerne's deep-roots for extraction of stored moisture from deeper in the soil profile over summer may be reduced due to constraints such as boron toxicity, high pH, salinity and sodicity, or high bulk density. It has been recommended that where sub-soil water is not available for optimum production of lucerne throughout the year summer irrigation might be necessary for maintaining forage supply (Snaydon *et al.* 1972, Carter and Sheaffer 1983a). However, irrigation is not an economically viable option for large areas of southern

Australia due to scarcity of water supplies, and an increasing social awareness of adverse environmental impacts. In dryland farming systems in southern Australia the major role of lucerne is perceived as reducing recharge by maximising interception of rainfall. However, there are other agronomic reasons why lucerne is considered an advantage in the systems, including increasing fertility (N) in rotations via di-nitrogen (N_2) fixation (Peoples *et al.* 1998), wider weed management options and maintenance of groundcover to reduce erosion risk. Lucerne is potentially capable of fixing greater amounts of N_2 compared to many other legume species, estimates range from 33-284 kg N_2 ha^{-1} $year^{-1}$ in Australia (Gault *et al.* 1995, Peoples and Baldock 2001). Estimated N inputs, based on aboveground residues, of more than 100 kg N ha^{-1} $year^{-1}$ have been reported under lucerne in these conditions (Holdford 1981, Gault *et al.* 1995). In addition to this, lucerne has also been considered effective for accessing deep leached nitrates (Kelner *et al.* 1997, Peoples *et al.* 1998, Dear *et al.* 2001), and is extremely suited to effective management of N, particularly where N accumulation under annual pasture has had a deleterious impact on sustainability of the system (Peoples and Baldock 2001, Blumenthal and Russelle 1996). Often, the drought resistant character of lucerne will be relied upon to enable it to survive over summer in situations with Mediterranean type climate. Productivity in response to rainfall during summer, which can provide useful forage, may be an additional benefit of having lucerne in the system. The adoption of lucerne by farmers in dryland areas of southern Australia will be largely driven by the productivity and profitability of lucerne enterprises. Information that enables a comparison of the productivity of lucerne with annual medic-based pastures including data concerning potential forage production in response to summer rainfall is needed to give farmers confidence in switching from annual to perennial pastures.

Constraints imposed by the short-term nature of research studies limit the amount of data that can be collected and furthermore, data will generally be site specific and representative of a selective number of climate years. Simulation modelling can assist in understanding relationships between climatic and edaphic variables and in explaining specific experimental results. Simulation can also facilitate the testing of experimental results over a longer period of time and the effects of seasonal variation, other soil types and management. The simulation model APSIM-Legume has wide scope and is suited to simulate lucerne for a range of agro-environments (Probert *et al.* 1998), although it has not been widely applied for dryland regions of South Australia and requires further validation in this respect.

The primary aim of the research reported by this thesis (Figure 1.1) was to quantify the agronomic performance (productivity) of lucerne in the Mediterranean climatic region of South Australia (Chapter 3), and to describe associated plant-soil processes (with respect to water and nitrogen) for the duplex soil that is characteristic of much of the region (Chapters 4 & 5). The response of lucerne to summer rainfall events (supplied by irrigation) was assessed in order to determine the importance of the variability in such events to lucerne productivity (Chapter 3). A secondary aim, given the highly variable distribution of summer rainfall in southern Australia, was to complement the experimental approach with simulation modelling (Probert *et al*. 1998) to better understand the potential production of lucerne in this environment (Chapter 6). A subsidiary aim of the work (Figure 1.1) was to compare the efficiency with which lucerne utilises water supplied at the surface of the soil or deeper in the soil profile using sub-surface dripper irrigation equipment (Chapter 4).

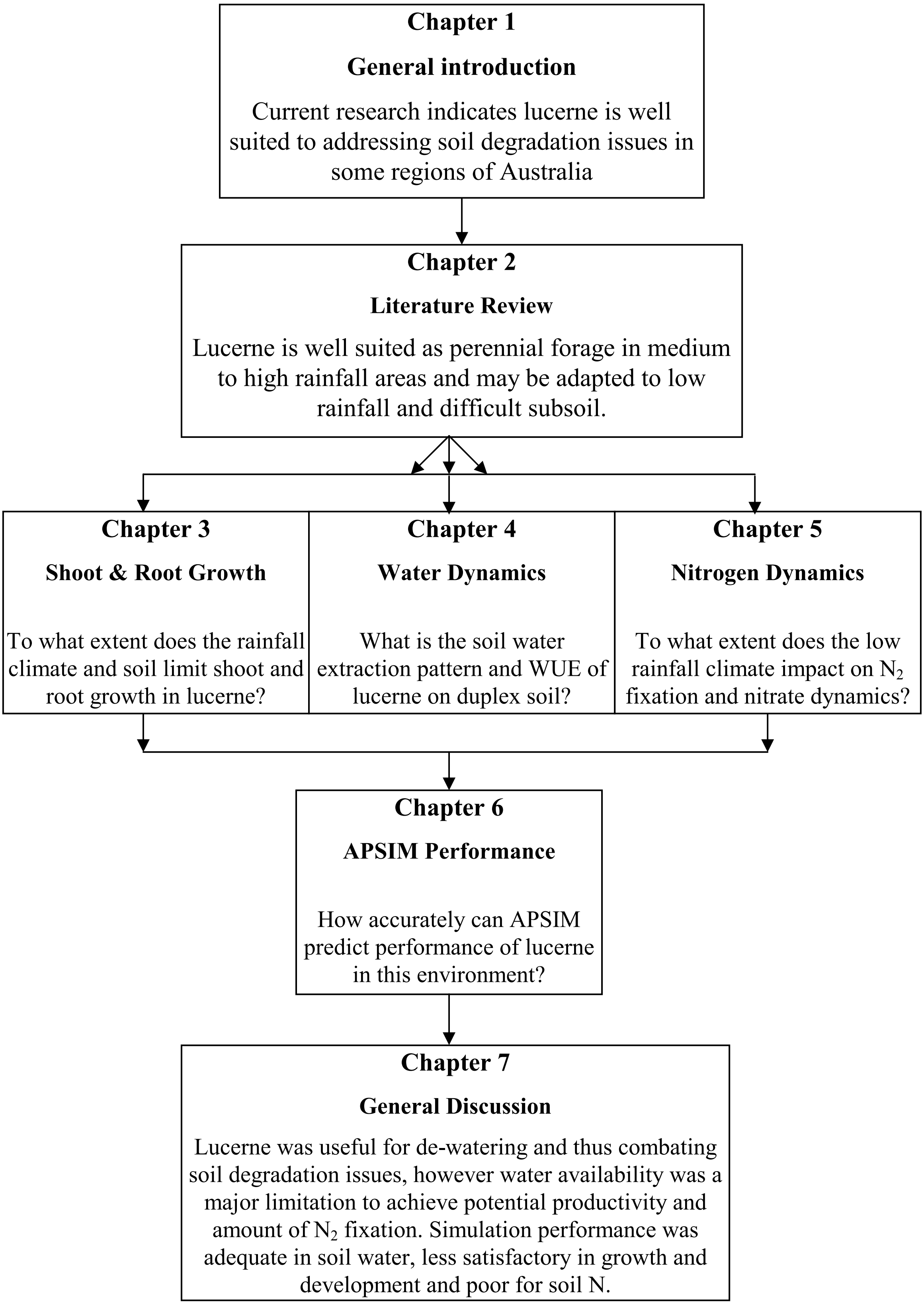

Figure 1.1 Illustration of the structure of this thesis.

Chapter 2

2 Literature review

2.1 Introduction

This review sets the scene for the agronomic studies undertaken in this thesis. It discusses growth and development of lucerne in conjunction with climatic and edaphic influences and the dynamics of water and N in lucerne-soil systems, the influence that management has on these processes, and the use of simulation modelling to predict long-term impacts of perennial legumes in farming systems. The first three sections describe major morphological, physiological, and agronomic characteristics of lucerne that regulate productivity (yield), including dry matter accumulation, leaf area index, stem and node numbers, radiation use efficiency (RUE), root growth, carbohydrate storage in taproots, water balance under lucerne and symbiotic N_2 fixation. The responses of these parameters to inter- and intra-seasonal variations in temperature and water supply are explored. The paucity of data concerning morphological and physiological response of lucerne to the diverse range of conditions encountered during an annual cycle under Mediterrranean-type climate, particularly in southern Australia, is highlighted. The fourth section details the effects of management practices, particularly defoliation and irrigation, on lucerne productivity, stand density and persistence. The fifth section overviews the application of the APSIM model to predict performance of lucerne under dryland conditions. A requirement for further testing of the model, using data obtained for lucerne grown under Mediterranean climatic conditions, is demonstrated to enable improved confidence in model predictions.

2.2 Growth, development and water use of lucerne

Water, one of the world's most valuable natural resources, is a highly important factor controlling plant growth and is therefore critical for crop production. Water is indispensable for various plants functions (Gardner *et al.*1990). Water is also a medium that gives turgor to plant cells. Turgor promotes cell enlargement, plant structure and foliar display and hence makes growth possible. Water provides raw material for photosynthesis and is used in forming reductants for driving biochemical processes.

Water transpiration also provides cooling to plant surfaces (Gardner *et al.*1990). Therefore, water deficit can affect every aspect of plant growth including above ground shoot and below ground root size and distribution. Lucerne is both morphologically and physiologically adapted to a wide range of soil moisture conditions and can persist under limited water supply by extracting water from deep in the soil profile using a taproot, and by becoming semi-dormant under stressed conditions (Sheaffer *et al.* 1988).

2.2.1 Growth

The growth of a crop is defined as the accumulation of dry matter as a result of light interception and partitioning of the products of photosynthesis (Moot *et al.* 2003). It is the end result of resource capture (radiation and water) that fuels cell division and associated physiological processes that lead to achievement of dry matter and yield. Dry matter is a function of the total light energy intercepted (Monteith, 1977) which drives photosynthesis, and of total amount of CO_2 assimilated minus losses via respiration (Souki *et al.* 1998). Yields may be defined as the accumulation of dry matter over time (Gardner *et al.* 1990).

2.2.1.1 Photosynthesis and respiration

Photosynthesis is the cornerstone of crop production and it occurs at chloroplasts in the leaves of a plant in the presence of photosynthetically active radiation (PAR) i.e. 400-700 nm, water and CO_2 (Gardner *et al.* 1990). In this process radiation energy splits the water molecule and the proton and electron produced as a result of this reaction aids phosphorylation (conversion of ADP to ATP) and reduction of NADP to $NADPH^+$, which is usually called the light reaction. Both NADPH and ATP are required to reduce CO_2 to form a stable organic molecule in the Calvin cycle, from which dry weight results (Gardner *et al.* 1990). The organic molecules formed in this reaction can be in simple hexose form and stored or transported to active growth areas (meristem) for conversion to a variety of structural or storage compounds (Gardner *et al.* 1990). Most (99%) of the water used by plants is transpired and only approximately 1% of plant water use is for photosynthesis, and consequent growth (Gardner *et al.* 1990).

Respiration is the reaction where hexose forms of organic compounds are broken down to release energy or are converted to complex organic compounds used in important structural, metabolic and storage compounds (Gardner *et al.* 1990). Although it can result in plant weight loss, respiration is an essential component of growth, like photosynthesis, and in general represents 25-30% of total photosynthesis in most crop species (Gardner *et al.*1990). The balance between photosynthesis and respiration, which controls the rate of dry matter increase in all plants (Fick *et al.*1988), is also controlled by a complex of environmental factors such as light, CO_2 and temperature (Gardner *et al.* 1990).

2.2.2 Development

Development is represented by the progress of growth stages such as juvenile, reproductive, maturity and senescence within a cycle (Christian 1977, Kalu and Fick 1981). Lucerne, like most plants, undergoes both morphological and phenological phases of development. Morphological developments describe the change in dimension or number of crop organs such as leaves and roots whereas phenological development is change in crop age through vegetative and reproductive stages. In lucerne, Kalu and Fick (1981) described development stages comprising of expansion of vegetative nodes on stem, flower bud initiation and flower opening. Vegetative growth and development are based on the production of new nodes and attached leaves, the growing point remains at the top of the shoot as it continues to grow, and at flowering, growth slows down and new buds become active in the crown (Fick *et al.* 1988). Following defoliation of primary growth in lucerne, subsequent shoot growth arises from basal buds that emerge from the crown of the plant. Carbohydrates along with N reserves are the driving force for new growth in the roots and crown of the lucerne plant (Stanley and Christinat 1994, Heichel *et al.* 1988, Lodge 1991, Volenec *et al.* 1996, Avice *et al.* 1996).

2.2.2.1 Environmental influences on seasonal growth and development

Generally shoot growth rates increase with increased temperature; however, it is higher in spring than in autumn at the same temperature (Moot *et al.* 2003). The reason being the transfer of more assimilates from roots to shoot in spring (Khaiti and Lemaire 1992) and from shoot to root in autumn (Hendershot and Volence 1992, Kim *et al.* 1991). Both the development processes (phenological and morphological) respond differently to environmental factors across seasons (Moot *et al.* 2003). Amongst these, temperature and photoperiod are the most important (Fick *et al.* 1988).

Like growth rate, the development process also proceeds faster at warmer temperatures; an example is increased appearance of vegetative nodes and consequently leaf area expansion in spring and summer (Moot *et al.* 2001). The influence of temperature on the development process is usually presented in relation to thermal time (Tt in °Cd). 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. The time from defoliation to flowering is also thermal time dependent (Moot *et al.* 2001). However, the amount of thermal time required for lucerne to reach flowering is modified by photoperiod (Brown *et al.* 2005b). Lucerne is an inherited long day plant; therefore, the thermal time interval from defoliation to flowering increases as day-length decreases (Major *et al.*1991). An example is provided by Moot *et al.* (2001), who observed an increase in accumulated thermal time from 380 to 559 °Cd from defoliation to flowering as the mean photoperiod decreased from 16 to 13.5 hours during the different growing seasons. Lucerne takes less time to reach maturity during regrowth periods, compared to initial growth, although this is, undoubtedly influenced by seasonal temperatures and photoperiod (Dent 1959).

2.2.3 Water-yield relationships in lucerne

Under non-limiting conditions, aboveground dry matter production in lucerne is linearly related to water use i.e. evapotranspiration (Bauder *et al.* 1978, Hanks *et al.* 1976, Sammis 1981, Sheaffer *et al.* 1988, Bolger and Matches 1990, Grimes *et al.* 1992, Saeed and El-Nadi 1997, Brown *et al.* 2005a). However, this relationship will vary according to climate (Hill *et al.* 1983, Sheaffer *et al.* 1988, Hirth *et al.* 2001, Latta *et al.* 2001), edaphic conditions (Sheaffer *et al.* 1986, Tesar and Marble 1988) and management practices (Sheaffer *et al.* 1986, Undersander 1987). Therefore, the relationship between water use and growth in lucerne must be studied in conjunction with environment (Christian 1977, Teare *et al.* 1973, Carter and Sheaffer 1983a).

Under rainfed conditions there is a wide range in mean shoot biomass production for lucerne, both within and between climatic regions (Table 2.1a). Reported data for Mediterranean regions ranges from 2.9 - 9.3 t $ha^{-1}yr^{1}$, compared to 3.7 - 12.3 t $ha^{-1}yr^{-1}$ for sub-humid regions and 6.8 - 11.7 t $ha^{-1}yr^{-1}$ for temperate regions, indicating an interaction with environment. The potential for productivity is clearly greatest for regions where annual rainfall is high and reliable. Under irrigated conditions shoot dry matter production is invariably higher in all climatic regions (Table 2.1b), highlighting that water supply is a major influence on productivity.

Soil type, and in particular the water-holding capacity of the soil profile, will also be a key factor contributing to the variability in productivity of lucerne within and between climatic regions. Theoretically, lucerne plant growth will be greatest when soil water is easily available (Christian 1977) and where rainfall is adequate to meet its water requirements of 56-83 mm water per hectare per tonne (Sheaffer *et al*. 1986). Lucerne generally requires a well-drained soil, reasonably deep (>1 m) and relatively salt and alkali free with good moisture holding capacity, for maximum production (Eck *et al*. 1977). Several studies have shown that limited soil water availability results in reduced growth and yield of lucerne (Kemper and Amemiya 1957, Snaydon *et al*. 1972, Carter and Sheaffer 1983, Brown and Tanner 1983, Grimes *et al*. 1992, Saeed and El-Nadi 1997). On the other hand, many studies have shown the yield benefits under optimum soil moisture conditions (irrigated lucerne) in semi-arid regions (Snaydon 1972, Jonson 1975, Bauder *et al*. 1978, Lowe *et al*.1985, Gramshaw *et al*.1993, Frate *et al*. 1988, Metochis and Orphanos 1981, Grimes *et al*. 1992, Saeed and El-Nadi 1997).

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

(a) Rainfed

Location	**Climate**	**Rainfall (mm yr^{-1})**	**Yield (t ha^{-1}yr^{-1})**			**Mean (t ha^{1} yr^{-1})**	**Reference**
			1st	**2nd**	**3rd**		
Rutherglen (Aus)	Mediterranean	407-786	4.32	8.66	11.63	8.20	(Hirth *et al.* 2001)
WA Australia	Mediterranean	341-576	2.25	16.05	-	9.15	(Latta *et al.* 2001)
Degan, Israel	Mediterranean		2.50	3.30	-	2.90	(Kipnis *et al.* 1989)
NSW Australia	Temperate		8.18	4.86	1.46	4.83	(Lodge 1985).
Minnesota USA	Temperate	421	May- Oct			6.80	(Carter & Sheaffer 1983)
Wagga Wagga (Aus)	Temperate	462-697	10.4	9.20	5.50	8.36	(Dunin *et al.* 2001)
Victoria (Aus)	Temperate	335-743	-	-	-	11.73	(Lolicato 2000)
Imp. Valley USA	Sub-humid	1620	-	-	-	12.26	(Donovan & Meek 1983)
Dakota USA	Sub-humid	163-478	5.14	4.38	11.05	6.84	(Bauder *et al.* 1978)
Qld (Aus)	Subtropical	525	-	-	-	3.73*	(Bishop & Gramshaw 1977)

*low lucerne yield in mixture with volunteer species. Whereas (-) denotes data not available.

(b) Irrigated

Nicosia (Cyprus)	Mediterranean	Irrigated	21.60	21.40	-	21.20	(Metochis & Orphanos 1981)
Degan, Israel	Mediterranean	Irrigated	18.00	19.80	-	18.90	(Kipnis *et al.* 1989)
Victoria (Aus)	Temperate	Irrigated	-	-	-	17.30	(Slarke & Mason 1987)
NSW (Aus)	Temperate	Irrigated	10.12	15.60	12.40	12.70	(Lodge 1986)
Minnesota (USA)	Temperate	Irrigated	May- Oct			14.30	(Carter & Sheaffer 1983)
Imp. Valley USA	Sub-humid	Irrigated	-	-	-	17.23	(Donovan & Meek 1983)
Dakota (USA)	Sub-humid	Irrigated	10.33	8.89	12.75	10.70	(Bauder *et al.* 1978)
Gilgit (Pakistan)	Subtropical	Irrigated	One year			29.50	(Mohammad 1996)
Qld (Aus)	Subtropical	Irrigated	25.11	23.72	18.10	22.30	(Lowe *et al.* 1985)
Qld (Aus)	Subtropical	Irrigated	20.37	21.25	-	20.80	(Gramshaw *et al.* 1993)

The relationship between dry matter production and water use of lucerne also changes between seasons (Stewart and Hagan 1969, Reta and Hanks1980, Hirth *et al*. 2001, Latta *et al*. 2001), from one harvest to another (Bauder *et al*. 1978, Metochis and Orphanos 1980, Myer *et al*. 1991), and is strongly influenced by crop growth stage at harvest (Wright *et al*. 1988, Slark and Mason 1987). Under Mediterranean climatic conditions in Victoria growth rates and yield for lucerne during autumn-spring periods were much less variable than those during spring-autumn periods (Hirth *et al*. 2001, Table 2.2), largely due to more reliable rainfall and lower temperatures in winter.

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

NOTE:
This table is included on page 12
of the print copy of the thesis held in
the University of Adelaide Library.

After Hirth *et al*. (2001).

In Mediterranean climates the majority of shoot growth in dryland lucerne occurs in winter and spring with less in summer and autumn (Lodge 1985, McCallum *et al*. 2000), the exception being when significant summer rainfall (>20 mm in a single event) occurs (approximately a one in ten year event in Mediterranean climatic areas of southern

Australia). On the Mediterranean island of Cyprus, lucerne yield declined markedly in July to August when air temperatures reached 40°C (Metochis and Orphanos 1981). Sammis (1981) also reported that lucerne yield was adversely affected by high temperature during summer months. Retta and Hanks (1980) observed differences in yield between seasons in lucerne but not between different varieties. There is little information on the effect of high summer temperatures on lucerne growth and development in South Australia.

2.2.4 Yield components of lucerne

The major yield components of a forage crop are the number of plants per unit area (population), number of shoots (or stems) per plant, and mass per individual shoot or area. In addition to this, LAI, leaf area distribution and orientation, specific leaf area and leaf mass per plant, leaf expansion and senescence should also be taken into account due to important links between yield components, light interception and growth processes (Fick *et al*. 1988, Heichel *et al.* 1988). Furthermore, the angle of leaves relative to incoming radiation, leaf arrangement and thickness, shape and surface properties have also implications for efficient radiation utilization (Gardner *et al*. 1990).

All these components contribute to an effective leaf canopy with the potential to intercept virtually all (>95%) the incident radiant energy (PAR) and to use this radiant energy efficiently to enhance photosynthetic activity and ultimately the biomass or yield. The process of light interception and conversion into plant growth is measured by the term radiation use efficiency (RUE, Heichel *et al*. 1988, Sinclair and Horie 1989). Major yield components are discussed further in the following sections.

2.2.4.1 Plant population, stem number and mass

Efficient interception of radiant energy incident to the crop surface requires adequate leaf area. This can be achived by optimum plant population uniformly distributed over the land surface (Gardner *at al*. 1990). A significant relationship between yield and plant population, independent of stand age, has been directly established (Table 2.3) in a plant population trial carried out by Peoples *et al*. (1998). Since plant population generally declines with increasing stand age in lucerne cultivars (Bishop and Gramshaw 1977, Heichel *et al*. 1984, Lodge 1985), there is usually a concurrent yield decrease (Table

2.3). The relationship does not necessarily apply during the establishment year (Table 2.3) because the number of lucerne plants per unit area is generally very variable and highly dependent upon seeding rate (Bishop and Gramshaw 1977). Factors associated with stand decline in lucerne are plant competition, disease, harsh environmental conditions and defoliation management (Bishop and Gramshaw 1977, Sheaffer *et al.* 1988, Lodge 1985).

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

Temperate*			**Mediterranean**			**Sub-humid**		
Age	Population	Yield	Age	Population	Yield	Age	Population	Yield
2	5	2.17	4	10	NA*	4	55	8.25
2	10	3.09	3	18		3	73	10.2
2	20	4.02	2	23		2	120	11.6
2	40	4.88	1	26		1	270	7.4

Source: Heichel *et al.* (1984), Latta *et al.* (2001), Peoples and Baldock (2001),

NA*Data for temperate climate from density trial in single year whereas for other Mediterranean and Sub-humid climates data are for consecutive years in a single stand

In contrast to the decrease in plant population, the number of stems per plant is reported to increase with stand age of lucerne (Fick *et al.*1988). For example, shoot number increased from 2.4 to 6.5 per lucerne plant over four sequential harvests (McLaughlin and Christie 1980) in one year. Shoot numbers per plant also increased as the plant population decreased over several years (Pulli 1980). Stem numbers are influenced by interactions with soil moisture and air temperature, as well as being a function of variety (Singh and Winch 1972). Moisture stress is believed to have a detrimental effect on stem numbers per plant (Cowet and Sprague 1962, Cohen *et al.* 1972, Perry and Larson 1972, Brown and Tanner 1983). Stem height, node number & internode length and branching were all reduced under limited soil water availability (Vouge and Marten 1971, Perry and Larson 1974, Donovan and Meek 1983, Bolger and Matches 1990, Saeed and El-Nadi 1997). Flooded soil conditions that can cause anaerobic conditions can also reduce number of stems per plant in lucerne, an effect that was enhanced at higher temperatures (Chemeron 1973).

2.2.4.2 Leaf, leaf:stem ratio and node development

Leaf development is a key growth regulator for all plants and is strongly influenced by water availability and temperature. The major parameters used to assess canopy development in lucerne are leaf area, stem growth (height and number) and the relationship between these two, i.e the leaf to stem ratio.

Lucerne invests in relatively thin leaves (Sheehy and Popple 1981) thus favouring leaf area development for maximum light interception in the canopy and subsequent biomass production. Leaf area index (LAI) is usually derived or calculated as the ratio of leaf area (one side only) to ground area. A LAI of 3-5 is necessary for maximum dry matter production in most crops and a higher LAI is required for forage crops where total biomass, not the economic yield, is an objective (Gardner *et al.*1990). The LAI at which 95% of incident radiation is intercepted is termed the critical LAI, and is assumed to be the LAI at which shoot productivity is maximised (Gardner *et al.*1990). Recently, Teixeira *et al.* (2007b) reported a critical LAI of 3.6 for lucerne under irrigated conditions in a temperate climate.

Leaf expansion and senescence are known to be very sensitive to water deficit in lucerne (Whitfield *et al.* 1986). Indeed, LAI decreases sharply under water stress in lucerne (Brown and Tanner 1983, Carter and Sheaffer 1983a, Bolger and Matches 1990). Kemper and Amemiya (1957) reported a 60-70% decrease in canopy growth rate when soil water potential decreased from 0.2 to 0.25 MPa at soil depths of 0.25 to 0.50 m. However, despite an overall decrease in canopy growth rate, soil moisture stress results in a greater number of smaller leaves (Vouge and Marten 1971). Similarly, Brown and Tanner (1983) supported the findings that leaf size was more affected by water stress than leaves per stem. Conditions of moisture stress are often accompanied by high temperatures that also directly reduce leaf area and mass (Bula 1972).

Stem growth is more sensitive to moisture stress (Brown and Tanner 1983, Carter and Sheaffer 1983a) than leaf area and leaf expansion, consequently water stress increases leaf:stem dry matter ratio (Whitfield *et al.* 1986, Halim *et al.* 1989). Data for Australian rainfed conditions (McCallum 1998) show that leaf:stem ratios in lucerne increased from

0.9-1.6 to 2.6-3.2 in summer under water stress conditions. It is suggested that leaf folding and paraheliotropic movement reduced the projected leaf area exposed to sunlight by 14-29%. Additionally, leaf:stem ratio is also directly reduced by high temperature, as shown by Carter and Sheaffer (1983) who obtained greater leaf:stem dry matter weight ratios in cooler seasonal temperatures. They also noted that stem and leaf weight was higher for plants grown at 25^{o}C than plants grown at 35^{o}C under controlled environment conditions because of extended growth periods in cooler environments. Carter and Sheaffer (1983a) further clarified that partitioning of dry matter to leaves in lucerne under soil moisture stress can be attributed to decreased plant height, internode length and stem diameters of water stressed plants.

Node development is a key driver of leaf appearance on the main stem and node appearance on the main stem is function of accumulated thermal time (Tt ^{o}Cd); the amount of thermal time required to produce a single main-stem node is called phyllochron. Robertson *et al*. (2002) reported a single phyllochron of 35 ºCd per leaf appearance on the main stem. Brown *et al*. (2005b) established a constant thermal time of (37±7 °Cd) for node appearance during winter, spring and summer for the 'Kaituna' variety of lucerne in temperate climate of New Zeland under fully irrigated conditions. However, phyllochron of lucerne is also affected by photoperiod (Moot *et al*. 2001, Teixeira *et al*. 2007b). Therefore, the phyllochron calculated for autumn may increase up to (60±0 °Cd).

Water stress also reduced the number of nodes per stem in lucerne (Perry and Larson 1974), whereas, Brown and Tanner (1983) refuted this evidence and reported that internode length was reduced significantly rather than node number. Perry and Larson (1974) also found that cold hardy cultivars have significantly more number of nodes per stem than non-hardy cultivars under the same level of water stress. Conversely, Medler *et al*. (1955) concluded from a study of nine winter hardy cultivars that number of nodes in cultivars is associated with day length. They also demonstrated that plants bred for adaptation to long day length produced more nodes per stem than short day length plants; a relationship that was confirmed by the work of Carlson (1965).

The relationships between node appearance and thermal time are poorly understood for the Mediterranean type climates of southern Australia.

2.2.4.3 Radiation use efficiency

Radiation or sunlight is a major determinant of crop yield since radiation plays a pivotal role in photosynthesis and hence there is a close relationship between the amount of light intercepted by a crop and growth (Sinclair and Muchow 1999). However, the proportion of radiant energy received at the earth's surface is determined by the geometry of the earth's surface with respect to the sun and depends on latitudes and season (Sinclair and Muchow 1999), and this has implications for potential yield in different regions. Radiation use efficiency (RUE) is defined as the efficiency with which the crop uses the intercepted radiation to produce dry matter (Sinclair and Horie 1989). Energy input in any environment is determined by the seasonal distribution of solar radiation, in addition to this, optimum levels of water and nutrients are also prerequisites of potential productivity in any environment (Loomis *et al.* 1971, Monteith 1972).

Large variability has been reported in RUE depending upon different species, varieties, developmental stages, climate, nutrients and water deficit (Sinclair and Muchow 1999). For instance, at the species level, RUE values are in the range of 1.6-1.7 g MJ^{-1} for maize, 1.2-1.4 g MJ^{-1} for sorghum, 1.7 g MJ^{-1} for sugarcane, 1.6-1.7 g MJ^{-1} for potato, 1.38 g MJ^{-1} for wheat 1.30 g MJ^{-1} for barley, 1.1-1.30 g MJ^{-1} for rice, 1.27 g MJ^{-1} for sunflower, 1.02 g MJ^{-1} for soybean, 1.12 g MJ^{-1} for peanut and 1.03 g MJ^{-1} in faba bean. These authors concluded that C_4 crops species, which have higher photosynthetic capacity, have higher RUE compared to C_3 crops species. Further, leguminous crops have lower RUE because of their energy-rich plant product and the requirement for extra energy to fix nitrogen (Sinclair and Horie 1989). Further, perennials like lucerne have also variable RUE in different regions. For example, taking account only of shoot biomass, Goose *et al.* (1984a) proposed a uniform RUE of 1.76 g DM MJ^{-1} for lucerne. Later on, Khaiti and Lemaire, (1992) found that a uniform value might be true only for a given season and only for specific regrowth cycles, and determined different values of RUE for different seasons. For instance, they found RUE (shoot only) of 0.4 g DM MJ^{-1} for the growth period after seeding, 0.9 g DM MJ^{-1} for summer regrowth and 0.7 g MJ^{-1} for autumn regrowth, indicating different partitioning of assimilate below ground in different seasons. However, when these authors included lucerne roots in the calculation of RUE they found a constant value of 1.12 g DM MJ^{-1} over three growth cycles. Varietal and cutting regime effects on RUE values have been noted in a study by Avice *et al.* (1997) who reported shoot RUE values of 1.67 and 1.45 (g DM MJ^{-1}) in two different varieties, Lodi and Europe, for 45 day cutting interval, and 1.60 and 1.45 (g DM MJ^{-1}) for 30 day cutting interval respectively, in a temperate region of France. Whereas in the cool temperate climate of Canterbury, New Zealand, the reported RUE value for lucerne shoot DM ranged from 0.29 to 1.09 (g DM MJ^{-}) being impacted by both season and temperature (Brown *et al.* 2006). However, under the same temperate climatic conditions, Teixeira *et al.* (2008) found a range of 1.7 to 2 g DM MJ^{-1} decreasing to 1 g DM MJ^{-1} in autumn under irrigated conditions. All these researchers have performed sophisticated physiological studies that have greatly increased knowledge about RUE in lucerne. However, most of these physiological studies were performed under non-limiting resource/low-stress environmental conditions and even then the reported variability was wide, indicating that their applicability to crops grown under resource limited conditions may not be justified. Effects of water limiting conditions and decreased temperature (below 21.4°C) on RUE of lucerne have been reported (Colliono *et al.* 2005). Extreme fluctuations in temperature and water supply are inherent in southern Australian environments and if lucerne is to be promoted in these farming systems then more information on the influence of these conditions on RUE in lucerne is required.

2.2.5 Root growth

There is some debate as to whether root growth is purely a seasonal activity or is also a heritable character. Traditionally, it was believed that lucerne was not essentially or genetically a deep-rooting plant, although its roots grew where water was available (Paltridge 1955). However, Johnson (1992) reported that taproot size, number of lateral roots and amount of fibrous root were highly heritable characters. Lucerne root development is certainly modified by season and age of the plant with new roots occurring primarily in the spring and immediately following rainfall (Johnson *et al.* 1998, Pietola and Smucker 1995). Lou *et al.* (1995), studying the seasonal pattern of vertical distribution of fine roots in lucerne, confirmed that root mass was generally greatest in the spring and autumn when mild soil temperatures (range 5-15°C) and moisture were not limiting, and root mass was least during the summer under dry conditions. They further noted that frequent harvest and soil temperature reduced root mass in summer. Complex linking between seasonal and genetic control of root characteristics was highlighted by the work of Bennet and Doss (1960) which found that root mass for a moderately winter-hardy variety of lucerne (Atlantic) was greater under low soil moisture, whereas root mass of a non-winter-hardy variety (African) was greater under high soil moisture conditions.

Total root length density or root distribution of any plant is generally considered to be positively related to the amount of water taken up by plants, and the rate of water uptake (Hamblin and Tennant 1987). Therefore, root growth and distribution pattern of lucerne will have important implications for water extraction and nutrient uptake, and consequently for above ground dry matter production. Root growth in lucerne is largely controlled by carbohydrate supply in the tap-root (Klepper 1987) but also substantially influenced by the soil environment (Cameron *et al.* 1990), significantly affected by age of the plant and season (Pietola and Smucker 1995), and partially influenced by defoliation pattern (Feltner and Massengale 1965). A considerable amount of research work has been reported on the effects of environmental factors, such as soil moisture and temperature, on root dynamics of lucerne (Abdul-Jabbar *et al.* 1982, Carter *et al.* 1982, Jodari-Karimi *et al.* 1983, Luo *et al.* 1995) but results are contrasting and inconclusive. One reason for this might be that traditional means of studying root growth in the field are difficult and require large amounts of labour and/or equipment (Abdul-Jabbar *et al.* 1982, Hansson and Andren 1987). Another reason might be a high level of variability in soil environments and plant response, as well as differences in the age of the root systems studied (Schuurman 1965, Sheaffer *et al.* 1988). There are no published reports regarding root development in lucerne on different types of soils for South Australia.

2.2.5.1 Root:shoot ratio

Lucerne, like many other crop plants, diverts assimilates to root growth under water stress resulting in a high root:shoot ratio (Whitfield *et al.* 1986b). Generally, shoot growth is more vulnerable than root growth in mature plants under water stress (Cohen *et al.* 1972). Cool temperatures also increase partitioning of assimilates to roots thus increasing root:shoot ratio in lucerne (Smith 1962). A comparison of irrigated and non irrigated lucerne measured an increase in root:shoot ratio from 0.22 to 0.62 (Jodari-

Karimi *et al.* 1983), which supports the idea that substantial allocations of photosynthate are diverted to below-ground components of lucerne given conditions of moderate water stress (Brown and Tanners 1983, Whitfield *et al.* 1986b). Khaiti and Lemaire (1992) established that lucerne partitions greater assimilate below ground in autumn, resulted in lower shoot DM in autumn compared to spring. Under dryland conditions in southern Australia, McCallum (1998) found that lucerne appeared to divert a much larger proportion of assimilate (75-83%) below ground than had previously been reported. He postulated that this may be due to the extreme stress levels lucerne encounters in this environment. Little is known of the influence of local conditions (Mediterranean climate and duplex soils) on the partitioning of assimilate between shoot and root in lucerne.

2.2.5.2 Root response to soil water

Soil moisture is a key factor that affects root growth and the pattern of root distribution in all crops (Danielson 1976). The rate of water (and nutrient) absorption depends, in principle, upon the ability of the roots to absorb water from the soil with which they are in contact, and the ability of soil to supply and transmit water toward the roots at a rate to meet plant transpiration and growth requirements (Gardener 1960, Huckle and Hill 1983). Generally, excess or deficit of soil moisture markedly influences root growth and function in lucerne (Simpson *et al.* 1973, Jodari-Karimi *et al.* 1983). In early research, Jones (1943) found that root mass varied with change in soil moisture and reached a minimum during the dry summer. Root mass also became more concentrated in upper soil layers as soil moisture increased (Bennet and Doss 1960). Later research work with lucerne indicated that depth of rooting, and root growth rate, were linearly related to the amount of water (or irrigation) supplied (Janson 1975). Furthermore, Abdul-Jabbar *et al.* (1982) found that lucerne root mass, rooting depth; root length density and root-shoot ratio were higher with increased soil moisture levels. Additionally, they found a positive relationship between evapotranspiration and root mass, as well as root length density. Similarly, Elhaak (1991) reported that root numbers increased in dry conditions, and root length under wet conditions, and that root-shoot ratio increased in the dry season as a result of shoot deterioration due to water stress. As mentioned earlier (Section 2.2.2.1) this emphasized that lucerne shoots are more vulnerable to water deficit than roots (Cohen *et al.* 1972).

Although there is much evidence to suggest that lucerne roots respond positively to soil moisture there are a number of reports that contradict this suggestion. Beckett and Huberty (1928) observed that root distribution was not affected by frequency or amount of irrigation after a wet winter. Luo *et al*. (1995) also reported that soil moisture has little influence on root dynamics, and Knock *et al.* (1957) found that the root system of lucerne could grow deeper and become more fibrous under dry conditions compared to irrigated conditions. Carter and Sheaffer (1982) confirmed that non-irrigated lucerne had greater root length and mass than irrigated lucerne, and concluded that although increased root length is usually associated with increased drought avoidance, cultivars with greater root lengths had lower plant water potential under moisture stress. They suggested that further investigations in this regard in the field may be useful for the improvement of lucerne. Several other investigators corroborated that the onset of water stress actually stimulated downward root growth in lucerne (Jodari-Karimi *et al*. 1983, Fick *et al*. 1988, Smith *et al*. 1996). A study of the branching-root trait in lucerne in relation to soil moisture levels, indicated that plants grown under lower moisture content had a lower incidence of branching roots (Mclntosh and Miller 1981) which contradicts very early reports that roots of dryland lucerne had greater primary and secondary branching roots than those of irrigated lucerne (Jean and Weaver 1924).

Overall it is clear that root development in lucerne, as for many species, is strongly influenced and modified by soil moisture and that, although root distribution usually reflects the pattern of available soil water (Paltridge 1955), there are situations where the relationship may be altered. Many of the studies referred to by this review were carried out under controlled environment conditions and the results are not necessarily comparable to those from field studies since container size is likely to limit rooting pattern (Saini and Chow 1982, Carter *et al*. 1982). Indeed, Carlson and Hanson (1988) affirmed that our understanding of the dynamics of lucerne root growth in relation to environmental influences is considerably less than that for shoots, and that future research should focus on this issue. There is virtually no data to describe the growth of lucerne roots in relation to soil constraints imposed by inherent soil characteristics such as high pH, penetration resistance or boron concentration. Improved qualitative and quantitative data needs to be provided concerning the response of lucerne roots to different soil moisture regimes and seasonal patterns, including the interaction with inherent soil constraints, particularly under field conditions for southern Australia. Such data will enable researchers to improve selection of lucerne varieties adapted for maximising water extraction and productivity in these environments.

2.3 Lucerne Soil-Water balance

The soil-plant water balance is central in terms of plant productivity and sustainability in Australian farming systems particularly in Mediterranean-type climate. Water that is not captured by plants represents a reduction in potential yield and also intensifies natural resource degradation via erosion, salinisation, acidification and nutrient losses to surface and ground waters (French and Shultz 1984, Gregory *et al.* 1992, Cass *et al.* 1996, Bolger and Turner 1999). It is therefore clearly important to understand the components of the soil-plant water balance for any particular system to enable maintenance of productivity and sustainability. The water balance of a soil-plant system can be represented by the following equation:

$$P+I= Et+Es+D+RO+\Delta S \qquad \text{(Eq. 2.3.1)}$$

Where P= precipitation, I= irrigation, Et= Transpiration from plant, Es= evaporation from soil, RO= runoff, D= drainage and ΔS= change in soil water content. Under rainfed conditions where rainfall is the sole source of input, the equation can be simplified to:

$$P= Et+Es+D+RO+\Delta S \qquad \text{(Eq. 2.3.2)}$$

2.3.1 Deep drainage and groundwater recharge under lucerne

Perennial pasture species can generally reduce groundwater recharge compared to annual species due to higher water use, deeper root systems, greater herbage production and a longer growing season which maximises ET whilst minimising RO and D (Cook 1992, Ridley *et al.* 1997). Lucerne, as one such perennial species, has proven suitable to dry the soil profile and be productive in regions of Australia having ground water recharge potential leading to dryland salinity (Loane 1993, Crawford and Macfarlane 1995, McCallum *et al.* 1998, Pitman *et al.* 1998 Latta *et al.* 2001, Ridley *et al.* 2001). Lucerne is able to draw water from deep in the soil profile because it has a high transpiration rate, a deep and extensive root system and is active in summer and winter (Scott and Sudmeyer 1993). Indeed, lucerne may access water that has escaped below the root zone of shallow rooted crops in previous years (Kelner *et al*. 1996, Lolicato 2000). Some dryland lucerne crops are also capable of using ground water, and in situations where the water table was 1.2 to 1.7 m below the soil surface have been reported to produce nearly as much herbage as irrigated lucerne (Benz *et al*. 1984, Zhang *et al*. 1999).

Ground water recharge or deep drainage under Mediterranean climate generally occurs in the winter months (June-July) when the water demand by annual crops is relatively small because they do not have sufficiently large root systems or leaf area to utilise all the water that is supplied by rainfall. In addition to this, large rainfall events in summer-autumn or episodic recharge (i.e out of season) can cause similar situations in the absence of any crop (Nulsen 1993, Eberbach 2003). Extreme variability in precipitation events, characteristic of Mediterranean type climates, also plays a significant role in the recharge process (Zhang *et al*. 1999). The effect of low water demand by annuals is compounded by the fact that, during this winter period of low temperatures, rainfall generally exceeds the maximum evapotranspiration rate of 1 mm d^{-1} (Zhang *et al*. 1999). Lucerne water use, however, can almost match incident rainfall during winter (June-July) and prevent recharge (Zhang *et al*. 1999, Lolicato 2000, Ridley *et al*. 2001). Also by providing a dry soil profile over summer-autumn, lucerne creates a buffer for storing soil water (Ward 2006). Therefore, the effect of growing lucerne will always be specific to site and season, and may change from year to year depending on the distribution of rainfall (Ridley *et al*. 1997, Lolicato 2000). Although it has been recognised that lucerne can successfully eliminate or reduce recharge in low to moderate recharge areas (Loane 1993), where recharge is more than 10 mm yr^{-1} other measures, along with agronomic options may need to be incorporated, such as revegetation with trees or engineering solutions, into any management strategy for reducing recharge (Greiner 1992).

2.3.2 Evapotranspiration from lucerne stands

Evapotranspiration (ET) is of particular importance in the Mediterranean-type climate because of the expanding threat of dryland salinity (Ward and Dunin 2001). ET is the sum of Et and Es, (Eq. 3.2.1) where, Et (transpiration) is water loss by evaporation from moist mesophyll surface and diffusion of water through stomata and Es (evaporation) is water loss from soil wherein the crop has been planted. ET is determined by atmospheric demand and crops factor (Meinke *et al*. 1993). Evaporation from any surface is driven by solar radiation and air temperature that provides the latent energy (λ) for vaporisation and requires a sink in the form of atmospheric saturation vapour pressure deficit (VPD) created by air humidity and wind run (μ) that makes atmospheric turbulence. Es under crop is difficult to assess, however, from the bare soil as first explored by Ritchie, (1972) it proceeds in two successive stages, the energy dependent first stage (constant but short lived) and the water supply dependent second stage.

Lucerne has a high evapotranspiration rate that can be highly variable under different types of climate and seasons. The range of reported daily evapotranspiration rates for lucerne-stands is very large; for example 3.1 to 14 mm d^{-1} (Table 2.4). Variability in evapotranspiration may be due to season, growth stage of the crop, soil moisture availability and VPD in the area. High ET values for lucerne reflect an ability to maintain leaf area or ground cover and also to access deeper soil water, and hence affect water use via transpiration, over long periods of time (Grimes *et al*. 1992). However, it also requires multiple harvests that repeatedly expose the soil surface to direct sunlight and accelerate evaporation from the soil (Jodari-Karimi 1983).

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

Season	**Evapotranspiration (mm d^{-1})**	**References**
Seasonal average	8-10	(van Bavel 1967)
Mid summer	7.5	(Rosenberg 1969)
Late spring	12.0	(Rosenberg 1969)
Late spring	12.0	(Blad and Rosenberg 1974)
Late spring	14.0	(Rosenberg and Verma 1978)
Seasonal average	3.1-10.2	(Ljungkull 1982)
Seasonal average	5.3-10.0	(Carter and Sheaffer 1983)
Seasonal average	8-10	(Wright 1988)

The use of lucerne to overcome or minimise the recharge problem has been successful across several agro-climatic zones in Australia. These include the high rainfall areas of north-eastern Victoria (Clifton *et al.* 1993, Day *et al.* 1993, Crawford and Macfarlane 1995, Ridley *et al.* 1997) and New South Wales (Beale 1993), and lower rainfall regions such as the Victorian Wimmera (McCallum *et al.* 1998), the South Australian and NSW mallee regions (Zhang *et al.* 1999) and Western Australia (Berry 1997). Clearly soil type will have an influence on recharge since drainage is more rapid on lighter textured soils compared to heavier clay soils that tend to have greater water holding capacity. Furthermore, duplex (texture contrast) soils may pose limitations in terms of water extraction if the soil conditions of the B horizon are hostile to root growth, although Ward *et al.* (2001) observed that on a duplex soil in WA lucerne roots were extracting water in the clay B horizon whereas annual pasture roots were unable to access this soil layer due to physical or chemical constraints.

2.3.3 Water use efficiency of lucerne

Water-use efficiency (WUE) is expressed as the ratio of dry matter produced against total evapotranspiration. In general, the most promising way to increase efficiency of water use is to encourage production of dry matter rather than to decrease water use (Kramer 1969). On a well-managed dryland farm WUE can be higher, although crop production and water use are relatively lower in comparison with irrigated or humid regions (Benz *et al.* 1984), because of higher evaporation losses due to higher water availability and atmospheric demand (VPD). These authors quantified their findings and reported that WUE was higher (25 kg ha^{-1} mm^{-1}) in plots where less water was applied compared to those where the quantity of applied water was higher (20.4 kg ha^{-1} mm^{-1}). Jodar-Karimi *et al.* (1983) supported these findings and showed that WUE was greater under low than high water regimes. Conversely, significantly higher WUE in irrigated plots rather than under natural rainfall conditions was obtained by Bauder *et al.* (1978). The availability of soil moisture is a key component of this variability (Joy *et al.* 1972, Wilson *et al.* 1983, Beukes and Bamard *et al.* 1985). Water is a scarce resource, therefore managing lucerne to achieve the best possible WUE is essential “for the crop to remain competitive for water supplies both within and outside agriculture” (Grimes *et al.* 1992). Reported WUE for lucerne varies widely (see Table 2.5), from 1.9 to 26 kg ha^{-1} mm^{-1} depending upon climate, seasonal conditions, soil water availability, soil fertility and cultivar. In addition to this, a considerable variation in WUE has also been observed within and among different lucerne cultivars (Cole *et al*. 1970), although another study refutes these findings (Abdul-Jabbar 1983).

Given the wide variability in water use for lucerne in various climatic regions and within different seasons; and considering the enormous variation in rainfall from year to year, it is clearly very important to characterise the response of lucerne (and it's potential to control deep drainage) under the specific Mediterranean type climatic conditions experienced in South Australia. In particular, there are little data to describe the performance of lucerne throughout summer, or on duplex soils, despite the fact that these soils, which are characterised by abrupt changes in texture, structure or consistency between the A and B-horizons, occur widely in South Australia (Chittleborough 1992). Improved understanding of the relationship between transpiration (water use) and WUE can be beneficial for better management of lucerne as well as general profitability (Hanks 1974, Sammis 1981, Wright 1988, Grimes *et al*. 1992, Hirth *et al*. 2001).

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

Location	**Irrigation/ rainfed**	**WUE (kg DM ha^{-1} mm^{-1})**	**Year**	**Reference**
North Dakota (USA)	Irrigated	16	1973-74	(Bauder *et al*. 1978)
North Dakota (USA)	Rainfed	13	1973-74	(Bauder *et al*. 1978)
Utah-State (USA)	Irrigated	26	1976-77	(Reta and Hanks 1980)
New Mexico (USA)	Irrigated	12	1976	(Sammis 1981)
Texas (USA)	Irrigated	18	1986-87	(Bolger and Matches 1990)
New Mexico (USA)	Irrigated	16	1982	(Abdul-Jabbar *et al*. 1983)
Khartoum (Sudan)	Irrigated	12	NA	(Saeed and El-Nadi 1997)
Kimberly	Irrigated	18	1975	(Wright 1988)
California (USA)	Irrigated	23	1985-86	(Grimes *et al*. 1992)
Vic (Australia)	Rainfed	13	1994-99	(Hirth *et al*. 2001)
Wagga Wagga (Australia)	Rainfed	5	1993-97	(Dunin *et al*. 2001)
Degan (Israel)	Rainfed	2	1979-81	(Kipnis *et al*. 1989)
Degan (Israel)	Irrigated	3	1979-81	(Kipnis *et al*. 1989)

2.4 Lucerne and the N cycle

Lucerne plays a key role in the N cycle of pasture-crop rotation systems via symbiotic N_2 fixation which results in residues with a narrow C:N ratio that are able to benefit cereal crops in the short term, and contribute to the long-term sustainability of soil fertility. Potentially lucerne is an acidifier (like all legumes) but this is counteracted by its' ability as a deep-rooted perennial to take up a proportion of nitrate too. The following sections will discuss quantities of N_2 fixed by lucerne, seasonal patterns of fixation, the key factors limiting N_2 fixed in dryland lucerne i.e water and root-zone temperature, the contribution that lucerne N makes to soil fertility (N) and the role lucerne plays in leaching and uptake of mineral N.

2.4.1 Lucerne N_2 fixation

Lucerne, as a legume, is able to benefit from assimilation of N_2 fixed via a symbiotic association with *Rhizobium meliloti* L. Quantitative estimates of annual N_2 fixation by lucerne across climatic regions of the world vary from 4 to 466 kg N_2 ha^{-1} yr^{-1} (Table 2.6). Until recently estimates of N_2 fixation have been based solely on measurements of aboveground shoot N. Fixed N_2 contained in roots and nodules will increase these estimates by up to 50% (Section 2.4.2.1).

The wide range in N_2 estimates might be due to differences imposed by many factors including age of stand, season, genotype, bacterial strain, management practices, climate and location, legume content and measuring technique (Burton 1972, Carter and Sheaffer 1983, Barnes *et al.* 1984, Wery *et al.* 1986 Kelner *et al.* 1997, People and Baldock 2001). The range in the proportional dependence of lucerne on N_2 fixation (Table 2.6) may also be affected to an extent by some of the above factors, but will be particularly influenced, as with other legumes, by the amount of plant-available (mineral) N in the soil (Allos and Bartholomew 1955, Armstrong *et al.* 1999).

There is generally a positive and relatively linear relationship between dry matter production and amount of N_2 fixed by annual and perennial pastures (Peoples *et al.* 1998). Studies of N_2 fixation by annual (subterranean clover) and perennial (lucerne) pastures under dryland conditions in Australia conclude that approximately 22-31 kg N is fixed for every tonne of legume dry matter produced (Hossain *et al*. 1995, McCallum 1998, Peoples *et al*. 1998).

Furthermore, it was confirmed that lucerne provided consistently greater annual forage yield than subterranean clover and therefore fixed 90-150% more N_2, thus proving a more reliable means of improving the soil fertility. Similarly, in another study under rainfed conditions, McCallum *et al*. (2000) reported that N_2 fixation by lucerne was consistently greater than annual medics because the deleterious effects of seasonal rainfall patterns were more pronounced on annual medics.

Table 2.6 Range of experimental estimates of the proportion of N in lucerne derived from the atmosphere (Ndfa %) and amount of N_2 fixed by lucerne growing in different locations in Australia and around the world.

Locations	**Climate**	**Irrigation/ Rainfall (mm)**	**Shoot N_2 Fixed**		**Reference**
			Ndfa (%)	**Amount (kg $ha^{-1}yr^{-1}$)**	
AUSTRALIA					
Canberra ACT	Temperate	Irrigated	68-74	185-284	(Gault *et al*. 1995)
Canberra ACT	Temperate	Irrigated	84-97	83-97	(Brockwell *et al*. 1995)
Warra QLD	Temperate	Rainfed (630)	82-93	83-92	(Hossain *et al*. 1995)
Emerald QLD	Temperate	Rainfed (639)	23-64	11-56	(Armstrong *et al*. 1999)
Wagga NSW	Temperate	Rainfed (560)	33-66	4 -138	(Dear *et al*. 1999)
Trangie NSW	Subtropical	Rainfed (504)	25-82	13-82	(Peoples *et al*. 2001)
Junee NSW	Subtropical	Rainfed (479)	57-76	47-167	(Peoples *et al*. 1998)
Horsham Vic.	Mediterranean	Rainfed (423)	62-77	19-90	(McCallum *et al*. 2000)
WORLDWIDE					
USA	NA	Rainfed	33-78	114-224	(Heichel *et al*. 1984)
Sweden	NA	Irrigated	70-80	242-319	(Wivstad *et al*. 1987)
Austria	NA	Rainfed	78-88	93-112	(Danso *et al*. 1988)
Canada	Temperate	Rainfed (372)	62-78	174-466	(Kelner *et al*. 1996)

Any factor that affects plant growth will eventually, either directly or indirectly, affect N_2 fixation (Sheaffer *et al*. 1988, Carter and Sheaffer 1983). The most important and significantly limiting factors are rhizobium and cultivar interaction, soil mineral N, soil pH, soil salinity, deficiency of other important mineral elements necessary for growth, soil or root zone temperature, defoliation management, and soil and plant moisture

(Vance *et al*. 1988). The next three sections discuss the effects of limited soil moisture, elevated soil temperature and mineral N on N_2 fixation, as these are considered major factors affecting symbiotic performance, and hence productivity, for dryland lucerne. Defoliation is another important factor and will be dealt with in Section 2.5.1.

2.4.1.1 Water stress effects on N_2 fixation of lucerne

It is well known that soil moisture markedly affects growth and N_2 fixation activity in legumes. Water stress directly depresses legume N_2 fixation by reducing activity of the nodule bacteroids (Sprent 1976, Abdel-Wahab and Zahran 1979). Indeed, Winstad *et al.* (1987) observed in lucerne a severe negative effect of water stress on N_2 fixation (measured as nitrogenase activity), whereas sufficient water supplied as irrigation doubled nitrogenase activity. Reduced nitrogenase activity under water stress corresponds with a loss in nodule weight, although activity may be restored partially (70%) when water supply is resumed (Aparicio-Tejo *et al.* 1980). It has also been reported that N_2 fixation was much more susceptible to drought than NO_3^- assimilation in lucerne, and that initially, recovery after drought was reliant upon the latter until sufficient time elapsed for the symbiosis to function again (Wery *et al*. 1986).

Anderson *et al*. (1998) have pointed out that no study of N_2 fixation can be adequately undertaken without concurrent consideration of soil water dynamics, although, at the time the comment was made, no such study for lucerne had been reported for any soil type in the rainfed cropping systems of Southern Australia. However, some studies had provided useful information on quantities of N_2 fixed and benefits for soil N fertility under irrigated conditions in NSW (Gault *et al*. 1995), under dryland conditions in NSW and Northern Victoria (Ledgard *et al*. 1985, Peoples *et al*. 1998) and in southern Queensland (Hossain *et al*. 1995). Since the comments by Anderson *et al*. (1998), some aspects of seasonal dynamics of N_2 fixation and soil water in dryland lucerne have been described (McCallum *et al*. 2000). However, it is uncertain whether information from these studies is directly transferable or applicable to the Mediterranean climatic conditions and duplex soils of South Australia and therefore, further research is needed into N_2 fixation by dryland lucerne under both summer and winter conditions.

2.4.1.2 Temperature stress effects on N_2 fixation of lucerne

Generally, any environmental factor unfavourable for plant growth can also affect symbiotic N_2 fixation. Barta (1978) indicated that N_2 fixation was depressed at a root zone temperature of 30^oC compared to 16^oC. It has also been demonstrated that lower temperatures, around $5\text{-}10^oC$ have decreased N_2 fixation (measured using C_2H_2 reduction) relative to higher temperatures ($20\text{-}25^oC$); however, varieties with different winter dormancy levels behaved differently (Duke and Doehlert 1981). In a study under rainfed conditions in southern Australia McCallum (1998) noted significant changes in N_2 fixation throughout the seasons and observed generally a lower proportional dependency on N_2 fixation in summer and autumn than winter to spring. There are few data reported in the literature regarding the relationship between N_2 fixation in lucerne and root-zone temperature, particularly under field conditions.

2.4.1.3 Soil mineral N effects on N_2 fixation

Generally, it is accepted that the presence of higher levels of mineral N in soil reduces the proportion of N derived from N_2 fixation, both for annual medics (Butler 1988) and for lucerne (Kelner *et al,* 1997, Armstrong *et al* 1999). However, the extent to which mineral N depresses N_2 fixation is extremely variable. Indeed, Lamb *et al.* (1995) found that although N_2 fixation in lucerne was reduced at rates of N fertiliser application as high as 840 kg N ha^{-1} yr^{-1}, substantial amounts of N_2 (184 kg) were still derived from fixation.

It is often reported that proportional dependence of lucerne on N_2 fixation increases with age of stand (Pettersson *et al.*1986); this is probably related to lucerne depleting the soil mineral N pool during the establishment year and subsequently removing the inhibitory effect of mineral N in the root zone. The regulatory mechanisms underlying N acquisition from different sources are not fully elucidated for lucerne (Blumenthal and Russelle 1996), or, in fact, for any pasture legume. Therefore any data concerning the interaction between soil nitrate and N_2 fixed by lucerne, particularly under field conditions, will be valuable.

2.4.2 Soil nitrogen fertility for lucerne pasture systems

Wani *et al.* (1995), in a review concerning the role of legume N_2 fixation in sustainability of farming systems, emphasized the need to include legumes that have the ability to add N to the system *and* extract excess water from the soil. Perennials, such as lucerne, certainly appear suited to meet these criteria. Lucerne is not only very efficient at extracting soil water (Angus *et al.* 2001), and hence deep nitrate, but also increases organic matter in the soil, improves soil structure, and builds up soil organic N reserves to improve fertility (Simpson 1974, Baldock *et al.* 1981, Carter *et al.* 1982 Holford 1981, Kelner *et al.* 1997). Consequently, via mineralisation of above-ground shoot residues and below-ground roots (Stevenson *et al.* 1998) the grain yield and protein level of succeeding crops may be increased following lucerne (Holford 1981, Smith *et al.* 1989). Inputs of fixed N_2 to soil by lucerne and subsequent mineralisation of these inputs will be discussed in the next part of this review, followed by consideration of the cycling of inorganic N in the soil system under lucerne pastures, particularly the uptake of NO^-_3 and loss via leaching.

2.4.2.1 Input of fixed N by lucerne

Due to the positive relationship between dry matter production and N_2 fixation referred to earlier (Heichel *et al.*1984, Peoples *et al.*1998) lucerne, as a perennial, has the potential to seasonally provide larger amounts of N input to soil than annual legumes. The input of fixed N_2 to soil by irrigated lucerne in Australia, in the second and third years after establishment, was at least the same as N removed (Gault *et al.* 1995), and this corresponded quantitatively to 195-384 kg N ha^{-1} yr^{-1}. Whereas, Kelner *et al.* (1997) in a N_2 fixation study in Canada, found that approximately 84, 148, and 137 kg N ha^{-1} were added to the soil by 1, 2 and 3 years old lucerne stand.

Of course all N_2 fixed by lucerne is not input to the soil N pool, because a portion is removed when it is harvested or grazed, with the balance remaining above-ground in residual leaves and stems, and below-ground in the crown and roots. Ta *et al.* (1985) found that most fixed N_2 in lucerne was rapidly partitioned to stems and leaves, rather than to roots. Therefore, the N in leaves (fallen and attached to stems) remaining after harvest of lucerne may be substantial, and should not be ignored as a contribution to the soil N pool (Wani *et al.* 1995).

Research has estimated that the amount of N_2 present in nodulated roots in various legumes ranges from 15-50 kg N ha^{-1} and represents more than 15% of the total plant N (Bergersen *et al.* 1989, Peoples *et al.* 1995, Chapman and Myers 1987, Unkovich *et al.* 1994). Total production of ash free dry mass for lucerne, inclusive of above- and below-ground material, has been measured as 1.84 kg m^{-2}, with below-ground production constituting 30-47% (Pettersson *et al.* 1986). Similarly, Zebarth *et al.* (1991) and Gault *et al.* (1995) have reported that about 50% of N in lucerne may be below ground.

During the growing season for lucerne there is evidence of excretion of recently fixed N_2 from lucerne roots and nodules to the adjacent rhizosphere. Ta *et al.* (1985) reported that about 3% of fixed N_2 compounds were excreted daily from roots to the rhizosphere. They further reported that the majority of these excretions consisted of organic N although some were ammonia. In addition to this, the direct interconnection of grasses and legume roots via mycorrhizal fungi is also a source of transfer of legume N_2 to grass and then soil (Haystead *et al.* 1988).

The quantity of N_2 returned to the soil at the end of a lucerne phase will vary, depending upon the time that the pasture is terminated and tillage occurs, and also the portion of herbage crown and root ploughed down (Vance *et al.* 1988). An estimated 290 kg N ha^{-1} in 12 tonnes ha^{-1} of organic matter was incorporated into the soil by ploughing a lucerne field (Pettersson *et al.* 1986). Similarly, Peoples and Baldock (2001) reported that lucerne can add 22 to 71 kg N ha^{-1} yr^{-1} to the soil, depending upon timing of lucerne removal and climate prevailing during the year. They further clarified that release of N to the succeeding crop, from mineralisation of these lucerne residues, may be relatively slow due to the soil being drier as a result of the greater water extraction by lucerne. The mineral N in the soil may also be low in autumn removal of lucerne, resulting in initially low availability and yield of the first crop after lucerne (Hirth *et al.* 2001). These authors also found that growing season rainfall was the strong stimulating agent for mineralisation. However, where adequate rainfall was received following lucerne removal, the N supplied by mineralisation of lucerne residues was sufficient for the next two cereal crops (Hirth *et al.* 2001).

2.4.2.2 Nitrate (NO_3^-) leaching and uptake

Mineral N, in $NO3^-$ form, moves with the soil water solution and is prone to being leached down beneath the rooting zone of annual crops, resulting in ground water pollution. Field studies around the world have shown lower mineral N concentration in soil (Muir *et al.* 1976) and NO_3^- leaching losses to surface and ground waters (Randall *et al.* 1994) under deep-rooted perennials like lucerne than annual species. Inclusion of lucerne in crop rotations might be helpful to slow down the rate of soil degradation (Helyar 1992). Lucerne's suitability for uptake of water, as well as NO_3^-, from deeper in the soil profile has been clearly demonstrated in regions of the world other than Australia (Boawn *et al.* 1963, Schertz and Miller 1972, Mathers *et al.* 1975, Peterson and Russelle 1991, Kelner *et al.* (1997).

One Australian study, in the sub-tropical climate of southeastern Queensland, has reported that in one year lucerne was able to deplete NO_3^- that had accumulated over several years previously (Catchpoole 1992). Similarly, Peoples *et al.* (1998) found that the soil profile under dryland lucerne pastures in a temperate climate generally contained uniformly lower concentrations of mineral N compared with annual pastures. However, data concerning soil NO_3^- uptake by lucerne in Australia are sparse, and insufficient for extrapolation to Mediterranean climatic environments in southern Australia. Therefore, more studies are warranted, especially in relation to the interaction between growth, N_2 fixation and soil NO_3^- uptake in lucerne.

2.5 Agronomic management of lucerne

Management plays a vital role in the success or failure of any crop or pasture system, and this is also true for lucerne. Yield and quality of any system depends on a combination of production practices which, in an effective management system, creates the opportunity for positive interactions among various components such as, variety; soil fertility levels, harvesting schedules, pest control and favourable environmental conditions (Lanyon and Griffith 1988). In general, management factors are interlinked with each other and deficiency in any one can adversely affect the performance of the other factors, and consequently the whole system. Therefore, to avoid such situations all factors must be considered properly to get optimum results. The following section will mainly emphasize the effects of defoliation and irrigation on performance of lucerne as these issues are comparatively most crucial in southern Australia.

2.5.1 Defoliation

Defoliation is an important aspect of management for forage yield, quality and stand persistence in lucerne. Once established, lucerne is a hardy plant, capable of surviving many years. However, proper defoliation management is essential to ensure long stand-life and to obtain optimum quality production. There are a number of factors affecting cutting intervals including soil moisture and fertility level, winter dormancy level, morphology, day length, temperature, season and age of the stand. Moot *et al.* (2003) have identified specific defoliation schedules for different seasons based on physiological processes and soil water patterns. These authors suggest that during spring and summer, defoliation should be at the appearance of open flowers or basal buds, whereas during autumn an extended period of flowering was required to allow sufficient recharge of root reserves. In cooler months when flowering is inhibited due to changing day length and temperature the appearance of new shoots (2 cm in length) from the crown should be used as the indicator of when to cut under Australian conditions (Stanley and Christinat 1994). Frequent cutting can have not only aboveground impact on yield and growth but also physiological implications for below ground root reserves, with subsequent implications for stand life and N_2 fixation. These effects are described in the following sections.

2.5.1.1 Defoliation - effects on persistence

Although lucerne is a hardy plant once established, adult plants are susceptible to poor grazing management, and prolonged mismanagement will lead to plant death. Judd and Radcliffe (1970) argued that persistence and production of lucerne is influenced by frequency of defoliation. Various researchers supported these findings (Leach 1970, Sheesley *et al.* 1972, Lodge 1986, Avice *et al.* 1996). Different researchers have established different criteria or schedules for harvesting of lucerne for optimum yield and longer stand life. These schedules are based on stages of growth, fixed time intervals and crown shoot development. Gramshaw *et al*. (1993) found that a 5-6 week cutting interval all year promoted persistence, yield and quality under irrigated conditions in Queensland. Crowder *et al*. (1960) and Gramshaw *et al*. (1981) recommended that the cutting of winter active cultivars in subtropics should occur when the new crown shoot begins to elongate. In another defoliation-scheduling study, yield was higher in 35-day cutting frequency in years 1 and 2, because 28-day cutting frequency invited weed invasion, ultimately effecting persistence under irrigated conditions in New South Wales (Lodge 1986). Similarly in a dryland lucerne experiment, Lodge (1985) found that 10% bloom or 6 week cutting frequency was appropriate for yield and plant survival irrespective of winter or summer activity level of the cultivars. Cutting lucerne at the pre-flower bud stage, a stage where nodes are with buds but no flower (Fick *et al*. 1988) rather than 10% bloom gave increased protein content and digestibility but decreased the plant stand markedly under irrigated conditions in Victoria (Slarke and Mason 1987). In summary, the weight of evidence supports cutting according to stage of development (10% bloom) over cutting at fixed intervals, in obtaining consistent forage yield, quality and longer stand life.

2.5.1.2 Defoliation - effects on roots

Improper defoliation affects shoot productivity in lucerne and has long-term deleterious impacts on root growth. Since it has been established that the defoliation treatment or cultivar having the highest root biomass and the greatest content of organic reserves gave the most rapid and extensive regrowth (Avice *et al*. 1997). Pearce *et al*. (1969) indicated a minor reduction in fine root mass after defoliation but a clear reduction in biomass of taproot in lucerne. Whereas, Pietola and Smucker (1995) reported that root development was more likely to be modified with season and age of stand than with defoliation in lucerne. Khaiti and Lemaire (1992), whilst estimating RUE on the basis of aerial biomass in various growing seasons, found different values of 0.4 g MJ^{-1} for the growth period after seeding; 0.9 g MJ^{-1} for summer regrowth and 0.7 g MJ^{-1} for autumn regrowth. However a constant value of 1.12 g MJ^{-1} was calculated for total biomass over three growth cycles. This confirms transfer of different quantity of assimilates in roots in different seasons indicating the seasonal impact of cutting on yield and root reserves. Earlier, Graber *et al*. (1927) revealed that root growth and distribution were influenced by harvest practice in lucerne. They further noticed that in unharvested lucerne, root dry matter yield increased throughout the growing season in the presence of adequate moisture, while there was little root mass increase with periodic harvesting at bud stage. Hodgkinson *et al.* (1969) further confirmed these findings and concluded that as a result of harvesting, rate of root extension and depth of root were markedly reduced in a 302 day old lucerne stand. Luo *et al.* (1995) concluded that frequent defoliation reduced root mass in summer but showed an increase in autumn from the prolonged growth rate in lucerne due to the decreased photoperiod. In a defoliation study of lucerne, Gramshaw *et al.* (1993) observed a considerable reduction in biomass of taproot of lucerne after defoliation, which could be overcome with the adjustment of defoliation time up to 5-6 weeks intervals.

Overall it appears that defoliation substantially reduces root growth in lucerne, although in water-limited (semi-arid) environments the influence of defoliation is likely to be confounded by interactions between defoliation, age of stand and season. The specific effect of season, and particularly rainfall, on lucerne root dry matter accumulation and distribution for dryland areas of southern Australia is not well documented. The work in this thesis therefore aims to provide data concerning lucerne root mass and distribution over a two year period in relation to water supply.

2.5.1.3 Defoliation - effects on carbohydrate reserves (TNC)

It has been established by a number of researchers (Section 2.5.1.1 and 2) that the stage of growth at which the shoots are harvested has a crucial impact on subsequent forage production and plant population of lucerne. Low levels of root reserves (carbohydrates), that are associated with frequent cutting (Hodgkinson 1969) diminish plant regrowth potential, influence yield of lucerne, and ultimately reduce stand life (Kust *et al.* 1961, Feltener and Massengale 1965, Cohen *et al.* 1972, Avice *et al.* 1996). This is because energy for lucerne regrowth originates from stored root starch and sugar reserves in roots and crowns or from residual leaves and stems which is collectively call (TNC) total non-structural carbohydrate (Sheaffer *et al.* 1988, Robison and Massengale 1968). TNC storage and utilization in lucerne roots and crown follows a cyclic pattern, decreasing just after defoliation and increasing with plant maturity to a maximum at flowering (Smith and Nelson 1967, Smith and Marten 1970, Cohen *et al.* 1972, Volenec *et al.* 1996). Pearce *et al.* (1969) observed a sharp decline in root carbohydrates after periodic cutting. In contrast, Brown *et al.* (1990), found no effects of harvest schedule on root carbohydrates in lucerne in USA. Soil moisture level also plays a vital role in storing and depletion of root reserve after cutting. Adequate soil moisture maintained close to field capacity just after harvesting doubled the rate of growth and decreased the TNC level 8 fold compared to the treatment where the irrigation was withheld for 10 days (Cohen *et al.* 1972). Therefore, a suitable defoliation schedule according to seasonal and climatic requirements is pivotal for optimum herbage yield and stand life in lucerne. The present study will define the impact of cutting and soil moisture level on carbohydrate reserves in roots, and will relate this to persistence, and ultimately productivity, on a seasonal basis.

2.5.1.4 Defoliation - effects on nitrogen fixation

Quantity of N_2 fixation is positively correlated with above and below ground dry matter production in lucerne (People and Baldock 2001). Therefore, the management factors which improve growth and yield also can enhance N_2 fixation (Carter and Sheaffer 1983). Defoliation management has been demonstrated to be a very important factor determining dry matter production and N_2 fixation in lucerne (Vance *et al.* 1979, Wivstad *et al.* 1987). Defoliation reduced N_2 fixation because of removal of the photosynthetic source necessary for maintaining N_2 fixation and nodule formation (Moustafa *et al.* 1969). A decrease in nodule number after shoot removal is amongst the causes of decline in N_2 fixation (Wilson 1942). In addition to this, Vance *et al.* (1979) observed an 88% reduction in nitrogenase activity (acetylene reduction) in lucerne within 24 hours after cutting.

Other studies emphasised in a different way the importance of photosynthate supply to N_2 fixation in lucerne. Sticker and Johnson (1959) found that non-dormant lucerne (i.e. winter active) produced greater dry matter and total plant N yields than the winter dormant cultivar when both types were not harvested in the seeding year. Whereas Groya and Sheaffer (1985) noticed no difference in total plant N between dormant and non-dormant cultivars of lucerne when cut 3 or 4 times in the seeding year. Cutting at bud or early flower stage of growth was found to be the most appropriate time for maximising benefits from N_2 fixation (Wivstad *et al.* 1987). Extreme climatic variability in any region may complicate any simple relationship between photosynthate supply and N_2 fixation.

Nitrogen input to the soil during a season of lucerne growth will consist of contributions from senescent shoot material, dead roots, nodules and any rhizodeposits. There are conflicting reports concerning the effect on inputs of N to soil in relation to frequency of defoliation. Smith (1967) suggested that frequent cutting, particularly in the seeding year of lucerne, reduced plant N inputs to the soil. Others argued conversely and established that cutting has little effect on N input to soil (Groya and Sheaffer 1985). Variability in results reported is probably due to effects of soil type, climate or plant age (Hesterman *et al*. 1986).

Root biomass of the lucerne crop plays an important role in N input to the soil (Section 2.4.2.1). Therefore, cultivars having greater root dry matter yield are capable of adding more N to the soil (Hesterman *et al*. 1986). Furthermore, these authors reported that cultivars with greater root dry matter added 84% (157 kg ha^{-1}) more N under a one-cut system than a three cut system (85 kg ha^{-1}). Reports of N input to soil during the seeding year of lucerne, when both defoliation events and dead leaf inputs would be minimal, range from 35 to 305 kg ha^{-1} (Sticker and Johnson 1959, Groya and Sheaffer 1985). The argument is that the management strategy which is capable of enhancing shoot and root growth may improve N input to the soil under lucerne.

The proposed study aims to define N inputs to soil by lucerne for different seasons in a Mediterranean climate by measuring changes in soil mineral N in relation to soil moisture content.

2.5.2 Irrigation

Lucerne in arid and semi-arid regions of Australia is mainly grown under dryland conditions (3.5 M ha) with the major objectives of optimising productivity, water use, improving soil fertility and increasing farm income. The soil moisture potential in some of these areas is usually less than -1500 Kpa (wilting point) at 0.2 metre from January-April and can remain less than -1500 Kpa at depths greater than 1 metre throughout the year (Snaydon 1972). Generally, therefore, forage yield over summer is low. In addition to this, summer rainfall in most Mediterranean climate zones of southern Australia is low (<100 mm), highly variable, ineffective and therefore considered as having little agricultural benefit (Cawood and McDonald 1996). In environments where water is the main limitation, other factors such as variety and nutrient inputs are less important than in regions where irrigation can be provided (Turner and Begg 1981). Clearly the addition of supplemental water through irrigation can increase total forage yields and economic output by providing a more uniform seasonal distribution (Kilmer *et al*. 1960, Bauder *et al*. 1978, Cameron *et al*. 1990). Indeed, a significant area of pure lucerne stand is being grown (192,000 ha; Irwin 2001) under full time or supplemental irrigation around Australia. Approximately 26,000 ha is grown annually in all major districts of South Australia (Irwin 2001) for hay, seed and cube production for local and export markets (Fairbrother and Thomson 1991).

The water requirements of irrigated lucerne are high (about 1000 mm $ha^{-1}yr^{-1}$) and there are serious concerns over possible negative impacts on soil and water resources. Furthermore, water resources available for irrigation are under extremely high demand for high value crops and it is highly unlikely that significant water resources will be made available for irrigating relatively low value commodities like lucerne. However, for those areas already irrigating lucerne the opportunity to improve water use, through the use of high frequency surface or sub surface drip irrigation, can offer the dual advantages of increased forage yield with a less detrimental effect on soil degradation compared to more conventional irrigation techniques (Hutamacher, *et al*. 1996, Ayars *et al*. 1999). The adoption of such practices will be driven by the need to improve water use efficiency as supplies of water increasingly become more expensive.

2.5.2.1 Irrigation effects on yield

Irrigation has been demonstrated as a means of increasing production where soil moisture is limiting (as discussed briefly in Section 2.2.3), and yield increases from 14 to 300% have been observed under varied climatic conditions (Snaydon 1972, Bauder *et al*. 1978, Brown and Tanner 1983, Carter and Sheaffer 1983, Saeed and Al-Nadi 1998). Indeed, a 68% loss in yield occurred when irrigation was withheld for only one growth period in the summer month of July in Cyprus (Metochis and Orphanos 1981). Dry matter yields of lucerne in Australia under irrigated conditions can approach 30 t $ha^{-1}yr^{-1}$ (Dickson and Asher 1974), although slightly lower yields ranging from 15-21 t ha^{-1} yr^{-1}

are more commonly reported (Lowe *et al.* 1985). The effectiveness of irrigation for increasing lucerne yield will be highly dependent on soil type and environment. There are no reports of the influence of increasing soil moisture by irrigation on lucerne growth for areas of southern Australia with Mediterranean climatic conditions and duplex soils. Largely this will be because irrigation is not considered a commercially viable proposition for many of these situations. However, in the study reported by this thesis, the use of irrigation to manipulate soil moisture provides a useful tool for investigating the response of lucerne to a wide range of soil moistures over a limited time period. A subsidiary use for the data generated is that the efficiency of the different irrigation systems can be compared, thus providing some idea of just how prohibitive the potential costs for irrigation in these semi-arid areas might be.

2.5.2.2 Irrigation effects on root development

Root morphology and development of lucerne in relation to water use has already been discussed (Section 2.2.5.2). Irrigation represents an opportunity to modify the root characteristics of lucerne (Cooke and Willatt 1983), since lucerne roots will normally follow the pattern of available soil water (Paltridge 1955). Surface irrigation has been shown to improve lucerne root mass and water uptake (Abdul-Jabbar *et al.* 1982). Lucerne roots are also capable of withdrawing soil water from the lower portion of the root zone when it is relatively dry (soil matric potential between -700 Kpa and -1000 Kpa) compared to the upper portion of the profile (> -200 Kpa) (Kohl and Kolar 1976). However, most of the reduction in soil water content via evaporation occurs in the upper 200-300 mm whereas sub-soil water is only slowly subjected to evaporation loss (Handerson 1979). This will particularly be the case for supplemental surface irrigation applied over summer in semi-arid environments. Therefore, placing of water below the surface with drip irrigation appears a more efficient option in this regard and will cause a different root pattern in lucerne (Plaut *et al.* 1996). An irrigation system that can place water below the soil surface at a rate that soil and adjacent roots can absorb has the potential to improve water use efficiency, although a surface irrigation system, that can deliver water at a rate that soil surfaces can absorb, can also improve water use (Hillel 1990). Optimisation therefore, is imperative and this can only be achieved with permanent installation of low intensity irrigation systems like sprinkler, dripper, micro-sprayer and sub-surface (Bucks *et al.* 1982).

2.5.2.3 Irrigation effects on plant population and persistence

Careful management of irrigation, and subsequent changes in soil moisture, is essential since over or under-supply of water can reduce yield, quality, stand density and longevity in lucerne, and ultimately profitability (Doorenbos and Kassam 1979, Donovan and Meek 1983). Initially, it was generally believed that less frequent, deep irrigation of lucerne could be more effective to reduce application and evaporation losses (Kemper and Amemiya 1957, Musick *et al.* 1963, Ekern *et al.* 1967, Jodari-Karimi *et al.* 1983) and also to extend stand life. However, many researchers have confirmed that more frequent light irrigation events attain higher yield, greater water use efficiency and longer stand life in lucerne (Snaydon 1972, Carter and Sheaffer 1983, Whitfield 1986, Saeed and El-Nadi 1997). Frequent light-irrigation improves leaf expansion, light interception and consequently yield of lucerne and root reserve maintenance (Whitfield *et al.* 1986).

Although irrigation generally increases lucerne yield (Section 2.2.3), an associated decline in plant persistence and production in the long-term has been reported (Schonhorst *et al.* 1963, Doorenbos and Kassam 1979, Donovan and Meek 1983). Losses may be greater for some varieties of lucerne than others (Wahab and Chamblee 1972). Sheaffer *et al.* (1986) attributed stand loss in irrigated plots to the severe winter conditions in Minnesota, USA. Although flooding has been a reported cause of reduced plant population during summer in Queensland (Tow 1993), no stand losses were incurred from over-irrigation in lucerne in other studies (Follet *et al.* 1974, Petterschmidt *et al.* 1979). Stand losses under irrigation have also been associated with frequent cutting (Lodge 1986, Slarke and Mason 1987 Gramshaw *et al.* 1993), warm summer days (Feltner and Massengale 1965), and warm summer nights (Robison and Massengale 1968). Conversely, irrigation significantly reduced the rate of decline of lucerne population and increased dry matter yield (Cameron *et al.* 1990). The effects of irrigation are influenced by many environmental and management factors and need to be defined for the particular climatic and edaphic conditions characteristic for lucerne growing areas in southern Australia.

Root carbohydrate storage is a key factor in the response of stand density and persistence to irrigation. Depletion of root carbohydrates of lucerne under irrigated conditions, coupled with high temperature forcing more rapid growth could contribute to stand loss

(Rice *et al.* 1989), which supports the theory that irrigation promotes growth that may deplete root carbohydrates. In contrast, in a recent field study Ottman *et al.* (1996), found that summer irrigation termination resulted in decreased root carbohydrates, yield, as well as stand life, although the two were not positively correlated. McCallum (1998) quantified 75-83% of assimilated carbon was partitioned belowground to roots and crown under water stress during summer in dryland lucerne. The reported variability in persistence supports the need for further exploration of this issue around the causes of yield and stand decline of lucerne under summer irrigation as well as through the year.

2.6 Simulation of growth, development and water use in lucerne

2.6.1 Simulation modelling

Models are the simplification of some aspects of reality and the aim of models used in applied or social science is to represent an understanding of the way a system works, and also to provide an insight into the dependence of the particular process or phenomena as an element of the system (Hook and Fleming, 1998). There is a long history of modelling in agriculture and use of these efforts has certainly led to improved scientific understanding of crop behaviour under field conditions (Sinclair and Seligman, 2000).

In terms of economics the simulation models have also been advocated as useful and cost effective tools to examine and devise management strategies for crops and soil under a wide range of agro-environments (Anderson *et al.* 1998, Huda, 1986, Probert *et al.* 1998, Keating *et al.* 2003). Choice of appropriate management strategies has always been difficult and in the presence of soil and crop diversity, coupled with a range of seasonal variability, it becomes a further complex issue (Asseng *et al.* 1998a, Probert *et al.* 1998). Modelling is considered the only approach potentially capable of integrating the complexity of regional landscapes and catchments into decision-making, taking into account the management options and climatic variability (Barnett *et al.* 1996). Further, simulation is a means of extrapolating the knowledge derived from experimentation from one site to other areas, soil types or seasons if successful prediction can be achieved (Asseng *et al.* 1998b, Probert *et al.* 1998b).

Generally, the objectives of crop growth models have been prescribed as explanation, calibration, validation, prediction, hypothesis comparison and universality (Fick *et al.* 1988, Pielou 1981, Sinclair and Seligman, 2000). The working philosophy of a computer model has been denoted by a model developer as "cause-and-effect manner by linking the environmental cause to physiological effects that modify calculated growth process" (Fick *et al.* 1988).

2.6.2 History of growth modelling in lucerne

There is long history of using models for lucerne growth internationally, and a list of the most widely known models along with their authors/developers and the objectives for which they were usually used is given in Appendix: A. It shows that a series of models have been developed during 1970 through 1980 to simulate lucerne growth and development and Penning de Vries (1982) classified these models as preliminary, comprehensive or summary in nature. Preliminary models were a very basic type of model in which simple environmental influences on growth and development were explained briefly. The LEVEL-0 and Gosse model are examples of preliminary models (Appendix A). Comprehensive models provided much more detail about the processes being simulated e.g. Alfalfa and SIMID (Fick *et al.*1988). Whereas summary models were a brief form of comprehensive model, usually used for extrapolation and accuracy, and ALSIM is an example of this type of model (Appendix A). However, as time progressed, the fact that most of these models were little used indicates their lack of applicability, probably due to limitations in 'handling' complex plant functions and the environmental interactions.

Some of the recently developed lucerne models like APSIM-Lucerne appear, in some circumstances, to be able to more accurately predict growth, yield and the impact of lucerne on the soil-water system in different agro-climatic-regions of the world. They have been used to extrapolate results for longer periods of time and wider sets of environments, to assess the impact of lucerne productivity on system sustainability.

2.6.3 APSIM (Agriculture Production System Simulator)

The Agricultural Production System Simulator (APSIM) is a software system that derives various inputs from different modules of crop and pasture production, residue decomposition, soil water and nutrient flow, and erosion, to be readily configured to simulate various production systems (McCown *et al*. 1996, Probert *et al*. 1998b, Keating *et el*. 2003). The key theme of the APSIM modelling framework that distinguishes it from single crop models denoted by Probert *et al*. (1998) "*is the central position of the soil; crops, seasons and managers come and go, finding the soil in one state and leaving it in another*". According to Keating *et al*. (2003) the main objective of APSIM development was to simulate different biophysical processes in farming systems focussing especially on the economic and ecological outcomes of management practices, with a focus on quantifying climatic risk. There is diversity in applications of APSIM because it has sets of modules that can be selected according to the needs of the users. A recently developed APSIM-Legume module has wide scope and is well suited to simulate many legume crops, pasture and forages including lucerne under irrigated as well as dryland conditions (Probert *et al*. 1998). The application of APSIM-legume has been accepted and verified for a variety of legumes in Australia (Robertson *et al*. 2002). Other researchers, while studying the behaviour of water and nitrate-N in cracking clay soil under legume cereal systems found APSIM was suitable to predict the movement of water, mineralisation of N and redistribution of nitrates (Probert *et al*. 1996). Similarly, Asseng *et al*. (1998) working on wheat indicated that the model successfully predicted soil water content, evaporation, deep drainage and overall NO_3^- leaching on deep sand in Western Australia. Herridge *et al*. (2001) used APSIM's simulation analysis to suggest that N_2 fixation improvement in soybean will be more successful through agronomic management rather than breeding. In soil water balance studies under grass legume pasture, Lilley *et al*. (2003) reported that biomass, yield and crop N uptake were well simulated by APSIM, however it is important to note that they stipulated that water balance and soil mineral N required initial re-setting each year. Yunusa *et al*. 2004 reported that NWHEAT and SOILN2 modules satisfactorily predicted above-ground growth and yield of grass/medic and wheat rotations, as well as soil water, but under estimated soil nitrogen. Keating *et al*. (2002) used the model to assess the water balance in different farming systems over the longer term and over wider range of sites in various agro-ecological zones and has shown that water accumulation under annual-based farming systems was more than the systems having perennial forages like lucerne. Robertson *et al*. (2002) tested a generic approach, using chickpea, mungbean, peanut and lucerne to further develop APSIM's performance and found that it was capable of predicting these diverse types of annual legumes with similar accuracy, but as a single crop.

These examples demonstrate that simulation modelling using APSIM has been explored for cereals and legumes grown on various soil types under different environmental conditions in Australia, although not for lucerne in South Australia. There are some studies in other regions of Australia detailing the performance of APSIM predictions for growth in lucerne. Probert *et al*. (1998) found that APSIM-modelling for lucerne was realistic for some treatments but highlighted the need for it to be tested under a wide range of environments especially under water stress conditions. In an integrated modelling study, it has been found that lucerne can reduce the rates of groundwater recharge and therefore, areas of salinized land (Pavelic *et al*. 1994, Dolling *et al*. 2007). Dolling *et al*. (2001, 2005) confirmed the ability of APSIM to predict lucerne growth in Western Australia after some parametric adjustments but they also suggested rigorous testing before it can be used to interpret production in a wider range of environments. Moot *et al*. (2001) also tested APSIM-lucerne performance for phenological development in the cooler climate of New Zealand and found that accurate predictions were parametric modification dependent. Relatively poor performance of APSIM-lucerne in this cooler environment was attributed to perennial aspects of the crop that are different to an annual crop. Chen *et al*. (2003) reported APSIM's satisfactory performance in predicting growth under highly winter dormant growth conditions in central western China, although a requirement for RUE adjustment was noted as the effect of cutting on biomass partitioning to roots is currently not included in the model. On the basis of these evaluations of APSIM-Lucerne it is apparent that the model has the potential to accurately predict lucerne growth, development and water use. However, it is also apparent that the model requires significant evaluation and local parameterisation before model output can be used with confidence.

2.7 Summary

The review has discussed the importance of lucerne, particularly for addressing some inadequacies of the unsustainable practices present in farming systems of South Australia currently based on annuals. It has highlighted the adaptation and constraints to production from lucerne, particularly in relation to the Mediterranean type climate of the region: it is a deep-rooted perennial, with a wide range of cultivars that can exploit subsoil moisture and tolerate drought, capable of fixing large amounts of N_2 under a wide range of edaphic conditions.

The review has also highlighted that data are not available in South Australia particularly, and to some extent in other regions, for:

1. Potential productivity of lucerne in response to summer rainfall events and there is also limited productivity data for all the seasons.
2. RUE under variable water supply and stressed environmental conditions.
3. Effect of environmental conditions (especially temperature and rainfall) on phenological and morphological development in lucerne shoots.
4. The relationship between root distribution and soil water extraction pattern, especially in duplex soils.
5. Quantification of the water-yield relationship in lucerne in an environment with extremely erratic and variable rainfall
6. Seasonal nitrogen fixation and subsoil NO_3^- utilization by lucerne.
7. Evaluation of the performance of APSIM-Lucerne under local conditions and the requirement for local parameterisation of the model.

Chapter 3

3 Seasonal shoot and root productivity in lucerne under semi-arid Mediterranean climatic conditions in response to varying water supply during summer

3.1 Introduction

The main determinants of growth, development and yield in lucerne (Section 2.2.4 & 2.2.4.1) are sensitive to climatic and edaphic factors. Crop canopy is very important since shoot yield in lucerne is linearly related to amount of solar radiation intercepted by the crop canopy during each regrowth cycle (Goose *et al*. 1984a), although this linear relationship only holds when temperature is favourable and water supply is not limiting growth (Brown *et al*. 2003). Lucerne growth rates increase with increasing temperature, and is higher in spring than autumn, showing seasonal variation (Moot *et al*. 2003), caused by differences in the relative allocation of carbohydrates between shoots and roots (Khaiti and Lemaire 1992). The effect of climate on growth components and processes of lucerne, and consequently on dry matter production, has been reported in many regions of the world (Carter and Sheaffer 1983, Brown and Tanner 1983, Grimes *et al*. 1992, Saeed and El-Nadi, Moot *et al*. 2003, Brown *et al*. 2006, Teixeira *et al*. 2007). Current research outcomes in Australia however, do not provide sufficient information concerning performance of lucerne under the highly variable conditions imposed by Mediterranean-type climate experienced in many of the agricultural regions in southern Australia. In particular the implications of extremely hot dry summers for productivity and persistence of lucerne are not fully understood, although potentially, the productivity of perennial lucerne pastures can exceed that of annual medic pastures in areas of WA and Victoria with Mediterranean-type climate (Lyons 2001, McCallum 2000, Latta, *et al*. 2001).

Radiation use efficiency (RUE) is considered useful as an independent physiological parameter to assess crop performance, to highlight yield limitations and also as a powerful tool to understand crop growth, especially in the context of environmental influences (Sinclair and Muchow 1999). Radiation use efficiency (RUE) is also the basis of many crop models like APSIM. Most of the studies on RUE (reviewed in Section 2.2.4.3) reported a wide range of RUE values even under non-stressed environmental conditions. There is pressing evidence that the application of such values is not justified under resource-limited conditions (Collino *et al*. 2005) and that estimation of RUE for specific stress environments such as the variable soil water deficits characteristic of Mediterranean climates, particularly over summer, is required.

Roots are pivotal for water and nutrient acquisition for plant growth and development, and hence for productivity and persistence of lucerne stands. Roots therefore play a vital role in the success or failure of any lucerne stand, as well as contributing to the long-term fertility of the soil via inputs of organic matter as dead roots and rhizodeposits. Results from research concerning the interaction between available soil moisture and lucerne root growth are largely from laboratory studies, or have been conducted under climatic conditions not applicable to southern Australia (Section 2.2.5) Further, there have been very limited reports concerning the quantitative relationship between soil water and lucerne root distribution in the soil profile, especially for texture contrast (duplex) soils typical of regions of SA, where root growth may be impeded in the sub-soil. Additionally, soil water, air temperature and defoliation all affect the quantity of total non-structural carbohydrate (TNC) in lucerne taproots, which in turn, has major implications for regrowth, yield and stand persistence (Sections 2.5.1.3 & 2.5.2.3). Whilst the relationship between TNC in taproots and lucerne growth and development has been explored relatively widely for many regions around the world, conflicting and inconclusive results suggest that this issue needs to be clarified for Mediterranean climatic conditions under variable water supply.

As mentioned in the literature review, in some regions lucerne is being grown economically under dryland conditions whereas in other regions economic production requires supplemental irrigation (Section 2.5.2). Although there are serious concerns about negative impacts of irrigation on soil and water resources. Further, there is intense competition for water used for irrigating high value crops rather than relatively lower value commodities like lucerne. However, high frequency surface or sub surface drip irrigation, offer the dual advantages of increased forage yield with a less detrimental effect on soil degradation compared to more conventional flood and/or overhead sprinkler irrigation techniques (Hutamacher, *et al*. 1996, Ayars *et al*. 1999).

The major aim of the work reported in this chapter was to collect quantitative agronomic data describing the impact of different amounts of water supplied during summer on shoot production and root growth of lucerne growing under Mediterranean climate conditions on a duplex soil over a two-year period.

3.2 Materials and Methods

3.2.1 Experimental site - climate and soil details

The field experiment used as a basis for the work reported in this thesis was conducted on the Roseworthy Campus Farm, The University of Adelaide, located approximately 50 kilometres (34°32′S, 138°45′E) north of Adelaide in South Australia. This study was carried out on a paddock sown to lucerne variety ‘Sceptre’ in June 1998, and was grazed intermittently by deer herds until just prior to the start of this study in December 1999. The soil at the site is classified as a deep, loamy/clayey, medium non-gravelly, supercalcic, sodic red chromosol (Isbell 1996) or a Natrixeralf in the order Alfisol (Soil survey Staff 2006). It is a dark brown sandy loam duplex characterised by sandy-to-sandy loam surface having 150 mm A-horizon. The B-horizon consists of medium textured, moderately well drained and fertile sandy loam of variable depth (400-600 mm), overlying a layer of abundant soft to rubbly carbonate that graded into calcareous clayey deep subsoil. Morphologically these soils are a bimodal group having a large accumulation of lime in the profile essentially derived from the highly calcareous material in the lower part of the profile. Some soil physical and chemical properties measured at the site are given in Table 3.1. Bulk density, measured to 1800 mm, was lower in the top 700 mm (<1.30 Mg m^{-3}) but due to the texture change at this point increased abruptly to 1.41 Mg m^{-3} and was 1.59 Mg m^{-3} deeper in the profile; bulk density above 1.4 are considered to impede root growth (Bengough and Mullins 1990). The soil was alkaline at the surface (pH_w=8.5) and extremely alkaline at depths below 600 mm (pH_w>9.0) due to the large amounts of carbonate. Boron concentrations ranged from 2 to 19.1 mg kg^{-1} (Table 3.1) with those above 15 mg kg^{-1} found at 1600 mm and deeper considered toxic for field crops and pastures (Moody 2003, Maschmedt 2004, Adcock *et al*. 2007). Electric conductivity (EC) was <0.2 dS m^{-1} in the top 700 mm (unlikely to be a problem for any but highly sensitive species) but thereafter gradually increased with depth and ranged from moderately to very saline (0.45-0.84 dS m^{-1}) which can cause growth reductions in even salt tolerant plants (Merry 1996).

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

Depth	**Bulk density**	**Boron**	**C_{org}**	**$CaCO_3$**	**N**	**pH_{CaCl2}**	**EC (1:5)**	**ESP**
mm	Mg m^{-3}	mg kg^{-1}	%	%	%		dS m^{-1}	
100	1.30	2.0	0.9	5	0.15	7.74	0.13	1.2
300	1.23	1.8	0.2	14	0.07	7.84	0.14	2.0
500	1.24	3.2	0.3	34	0.05	7.91	0.16	2.5
700	1.26	7.5	0.1	50	0.03	8.10	0.19	9.0
900	1.41	10.4	0.1	53	0.02	8.20	0.45	64.3
1200	1.49	12.7	<0.1	65	0.02	8.40	0.63	64.3
1600	1.56	15.2	-	-	-	8.80	0.72	44.2
2000	1.59	19.1	-	-	-	8.65	0.84	44.2
2400	1.59	-	-	-	-	-	-	-
2800	1.59	-	-	-	-	-	-	-

Threshold value above which lucerne root function likely to be impaired;
(B:15 mg kg^{-1}); (pH_{CaCl2} :8), (ESP:15) (EC:0.2 dS m^{-1}) (BD:1.4 Mg m^{-3})

The climate of the region is described as semi-arid Mediterranean type with typically hot dry summer periods and mild wet winters. The growing season for the site (Lower North land division) is usually considered April-October (French and Schultz 1984, Yunusa *et al.* 2004). However, for the purpose of this study the term growing season (covering autumn-winter and spring) is applied to the period April-November during which no irrigation was used; and the period December-March when rainfall was minimal and irrigation was applied, is termed summer. Average long-term annual rainfall (Figure 3.1) is 437 mm with 82% (355 mm) occurring in the growing season and only 18% (82 mm) occurring in the summer (Dec-Mar).

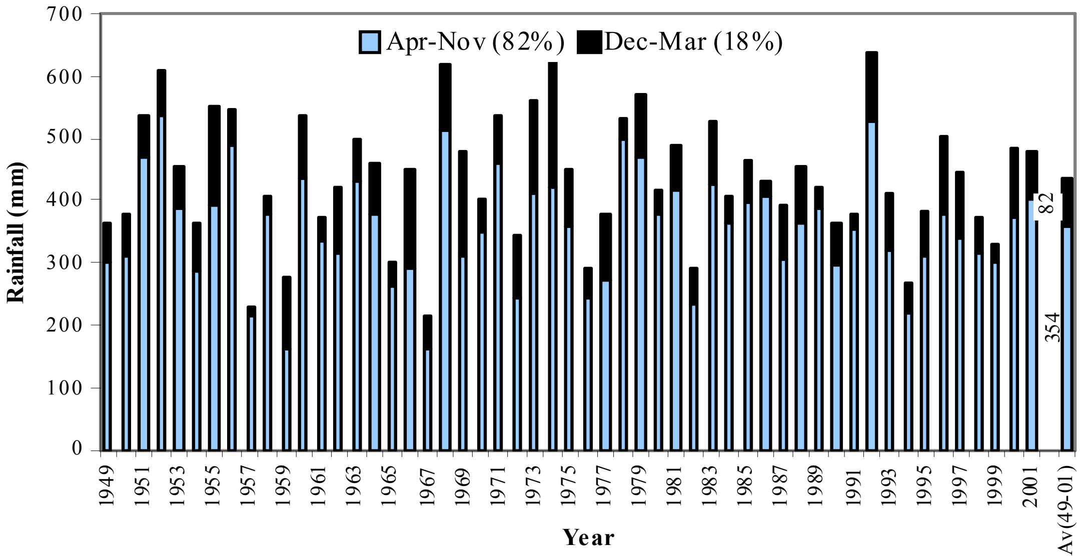

Figure 3.1 Long-term (1949-2001) annual, growing season (Apr-Nov) and summer (Dec-Mar) rainfall for Roseworthy Campus.

3.2.2 Treatments and design

Starting in December 1999 three treatments were imposed in a randomised complete block design experiment (Figure 3.2), replicated four times within a more than one-year-old established lucerne stand of winter active variety 'Sceptre' (sown in June 1998 using a seed rate of 5 kg ha^{-1}). A uniform plant density of 69 plants m^{-2} was measured just before imposing the treatments at various places in the proposed experimental area to assess uniformity of the stand. The area of each individual plot was 100 m^2 (10m x 10m, Figure 3.2), and each plot was separated from the next by a buffer zone of at least 5 m. The three treatments, designed to enable the simulation of various soil moisture regimes, were:

1. Rainfed (R_{fed})
2. Sub-surface irrigation (I_{sub})
3. Sprinkler irrigation (I_{surf})

Rainfall was the sole source of water for the R_{fed} treatment whereas additional water was supplied by irrigation for the other two treatments. Two different types of irrigation system, namely sub-surface drip and over-head sprinkler/surface, were installed during late autumn 1999 with the assistance of Trevor Eden of Greene Eden Watering Systems Pty Ltd, South Australia.

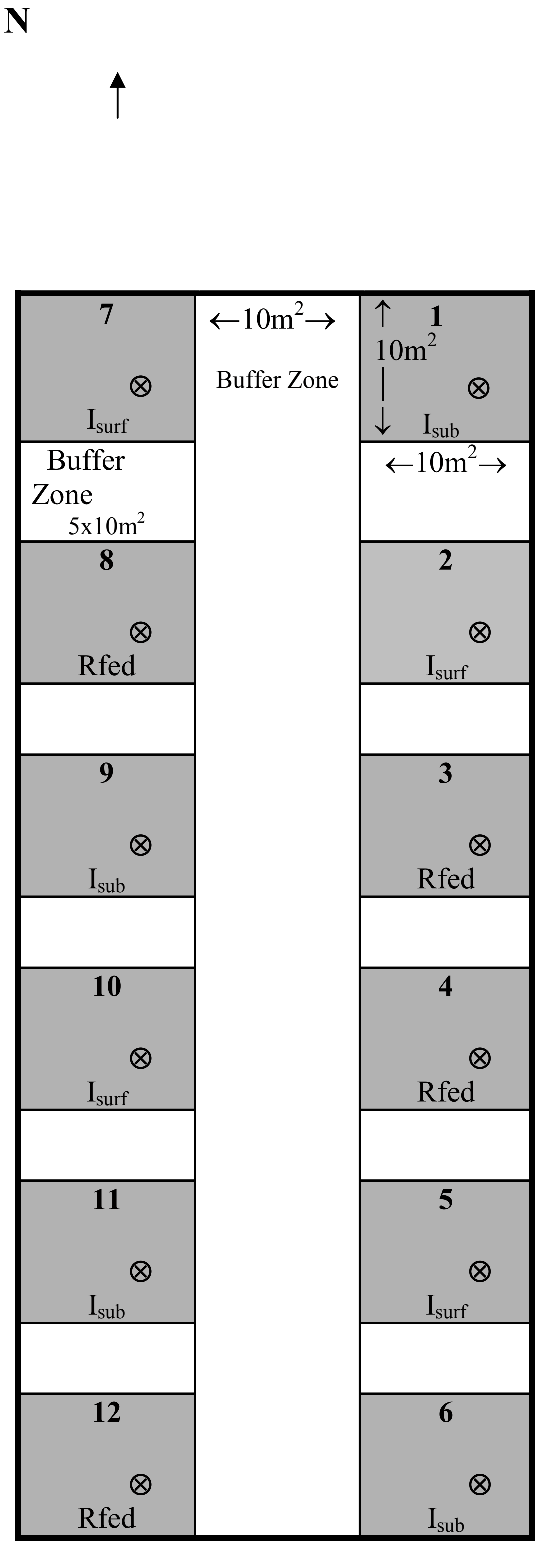

Figure 3.2 Randomised Complete Block Design of the lucerne experiment during the study period (Dec 1999-Sep 2001) at Roseworthy Farm site.

The subsurface drip irrigation system was installed very carefully at a depth of 35-40 cm in the soil with minimal observed impact on the established lucerne plants. It consisted of PVC pipe (diameter 32 mm) at intervals of 1 m apart, running in rows across the length of the plot (north-south). There were mesh-covered holes (16 mm diameter) at intervals of one m on the underside of the pipe for delivering water and a pressure valve (15 Psi) was also installed to ensure water was supplied at a constant rate across the plots equivalent to 2.5 mm hour^{-1}. For the surface irrigation system PVC pipes (32 mm diameter) were installed below the soil surface (40 cm) around the plot and an over-head sprinkler was fixed on each corner of the plot, at a height of 50 cm. A pressure valve (30 Psi) was also installed in this system to maintain supply of water at a constant rate of 23.5 mm hour^{-1}. The irrigation systems were both automatically controlled by a single timer and solenoid system manufactured by Boss (United States of America). Water was supplied from the domestic South Australian water supply system. During 1999-2000 summer the conditions were frequently hot and windy during irrigation and this sometimes caused drift effects in the surface irrigation treatment. However, during summer 2000-2001, for the majority of irrigation times, spatial uniformity of water delivery from both irrigation systems was inferred from the uniformity in crop growth responses observed across plots (Plate 1).

Plate 1 View of different treatments of lucerne experiment during March 2001 where rainfed lucerne (R_{fed}) looks very dry, experienced no effective rainfall event during this period and supplemental water applied over this period was very limited (60-65 mm) per regrowth cycle in I_{sub} and I_{surf} respectively.

The amount of water received via irrigation (bars) and by rainfall (line) in all the treatments during each of the four major periods of this study is shown in Figure 3.3. Overall, in the first summer (1999-2000) 642 and 480 mm of water was applied to I_{surf} and I_{sub} treatments respectively. However, during each of three growth cycles in the following summer (January to end of March, 2001), 60 mm of water was applied over a three-day period (20 mm d^{-1}) for the I_{sub} treatment and 65 mm for I_{surf} treatment (Figure 3.3). A detailed irrigation scheduling is also given in Appendix C.

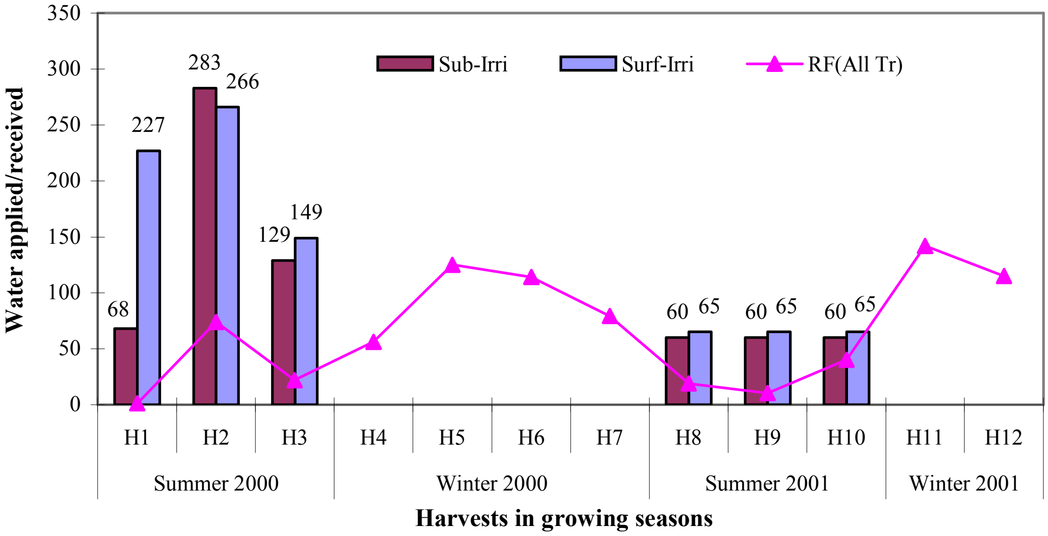

Figure 3.3 Water received (mm) through rainfall (presented in line for all treatments) or irrigation (presented in bars) at each growing cycle (H1-H12) from Dec 1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface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

3.2.3 Plant measurements

Growth parameters were measured on individual plants within fixed quadrats at three plant developmental stages for each growth cycle: (A) young shoot (juvenile), (B) late vegetative stage (flower initiation) and (C) 10% flowering (flowering) of main stem. These stages were separated by approximately ten-day intervals in summer and fortnightly intervals during the cooler growing season. Eight quadrats (0.25 m^2) were fixed per treatment (2 per plot) and the parameters given in Table 3.2 were observed. Also, LAI was measured by taking 12 observations per plot at the same three plant developmental stages in each growth cycle as other plant parameters, using a Plant Canopy Analyser LAI-2000 (LI-COR, Inc. Superior St. Lincoln, Nebraska 68504 USA).

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

Parameter	**Sample size**
No. of plants	0.25 m^2 (8 per treatment)
No. of stems	0.25 m^2 (8 per treatment)
Stem height	16 main stems per treatment
No. of nodes	16 main stems per treatment
Leave per stem	16 main stems per treatment
Leaf area index	12 observations per plot

3.2.4 Shoot dry matter and growth rate determination

Dry matter was estimated by taking four quadrats (0.25 m^2) per treatment in each growing cycle at 10% flowering of main stems in the plots. Plant material was cut to 50 mm above ground level for estimation of agronomic shoot dry matter productivity (yield) following regrowth. The remaining shoot residues were then also harvested to ground level from the same quadrat and the sum of the two (shoot material plus residues) was taken as total above ground shoot biomass for the purpose of the APSIM modelling (Chapter 6), for estimation of radiation use efficiency (RUE) and fixed N in shoots (Chapter 5). All the plots were harvested using a tractor-mounted harvester set to cut at 50 mm height from the ground. In total, seven cuttings (called harvests in this study) were taken in the 1st year (2000) and five in the 2nd year (2001) (Table 3.3). Each harvest date was the same for all plots and occurred when 10% flowering on the main stem was observed in any one treatment which meant that some treatments were not necessarily cut at the optimum time, especially in summer when there was often forced flowering in the rainfed plots. All plant samples were dried in an oven at 70°C to a constant weight.

Shoot growth rate (kg d^{-1} ha^{-1}) was estimated for each regrowth cycle for all treatments by dividing the herbage accumulated during the growth phase by duration of that period.

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

Date	Operation details
June, 1998	Sowing, Fertilizer application, 50 kg ha^{-1}, Super 0:20:0
10 September, 1998	Insecticide, Dimethoate for lucerne flea, red-legged earth mite control
5 November, 1998	Herbicides, Verdict for grasses
17 November, 1998	Insecticide for Sitona weevil
May, 1999	Fertiliser application, 50 kg ha^{-1}, Super 0:20:0
September, 1999	Herbicide, Broad strike for broad leaves weeds and Verdict for grasses
14 October, 1999	Insecticide, Dimethoate for insect control
19 January, 2000	1st cutting (H1) and soil sampling for soil mineral N
26 February, 2000	2nd cutting (H2)
28 February, 2000	Sampling for soil mineral N & root measurement
March, 2000	Fertiliser, 50 kg ha^{-1}, Super 0:20:0
31 March, 2000	3rd cutting (H3)
23 May, 2000	4th cutting (H4)
9 June, 2000	Soil sampling for soil mineral N
Jully, 2000	Herbicide, Broad strike for broad leaves weeds and Targa for grasses
30 July, 2000	5th cutting (H5)
August, 2000	Insecticide, Dimethoate for insect control
29 September, 2000	6th cutting (H6)
1 October, 2000	Sampling for soil mineral N & root measurement
23 November, 2000	7th cutting (H7)
12 February, 2001	8th Cutting (H8)
9 March, 2001	9th cutting (H9)
18 April, 2001	10th cutting (H10)
20 May 2001	Sampling for soil mineral N & root measurement
11 July, 2001	11th cutting (H11)
August, 2001	Herbicide, Broad strike and Fusion for broad leaves weeds and grasses
August, 2001	Fertiliser, 50 kg ha^{-1}, Super 0:20:0
19 September, 2001	12th cutting (H12)
8 October, 2001	Soil sampling for soil mineral N

3.2.5 Root measurement

Root sampling was carried out twice in the first year and once in the second year (due to time and resource constraints). At the first sampling (28th February 2000) sixteen soil cores (70 mm diameter) per treatment, eight directly over plants and eight in between plants, were taken to a depth of 1 m using a hydraulic rig. At the second sampling time (1st October 2000) cores (58 mm diameter) were taken to a depth of 1.20 m, and at the final sampling (18th July 2001) to a depth of 1.60 m. The cores were divided into 200 mm sections and individual sections were placed in a 'root-washing' machine to enable separation of roots from soil using the principle of hydro-pneumatic elutriation (Smucker *et al*. 1982). Roots were collected on a 1 mm sieve in the machine for the first year (sampling times 1 & 2), whereas at the final sampling a 0.5 mm sieve size was used to collect the roots. The roots from the sieves were further manually washed with water to remove organic matter and clay particles. They were then spread out in a tray containing water and images taken using a flatbed image scanner. The root images were analysed for length, diameter and surface area using a computer program (WinRhizo-3.10 B). After scanning the roots were dried in an oven at 70°C for four days and weighed.

Root length density was calculated using the formula,

$$\text{Root length density} = (\text{Root length}/2\,\pi\, r^2) \times \text{Core length} \qquad \text{(Eq 3.1)}$$

Root biomass was estimated from the soil cores using a method described by (Abdul-Jabbar *et al*. 1982).

3.2.6 Total non-structural carbohydrates (TNC) estimation

Prior to cutting at the end of each growing cycle a bulk sample of taproots (40/treatment) were taken from a row. Sampling was carried out on five occasions in the first year of the study and twice in the second year. Each bulk sample was assessed for TNC using the techniques (Appendix-B) described by Wolf (1978), and the taproots were then dried in an oven at 70°C to a constant weight.

3.2.7 Phyllochron determination

The phyllochron (°Cd) was calculated as a reciprocal of the slope of a linear regression between the number of main stem nodes and accumulated thermal time (Tt) within each regrowth cycle (Brown *et al*. 2005b). Thermal time (^oCd) was calculated using the equation reported by Black *et al*. (2003) with a value of 5°C used for T_b as recommended for hot areas (Fick *et al*. 1988, Robertson *et al*. 2002)

$$Tt = \sum[(Tmax + Tmin)/2]-T_b \qquad \text{(Eq. 3.2)}$$

Seasonal dynamics in phyllochron were explored by plotting node appearance against photoperiod (Pp) in each growth cycle following the method of Brown *et al*. (2005b). Since first node appearance was not noted directly in this study, first node appearance was calculated by linear interpolation between successive measurements and assumed to be 3-5 days after the beginning of crop cycle depending on season. The Pp was calculated from sun set and sun rise data of Geosciences Australia (Civil twilight, centre of the sun 6° below eastern and western horizons, Good Speed (1975).

3.2.8 Radiation use efficiency estimation (RUE_{shoot})

Radiation use efficiency for lucerne shoot DM (RUE_{shoot}) was estimated by regressing shoot DM (g m^{-2}) against accumulated radiation interception ($\sum PAR_i$ MJ^{-1}) for each regrowth cycle having at least three DM measurements (Brown *et al*. 2006). The slope of the regression (y = a + bx) was termed as RUE_{shoot} (Sinclair and Muchow 1998). The intercept of the regression was not forced through the origin, allowing for the fact that lucerne being perennial may have some allocation from perennial organ (taproot/crown) in early stages of regrowth (Avice *et al*. 1997). The PAR_i was calculated using the relationship given in (Avice *et al*. 1997) and described by (Goose *et al*. 1982, Varlet-Grancher and Bonhomme 1982).

$$PAR_i = 0.46 \text{ x } Rg \text{ x } (1 - e^{-0.88 \text{ x } LAI}) \qquad \text{(Eq. 3.3)}$$

Where PARi is the photosynthetic active radiation (400-700 nm), Rg (MJ m^{-2}) is the global radiation measured at the nearby Roseworthy meteorological station, and LAI is leaf area index. The daily value of LAI was estimated by linear interpolation between two successive LAI measurements (Khaiti and Lemair 1992).

3.2.9 Statistical analysis

Data collected were analysed using a split plot design in GenStat 6 Release 6.2 (Lawes Agricultural Trust, 2002) for simple ANOVA to compare the above ground growth and growth components, by considering treatment as main plot and date as sub-plots. Mean separation was performed using Fisher's least-significant difference (LSD) at 5% level ($\alpha = 0.05$). Two LSD bars were displayed on figures for comparison of means between the treatments and the same level of treatments between different times. Similarly, for root length density, analysis of variance was performed for each depth separately, with treatment as main plots and time of sampling as sub-plots. Root biomass was analysed using treatment as main plot and depth as sub plot. Linear regression analysis was carried out to establish the relationship between cumulative water received and cumulative dry matter produced in each treatment. Linear regression was also performed between radiation use efficiency (RUE_{shoot}) and monthly mean air temperature and vapour pressure deficit (VPD) of each regrowth cycle. Linear regression was also performed to assess any relationship between RLD and root biomass between different treatments. Data for TNC were analysed using treatment as main plot and date of sampling as sub-plot.

3.3 Results

3.3.1 Climate data 1999-2001

Monthly rainfall and pan evaporation data for the experimental period (1999-2001) are presented in Table 3.4. Long-term average rainfall for the Roseworthy Campus of the Adelaide University is 436 mm per annum, and 358 mm for the growing season (Apr-Nov). Total growing season rainfall during 1999 was 300 mm, 20% less than in the 2000 growing season where rainfall was 374 mm which was higher than average, and substantially less (26 mm) than the above-average 400 mm received in the 2001 growing season (Table 3.4). The summer season (Dec-Mar) in 1999-2000 was relatively wet, with 119 mm total rainfall, 49% more than the long-term average (80 mm), although one rainfall event in February was 74 mm, whereas the 2000-2001 summer season rainfall was 56 mm which was less than the long-term average (Table 3.4).

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

Month	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual**	**A-N**	**D-M**
1999															
Rainfall	3	0	5	9	62	35	33	24	36	47	55	22	331	300	-
Evaporation	295	234	176	104	92	51	50	75	122	152	177	230	1756	822	-
2000															
Rainfall	1	74	22	34	40	57	50	67	47	57	22	11	482	374	119*
Evaporation	305	298	221	133	77	59	63	84	112	146	231	286	2017	907	1054*
2001															
Rainfall	7	10	27	18	54	49	45	53	84	56	42	13	457	400	56**
Evaporation	314	241	193	126	73	43	45	82	105	128	175	206	1731	776	1035**
Long-term average															
Rainfall	19	19	19	36	48	49	54	51	48	43	28	23	438	358	80
Evaporation	272	236	195	122	75	52	56	73	99	148	204	246	1778	829	949

*Rainfall and Evaporation from Dec 99-Mar 2000

** Rainfall and Evaporation from Dec 2000-Mar 20

Pan evaporation data (Table 3.4) indicate that during 2000 annual evaporation was higher (2017 mm) than the long-term average of 1778 mm; less than average during 2001 (1731 mm) and very close to the average during 1999 (1756 mm). Monthly rainfall rarely exceeded pan evaporation during 1999-2001, a trend that was similar to the long-term average data (Table 3.4). However, occasionally in the growing seasons, and extremely rarely in the summer seasons, large daily rain events exceeded pan evaporation for a single particular day.

Temperature data (Table 3.5) reveal higher maximum monthly average air temperature in a few summer months of the years 1999, 2000 and 2001 compared to the long-term average. However, minimum recorded air temperatures for all the years of the experiment were similar to the long-term average, as was the case for radiation data for this site during the experiment years (Table 3.5).

Table3.5 Monthly maximum and minimum temperature (^{o}C) and Radiation (MJ m^{-2}) at Roseworthy Campus Farm Site from 1999-2001 compared with the 50 years average.

		Month											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1999	T Max	33	32	26	22	20	16	16	17	21	24	24	28
	T Min	16	16	13	7	10	6	6	5	8	10	10	13
	Rad	26	23	18	16	10	9	10	14	17	20	22	23
2000	T Max	30	34	27	24	18	15	16	16	19	22	29	30
	T Min	15	18	14	11	8	7	6	6	8	8	13	12
	Rad	24	22	18	15	11	9	10	13	16	20	25	26
2001	T Max	36	33	27	24	20	17	16	16	19	19	24	26
	T Min	17	17	12	9	8	8	6	7	8	7	9	10
	Rad	26	23	20	15	11	9	9	12	16	19	23	24
LT (av)	T Max	30	30	27	23	19	16	15	16	19	22	25	28
	T Min	15	16	14	11	9	7	6	6	7	9	12	14
	Rad	26	23	19	13	9	8	9	12	15	20	23	25

T Max (Maximum temperature), T Min (Minimum temperature), Rad (Radiation)

3.3.2 Lucerne shoot productivity and growth components

3.3.2.1 Shoot dry matter yield

There were significant ($P<0.001$) differences in shoot dry matter yield within and between treatments for mature lucerne shoot material, cut to a height of 5 cm above ground level, at all the harvest times (H1-H12) during the period January 2000 to September 2001. Dry matter yield for the rainfed (R_{fed}) treatment was significantly lower, ranging from 0-620 kg ha^{-1} in summer and 736-1289 kg ha^{-1} in winter-spring growing periods, compared to both the summer irrigation treatments having productivity ranges of 1357-3300 kg ha^{-1} in summer and 1412- 2597 kg ha^{-1} in winter over the two year study period at all the harvests (Figure 3.4a). In February and March in the summer season of 1999-2000 (H2 and H3), the surface irrigation treatment (I_{surf}) yielded significantly more shoot dry matter than the sub-surface irrigation treatment (I_{sub}), whereas, in May, July and November of the winter-spring season of 2000 (H4, H5 and H7), I_{sub} out-yielded the other two treatments. In the summer season of 2000-01 there was no harvestable shoot dry matter production in the R_{fed} treatment for H8 and H9 taken in February and March, and very little (143 kg ha^{-1}) at H10. However, shoot growth was obtained in the irrigated treatments during this period. Shoot dry matter yield during the winter 2001 growing season (H11) showed similar trend to the yields observed in June and July 2000 (H4 and H5), with I_{sub} yielding significantly higher than I_{surf}.

Shoot dry matter yields were also significantly different ($P<0.001$) over time for any single level of treatment, indicative of the seasonal climatic effects on all treatments. (Figure 3.4a). The R_{fed} treatment had lower yields in summer periods of growth compared to the winter/spring growing seasons. Whereas the summer irrigation treatments during summer 2000 in H2 and H3 produced significantly higher yields than any of the harvests (H4-H7) taken in the growing period of winter-spring 2000. Although this trend was reversed in summer 2001 when yields were less than in winter 2001.

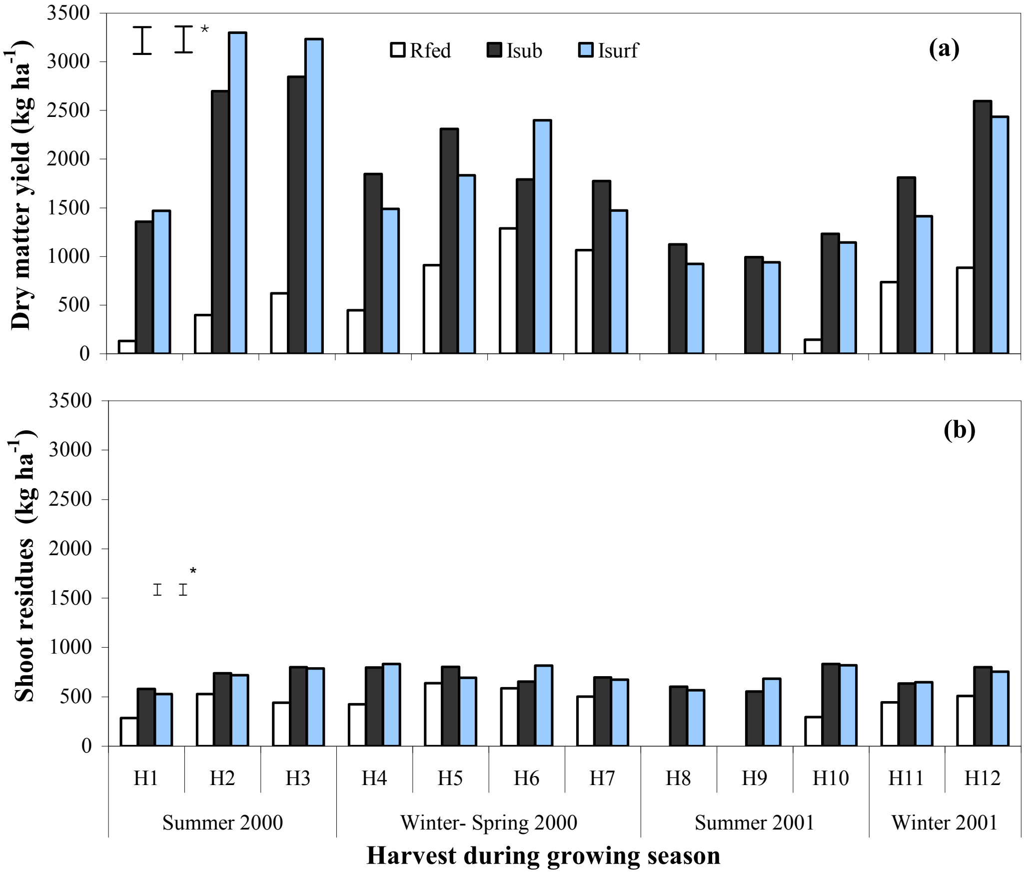

Figure 3.4 Dry matter yield and shoot residue dry matter at different harvests (H1-H12) during Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD (α=0.05) between treatments and *error bars are for comparison of a single set of treatment means over time.

3.3.2.2 Shoot residues

Shoot dry matter remaining after each harvest (i.e shoot residues) in all treatments reflected the trend observed for shoot dry matter yield, although, of course, quantities were much less ranging from (284-637 kg ha^{-1}) in the R_{fed} treatment over the 12 harvests. Shoot residue dry matter was significantly greater (P<0.001) after all the twelve harvests for the summer irrigation treatments than for the R_{fed} treatment (Figure 3.4b). Generally the amount of shoot residues was similar for the I_{sub} and I_{surf} treatments, with a few exceptions. Comparison of individual treatments over time showed significant (P<0.001) seasonal variation in the amount of shoot residues remaining after harvest and also within a single growth period. In the R_{fed} treatment there were generally less shoot residues in the summer than in the winter-spring periods, and the trend was similar, although far less marked, for the irrigation treatments.

Dry matter yield in lucerne was strongly related with the amount of water received through rainfall (R^2 = 0.98) or irrigation (R^2 >0.98) in this study (Figure 3.5) where the intercept of the I_{sub} and I_{surf} lines represent the evaporation loss, ~ 190 in I_{surf} versus ~30 mm in and I_{sub} - this will be further discussed in Chapter 4.

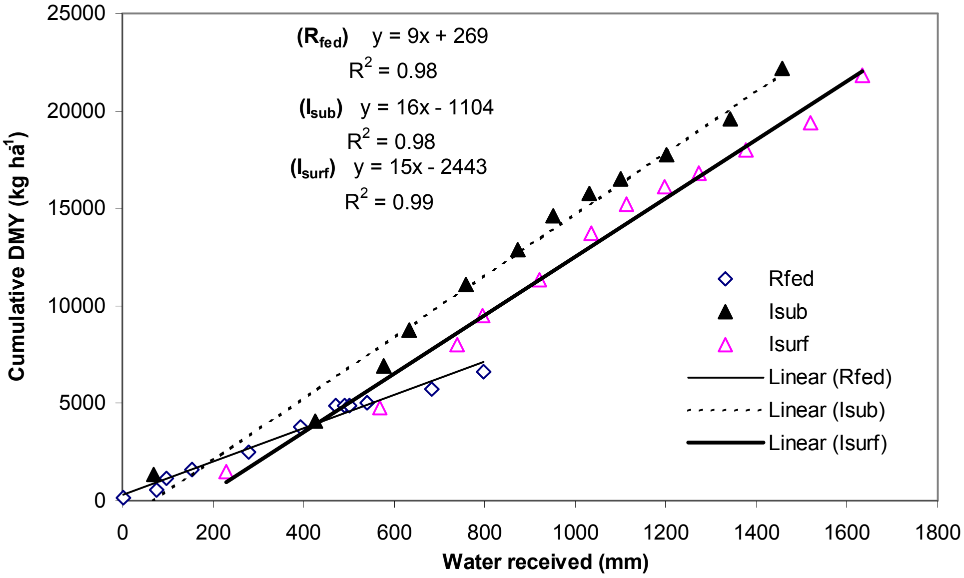

Figure 3.5 Cumulative shoot dry matter yield in relation to cumulative water supplied during Dec1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

3.3.2.3 Shoot growth rate

There were significant differences between treatments (P<0.001) in mean daily shoot growth rate (kg DM $ha^{-1}d^{-1}$) for each season (Table 3.6). The R_{fed} treatment demonstrated the lowest mean daily shoot growth rate (10 kg DM $ha^{-1}d^{-1}$), whereas the mean rate for both I_{sub} and I_{surf} treatments was more than four times greater (41 kg DM $ha^{-1}d^{-1}$) than the rainfed treatment. Mean daily shoot growth rate for the R_{fed} treatment was significantly lower in both summer seasons compared to the winter-spring growing seasons, where growth rate during winter 2001 was lower than in 2000. The highest mean daily shoot growth rates were obtained for the heavily irrigated treatments during the summer 1999-2000, being 65.4 and 75.6 kg DM $ha^{-1}d^{-1}$ for I_{sub} and I_{surf} respectively. The shoot growth rate for the R_{fed} treatment measured at each individual harvest never exceeded the two summer irrigation treatments but there was no consistent trend for differences between I_{sub} and I_{surf}.

Table 3.6 Rate of dry matter accumulation above 50mm (kg d^{-1} ha^{-1}) in each growing cycle during Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Treatment	Summer 2000			Win-sp 2000				Summer 2001			Win-sp 2001		Average
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	
R_{fed}	4	10	19	9	13	21	19	0	0	4	9	13	10
I_{sub}	39	71	86	35	34	29	32	42	32	31	22	37	41
I_{surf}	42	87	98	28	27	39	27	34	29	29	17	35	41
LSD (0.05)	7.0												
SLT*	6.5												

Comparing same level of treatments

3.3.2.4 *Plant and stem population*

Plant populations were (P<0.001) lower in the R_{fed} than the summer irrigation treatments for eleven out of the twelve assessment times during the two-year study period (Figure 3.6a), whereas plant population in the I_{surf} and I_{sub} treatments were similar to each other over the same period. Plant population decreased significantly over time in all the treatments from an initial value of 69 plants m^{-2}. The decrease in the R_{fed} treatment was from 69 to 20 plants m^{-2}. The greatest reductions in plant population in the R_{fed} treatment were observed over the summer periods, particularly during summer 2001. Although there were also decreases in plant population in I_{surf} and I_{sub} treatments over time, the decline was relatively slow and at a steady rate, so that at the end of the two year period plant population was still greater than 55 plants m^{-2} in both irrigation treatments.

Stem numbers per unit area (Figure 3.6b) generally reflected the trend for plant population across treatments. A consistently lower stem population was observed in the R_{fed} treatment at all the sampling times compared with the I_{sub} and I_{surf} treatments. There were fewer differences in stem population between the two irrigation treatments. However, in contrast to the plant population observations, overall stem population in each treatment at the end of the measurement period was not significantly different to that at the beginning. There were seasonal influences on stem population and a comparison over time showed that lower numbers of stems were produced during the summer periods in the R_{fed} treatment than in the corresponding winter periods, and this was particularly noticeable in 2001 after a particularly dry summer. Stem population was also lower in winter-spring 2001 (H11, H12) compared with winter-spring 2000 (H4-H7) in the R_{fed} treatment. The trends in the summer irrigation treatments were the reverse to the R_{fed} situation and stem population was generally higher during summer rather than winter for I_{sub} and I_{surf}, particularly in 2000.

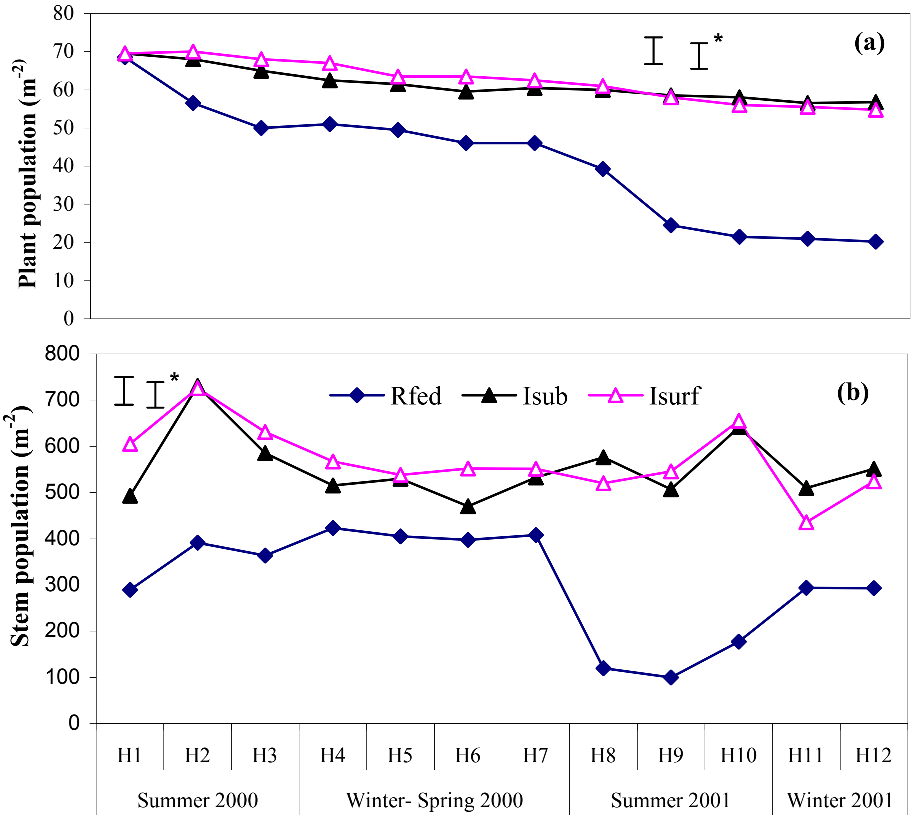

Figure 3.6 Plants and stem populations (m^{-2}) at different harvest (H1-H12) during Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Error bars represent LSD (α=0.05) between treatments and *error bars are for comparison of a single set of treatment means over time.

3.3.2.5 Plant (main stem) height, node number and leaves per stem

Lucerne plants at maturity were ($P<0.001$) taller in the I_{sub} and I_{surf} treatments than in the R_{fed} treatment for 11 out of the 12 harvests (Figure 3.7a). There were fewer differences in main stem height at maturity between the two summer irrigation treatments although plants were significantly taller in I_{surf} during summer 2000 (H2, H3) than in I_{sub}, whereas in 2001 (H8, H11) plant height was significantly higher in I_{sub}. Generally, in the R_{fed} treatment, greater plant height at maturity was achieved during the winter-spring periods than during summer. However, this trend did not apply for the summer irrigation treatments, which produced significantly taller plants during summer 2000 (H2, H3) than in any other growing-period, but much shorter plants in summer 2001 (H8-H10).

Number of nodes per stem for lucerne plants was higher ($P<0.001$) in I_{sub} and I_{surf} than in the R_{fed} treatment at all sampling times in the summer seasons and some of the sampling times in the winter (Figure 3.7b). There were no significant differences in number of nodes per stem between I_{sub} and I_{surf} treatments except in summer 2000 (H2) when nodes per stem for I_{surf} was greater than for I_{sub} and in summer 2001 (H8), when the reverse was the case. Overall, in the R_{fed} treatment number of nodes per stem was always lower in the summer than during the following winter-spring period, whereas this same trend was only noticeable in the second year (2001) for the summer irrigation treatments.

There were similar general patterns observed for leaf number per main-stem (Figure 3.7c) as was observed for node number. For example, leaf number per stem was higher ($P<0.001$) in I_{sub} and I_{surf} than in the R_{fed} treatment at all sampling times in the summer seasons except for one occasion (H10), and for some of the sampling times in the winter. Also, there were few significant differences between the two summer irrigation treatments apart from H2 where I_{surf} had more leaves per stem than I_{sub}.

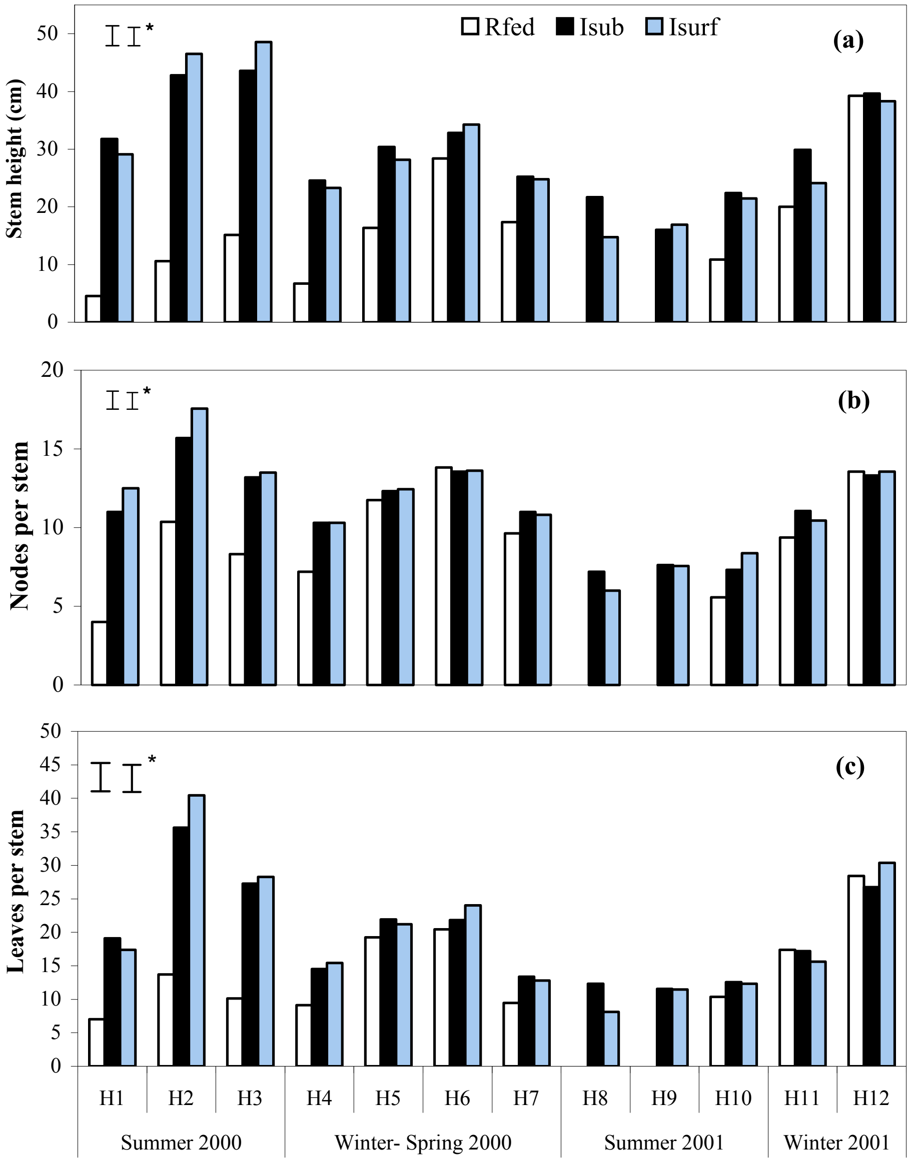

Figure 3.7 Height, node and leaf number (main stem) at different harvests (H1-H12) during Jan 2000 to Sep 2000 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Error bars represent LSD (α=0.05) between treatments and *error bars are for comparison of a single set of treatment means over time.

Daily lucerne stem growth rate (Figure 3.8) for young shoots, late vegetative and flowering was lower (P<0.001) in the R_{fed} treatment compared to both irrigated treatments. Data averaged across the two years shows that the stem growth rate was significantly higher in summer than winter in all treatments. The pattern of daily stem growth rate within in each growth cycle was similar and overall exhibited a gradual reduction in rate with increasing age of the plants.

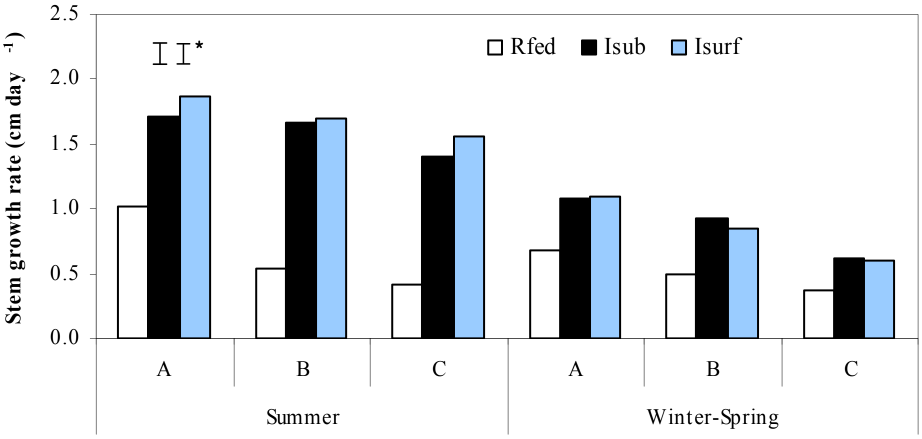

Figure 3.8 Average lucerne stem growth rate (cm day^{-1}) for summer and a winter-spring growing seasons of 2000 at three stages, (A) early shoot, (B) mid-vegetative and (C) maturity, during a growth cycle for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface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

Error bars represents LSD (α=0.05) between treatments and *Lsd is for comparison of a single set of treatment means over time.

3.3.2.5 Phyllochron seasonality

A plot of main stem node number against accumulated thermal time Tt_{b5} indicated a linear relationship for 9 of the 11 regrowth cycles (R^2>0.90) in both the irrigated treatments, and in 7 of the 11 regrowth cycles (R^2> 0.88) for the R_{fed} treatment (Figure 3.9). In some cases there was a decrease in the slope of the regression line at points near cutting, especially in summer under stressed conditions which induced early flowering. Those points which were affecting linearity of regressions were excluded from the data analysis (Brown *et al.* 2005b). Also, where node appearance was noted at three times only in each growth cycle a linear relationship could not be justified from 2 data points and therefore these growth cycles were also excluded from the estimation of phyllochron.

Phyllochron varied with season but not with treatment. The phyllochron was 46 ± 7 ^{o}Cd in late spring and summer, increased to 60 ^{o}Cd near autumn (equinox March 20), decreased sharply to 31 ± 4 °Cd in June and remained constant during winter and the start of spring (Figure 3.10).

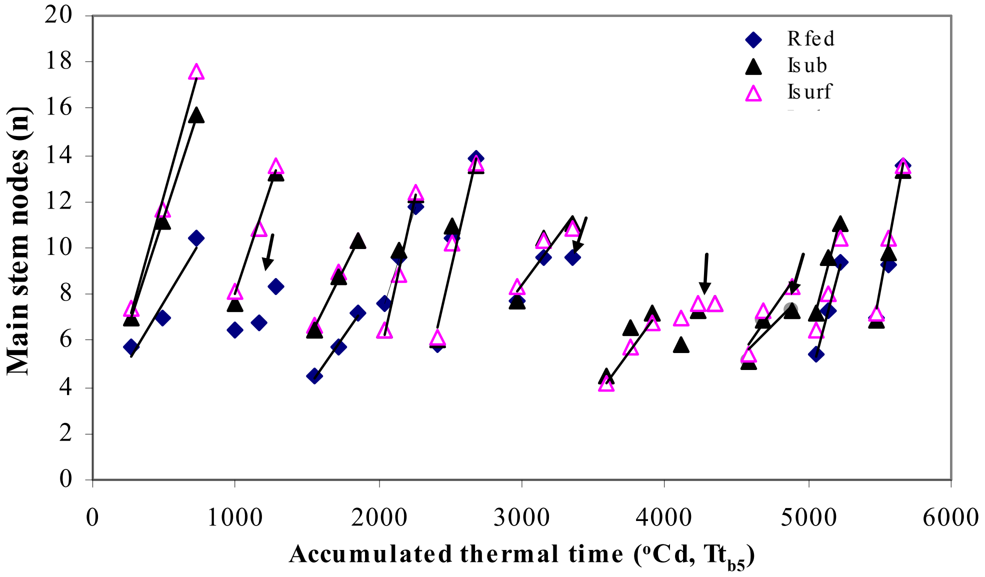

Figure 3.9 Main stem node appearance of during different regrowth for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Arrows indicated points flowering of crop excluded from date set.

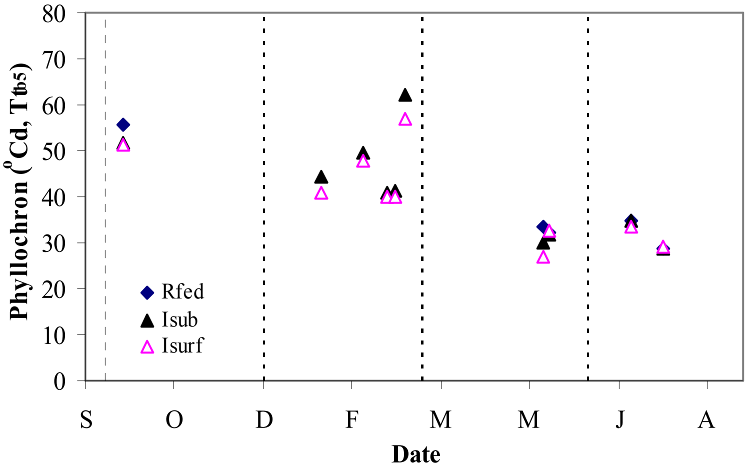

Figure 3.10 Phyllochron of lucerne crop measured over different growth seasons from during regrowth cycles from Jan 2000-Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}). Dash lines (----) represent equinox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

The relationship between phyllochron and photoperiod was influenced by season (Figure 3.11). The phyllochron increased with increasing photoperiod (taken as the photoperiod on the day of the first node appearance).

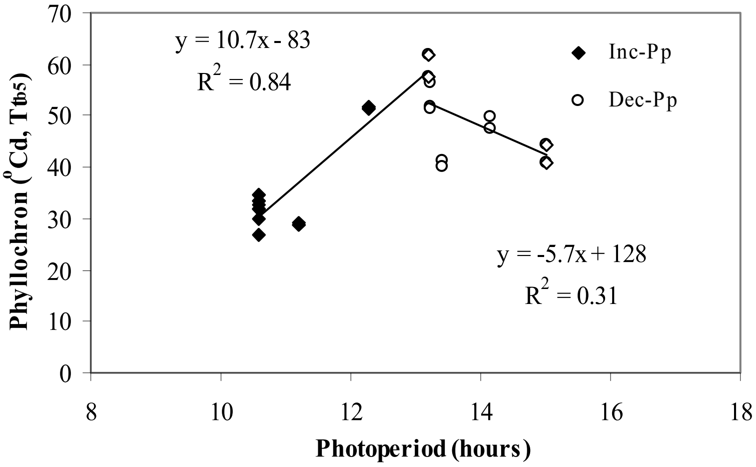

Figure 3.11 Phyllochron of lucerne crop measured over different growth seasons and for each growth cycle against photoperiod on the day of appearance of the first main stem node during regrowth cycles from Jan 2000-Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over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

3.3.2.6 Leaf Area Index (LAI)

The R_{fed} treatment had lower LAI ($P< 0.001$) on all measurement dates, ranging from 0-2.58 overall, compared to the summer irrigation treatments (Figure 3.12) where the lowest LAI recorded was 0.60. The highest value for LAI (>4.03) was recorded at flowering in the I_{surf} treatment during the summer in 2000 (H2 and H3), where large amounts (169 mm) of supplemental water were applied (Section 3.2.2). Generally LAI increased within each growth cycle as the stand increased in age, although on a few occasions LAI at maturity was less than or equal to LAI at the late-vegetative stage (H7, H8 and H10).

There was a linear relationship (R^2>0.90) between LAI and accumulated thermal time (Tt_{b5}) in 9 of the 12 regrowth cycles in both the irrigated treatments and in 7 out of the 12 growth cycles (R^2< 0.80) in the R_{fed} treatment (Figure 3.13). In irrigated treatments linearity was altered at the end of growing seasons in Oct-Nov 2000 and in summer 2001 where amount of water supply was reduced to ~ 60 mm per growth cycle. In R_{fed}

treatments this relationship was reduced by water-stress conditions in summer and also at the end of growing seasons (Oct-Nov).

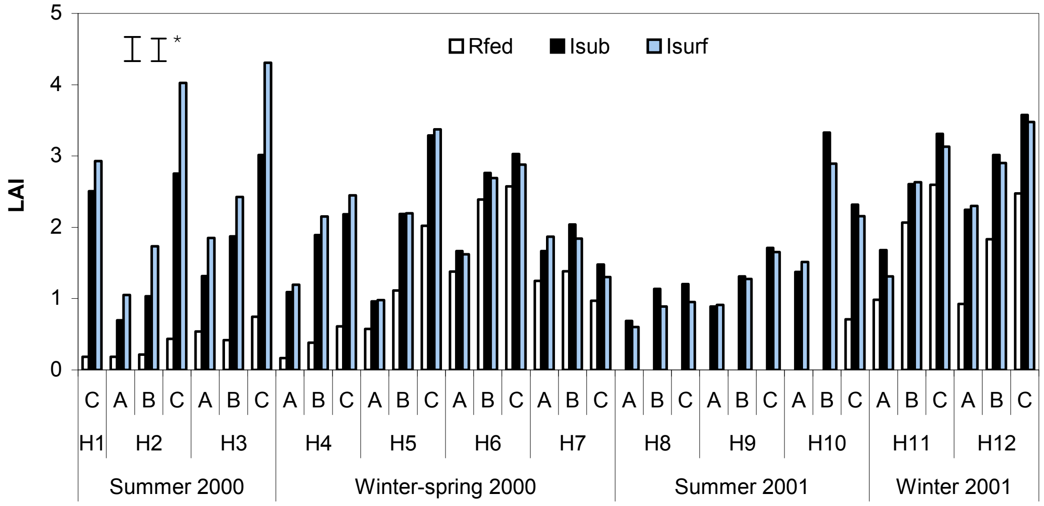

Figure 3.12 LAI of lucerne at three stages of crop development, (A) young shoot, (B) mid-vegetative and (C) maturity, during each individual growth cycle (H1-H12) from Jan 2000 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or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

Error bars represent LSD (α=0.05) between treatments and *error bars are for comparison of a single set of treatment means over time.

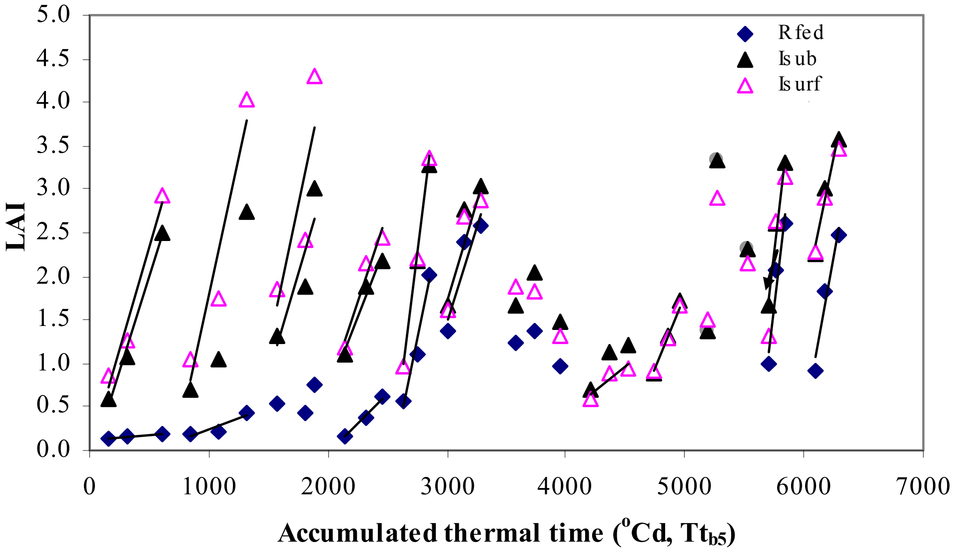

Figure 3.13 LAI versus accumulated thermal time of during different regrowth cycles for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

3.3.2.7 Leaf:stem dry weight ratio

Leaf:stem dry weight ratios were often variable between different treatments and also over time within the same treatment (Figure 3.14), although distinct trends were not discernible. However, leaf: stem dry weight ratios for the R_{fed} treatment, which exhibited the most variability and ranged from 0 – 2.69, were often equal to or greater than those for the summer irrigation treatments. The exceptions were at H1 where the ratio for R_{fed} was significantly lower than I_{surf}, at H4 where the R_{fed} was less, but not significantly so than both I_{surf} and I_{sub} and at H8 and H9 where there was zero growth in the R_{fed} treatment. Overall, the summer irrigation treatments showed less variation in leaf: stem ratio than the R_{fed} treatment, ranging from 1.28 - 2.32, and also few significant differences apart from H1 where I_{surf} had a higher leaf: stem ratio than I_{sub} and H8 where I_{sub} had a greater leaf:stem ratio.

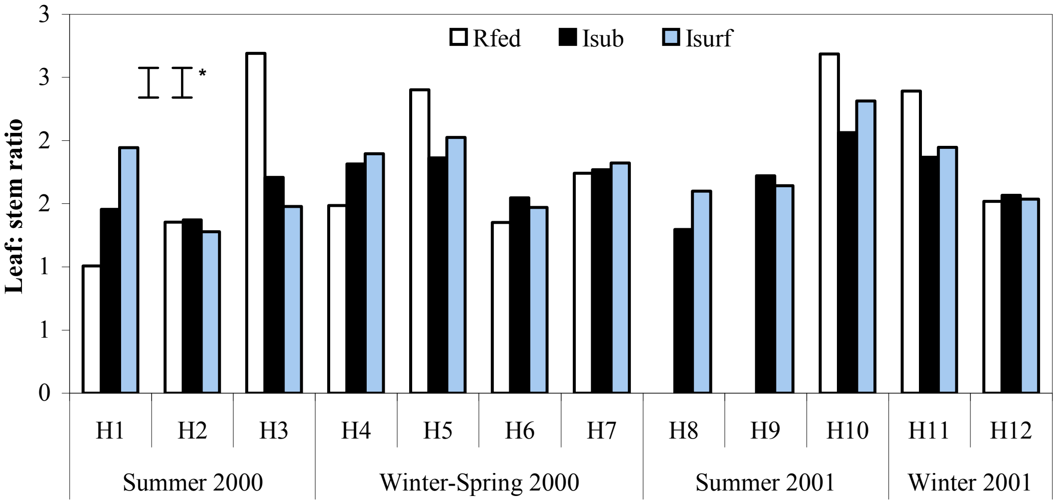

Figure3.14 Leaf:stem ratio at different harvest (H1-H12) from Jan 2000 to Sep 2000 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Error bars represent LSD (α=0.05) between treatments and *error bars are for comparison of a single set of treatment means over time.

3.3.2.8 Radiation use efficiency (RUE_{shoot})

Changes in leaf area index (LAI), intercepted photosynthetically active radiation (PAR_i MJ^{-2}), and shoot biomass (SBM g m^{-2}) during two growth cycles (summer and winter) were strongly correlated (Figure 3.15). In summer, LAI, PAR_i , and SBM were much greater under irrigated compared to rainfed conditions. The relationship of accumulated photosynthetically active radiation (∑PARi MJ^{-2}) with shoot biomass (SBM g m^{-2}) for this summer growing cycle (Figure 3.15c) was strong in both the irrigated treatments (R^2 >0.96) with a calculated RUE_{shoot} of 1.78 for I_{surf}, and 1.74 for I_{sub} . The corresponding regression for the R_{fed} treatment was weaker ($R^2 = 0.57$), and the calculated RUE_{shoot} was 0.49 (g DM MJ^{-1}). During winter there were smaller differences between the irrigated and rainfed treatments. Similar strong relations between LAI, PARi and SBM were apparent. The calculated RUE values for this winter regrowth cycle were 0.92 in $R_{fed,}$ 1.19 for I_{surf}, and 1.76 g DM MJ^{-1} in the I_{sub} treatment.

In general, accumulated SBM was strongly related to radiation interception in each growth cycle in both the irrigated treatments (mean of 12 harvests R^2>0.97) while this relationship was slightly weaker in the R_{fed} treatment (R^2>0.88). The seasonal pattern of RUE_{shoot} was explored by plotting it against the median date of each regrowth cycle (Brown *et al*. 200) from Dec-1999 to Sep-2001 (Figure 3.16). There were no clear seasonal effects on RUE. The highest RUE (~1.78 g DM MJ^{-1}) was achieved following summer irrigation (Feb-Mar 2000).

The relationship between temperature (°C) and vapor pressure deficit (VPD Kpa) with RUE_{shoot} (DM MJ^{-1}) was assessed by regressing RUE against the mean temperature and VPD values during each regrowth cycle in both years (Figure 3.17a & b). No clear trends were apparent.

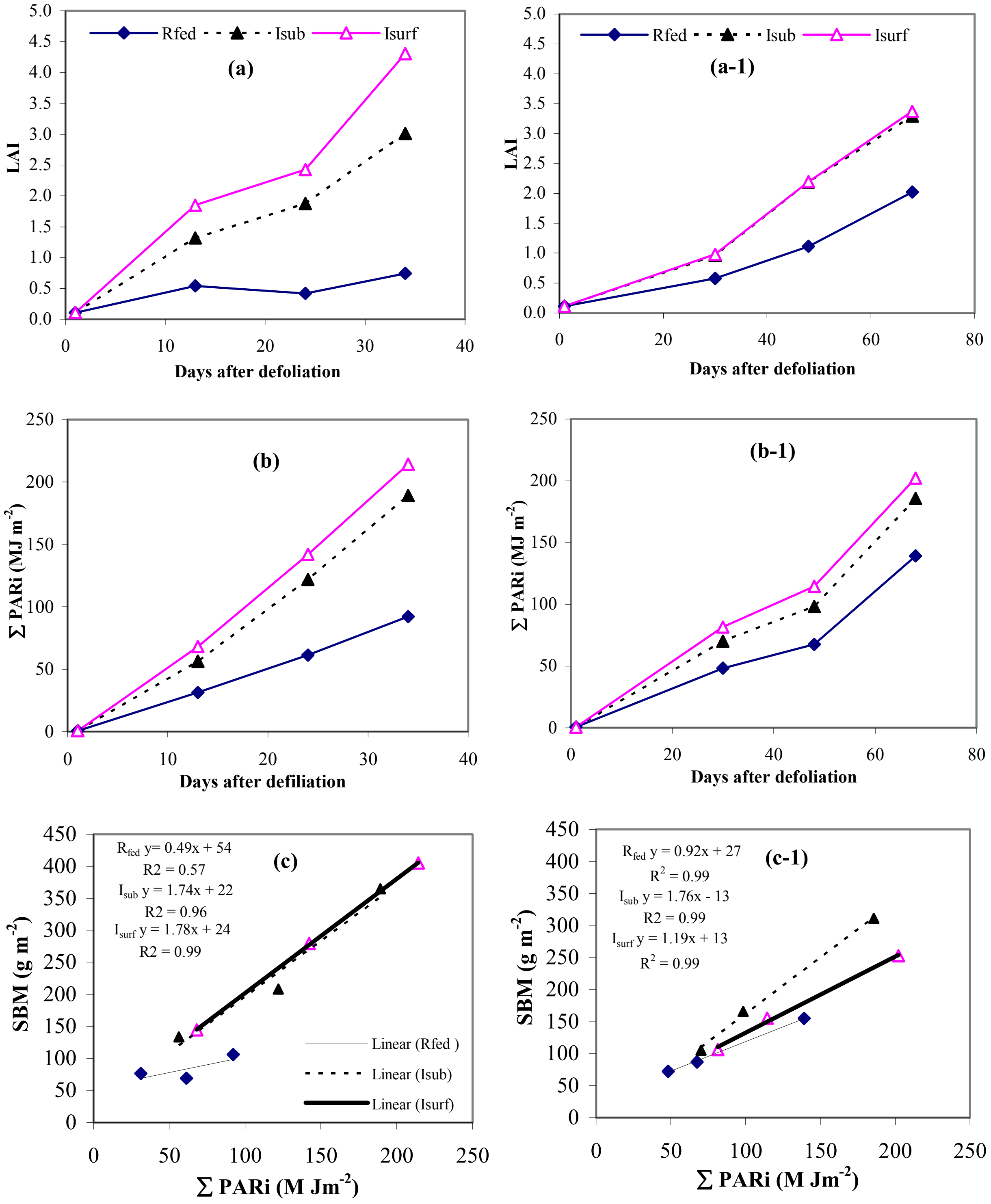

Figure 3.15 Pattern of LAI development at two different regrowth cycles (a) March 2000, (a-1) June 2000, corresponding PARi interception (b, b-1) and relationship between accumulated PARi and shoot biomass SBM (c, c-1) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer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

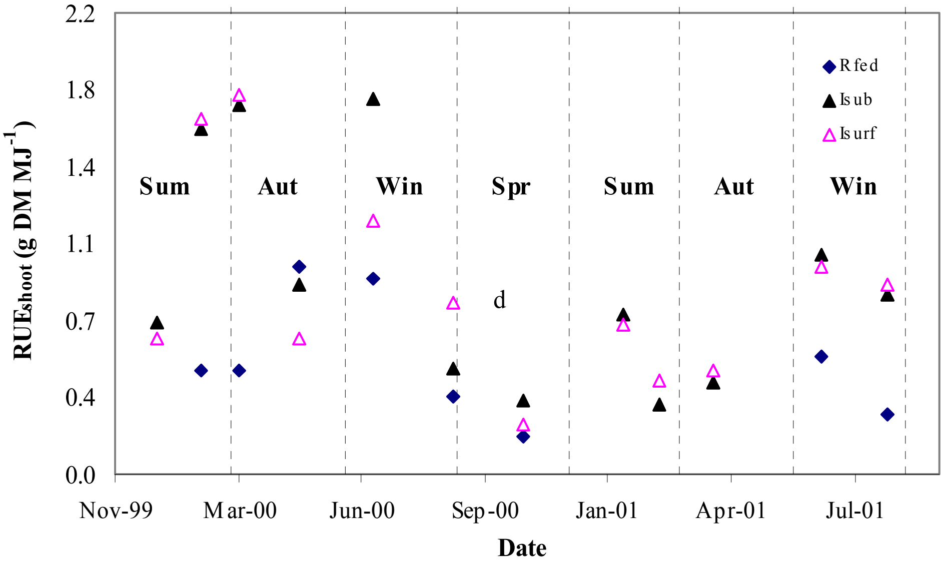

Figure 3.16 Seasonal pattern of shoot radiation use efficiency (**RUE$_{shoot}$**) for rainfed lucerne (R$_{fed}$) and lucerne supplied with supplemental water over summer via surface (I$_{surf}$) or sub-surface (I$_{sub}$) irrigation from Dec 1999 to Sep 2001. Lines (-----) separate different seasons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

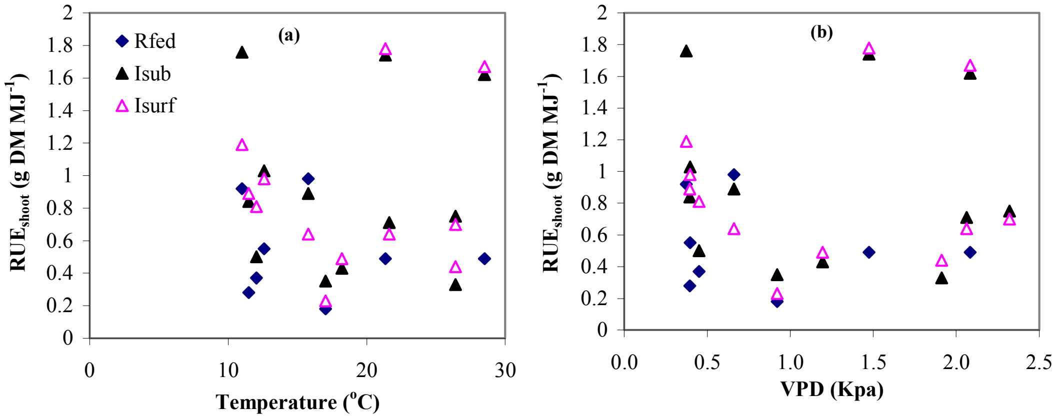

Figure 3.17 (a) Relationship between shoot radiation use efficiency (**RUE$_{shoot}$**) and mean air temperature, and (b) with vapour pressure deficit (VPD) during each regrowth cycle for rainfed lucerne (R$_{fed}$) and lucerne supplied with supplemental water over summer via surface (I$_{surf}$) or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

3.3.3 Root biomass

At the first sampling in summer 2000, root biomass (>1 mm), to a depth of 1 m, was consistently less for the R_{fed} treatment than for both the summer irrigation treatments (Figure 3.18a). The same trend was observed (Figure3.18b & c) to a depth of 1.2 m at the beginning of spring 2000 and in mid-winter 2001. Additionally, in summer 2000 root biomass for the I_{surf} treatment in the 0-20 cm soil depth was significantly greater than for the I_{sub} and R_{fed} treatments ($P<0.05$). In the 20-40, 40-60 and 60-80 cm soil depths root biomass was different only between I_{sub} and the R_{fed} treatment. Root biomass after winter 2000 (Figure 3.18b) was still significantly greater for the I_{surf} treatment at 0-20 cm soil depth than for the other treatments ($P<0.05$). Conversely, by mid-winter 2001 root biomass (>0.5 mm) in the I_{sub} treatment (Figure 3.18c) was significantly greater at 0-20 cm soil depth than that in the R_{fed} and I_{surf} treatments.

The quantity of root biomass in the top 60 cm of the soil profile was 93%, 89% and 91% for R_{fed}, I_{sub} and I_{surf} treatments respectively (Table 3.7). There was more roots biomass (13%) deeper in the profile for the I_{sub} treatment compared with R_{fed} (7%) and I_{surf} (9%). Total root biomass data showed that the trend for all treatments was a gradual significant increase over the autumn-winter period in 2000 and a further significant increase, at a faster rate (partly due to the smaller sieve size used for root collection), over the spring-summer period 2001 (Figure 3.19). Treatment interactions over time were also significant ($P<0.05$), with a more rapid increase between October 2000 and July 2001 for the I_{sub} treatment than for the other treatments.

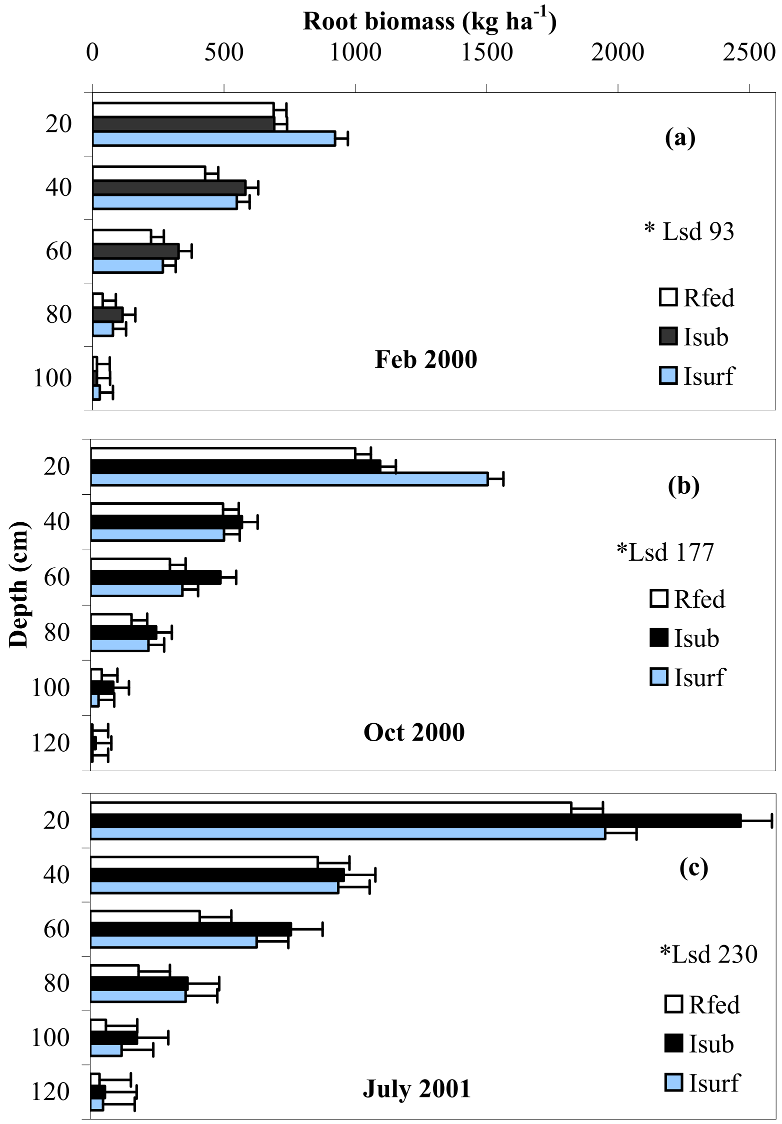

Figure 3.18 Root biomass (RBM) during 2000-2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Error bars represent LSD (α=0.05) between treatments and *Lsd is for comparison of a single set of treatment means over time.

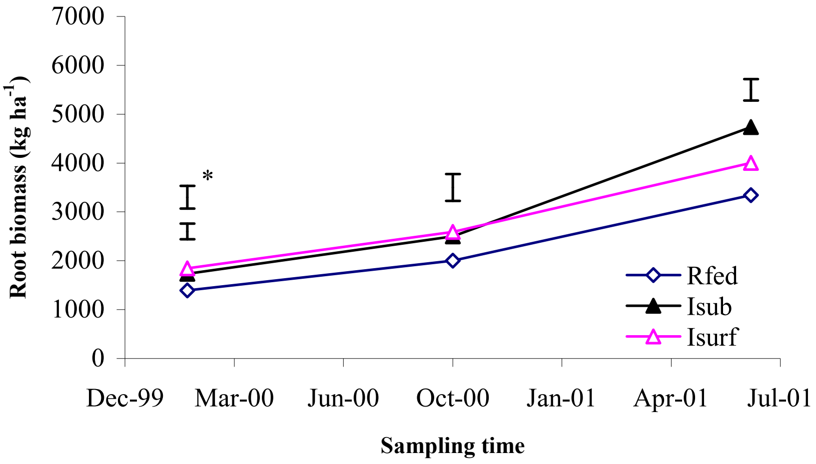

Figure 3.19 Total root biomass (kg ha^{-1}) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Error bars represent LSD (α=0.05) between treatments and *error bar is for comparison of a single set of treatment means over time.

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

Depth (cm)	Rfed	I_{sub}	I_{surf}
Feb 2000			
0-20	49	40	50
20-40	31	34	30
40-60	16	19	15
60-80	3	7	4
80-100	1	1	2
Oct 2000			
0-20	50	44	58
20-40	25	23	19
40-60	15	20	13
60-80	8	10	8
80-100	2	3	1
July 2001			
0-20	55	52	49
20-40	26	20	23
40-60	12	16	16
60-80	5	8	9
80-100	2	4	3

3.3.3.1 Root length density (RLD)

Overall treatment mean data show that RLD was higher for the I_{sub} treatment compared to the R_{fed} and I_{surf} treatments, and furthermore, that the R_{fed} treatment had the lowest RLD at all the soil depths compared to the treatments where water was supplemented in summer (Table 3.8). A similar pattern to root biomass was observed in RLD, with a consistent decrease with depth in all treatments. Also similar to root biomass, in summer 2000 RLD for the I_{surf} treatment in the 0-20 cm soil depth was greater ($P<0.05$) than for the I_{sub} and R_{fed} treatments, whereas at the 40-60 and 60-80 cm soil depths RLD was significantly greater for I_{sub} than for the other treatments. Treatment differences in RLD measured in early spring (Oct 2000) were not significant. However, at the final sampling in winter 2001 RLD was greater ($P<0.05$) for I_{sub} and I_{surf} treatments than for the R_{fed} treatment in all the soil depth increments sampled from 0-160 cm, apart from the 20-40 cm layer; whereas the two summer irrigation treatments were not significantly different.

RLD, for the 0-20 cm soil depth, increased significantly ($P<0.05$) in both of the summer irrigation treatments between each of the sampling times, whereas there was a significant increase for the R_{fed} treatment only between the initial sampling in summer (Feb 2000) and the subsequent sampling in early spring 2000 (Table 3.8). There was a trend for RLD in the 20-40 cm soil depth in early spring 2000 and mid-winter 2001 to be higher than in the first sampling in summer 2000 for all the treatments but results were not significant. There were some significant differences over time at the 40-60 cm soil depth in the R_{fed} treatment with RLD being higher in early spring 2000 than in summer 2000 and mid-winter 2001, and in I_{surf} where RLD was also higher in early spring 2000 than in summer 2000. The only significant ($P<0.05$) difference over time at the 60-80 cm soil depth occurred in I_{surf} where RLD was greater in early spring 2000 and mid-winter 2001 than in summer 2000. RLD at 120-140 and 140-160 cm soil depths was measured only towards the end of the study in mid winter 2001; it was significantly higher in I_{sub} than R_{fed} and I_{surf} treatments at these depths.

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

Sampling date		**Density (cm $_{root}$ cm^3$_{soil)}$**			**LSD (α=0.05)**
	Depth (cm)	**Rfed**	**I_{sub}**	**I_{surf}**	
28 Feb 2000	0-20	2.89	2.76	3.87	0.77*
1 Oct 2000	0-20	4.52	4.53	4.95	0.77**
18 July 2001	0-20	5.11	6.72	6.16	
28 Feb 2000	20-40	1.61	2.19	2.45	NS
1 Oct 2000	20-40	2.34	2.82	2.74	NS
18 July 2001	20-40	3.24	3.17	3.30	
28 Feb 2000	40-60	1.49	2.06	1.75	0.71
1 Oct 2000	40-60	2.46	1.87	2.46	0.52
18 July 2001	40-60	1.49	2.36	2.10	
28 Feb 2000	60-80	0.55	1.28	0.52	0.36
1 Oct 2000	60-80	0.81	1.28	0.96	0.38
18 July 2001	60-80	0.54	1.05	1.30	
28 Feb 2000	80-100	0.15	0.27	0.14	NS
1 Oct 2000	80-100	0.37	0.50	0.59	NS
18 July 2001	80-100	0.15	0.45	0.33	
28 Feb 2000	100-120	N	N	N	
1 Oct 2000	100-120	0.09	0.23	0.19	NS
18 July 2001	100-120	0.07	0.37	0.16	NS
28-Feb-00	120-140	N	N	N	
1-Oct-00	120-140	N	N	N	
18-Jul-01	120-140	0.04	0.31	0.07	0.08
28-Feb-00	140-160	N	N	N	
1-Oct-00	140-160	N	N	N	
18-Jul-01	140-160	0.03	0.13	0.03	0.03
Overall means	All depths	1.47	1.81	1.79	

* For comparison between treatments

** For comparison with in same level of treatment

N No sampling

NS Non-significant

The proportional distribution of RLD depicts (Table 3.9) a similar trend as was observed in root biomass. In the upper soil profile (60 cm) all the treatments have similar RLD proportion (~ 87%) but lower in the soil profile, treatment averages over time show a higher proportion in I_{sub} (17%) compared with 10% and 12% for the R_{fed} and I_{surf} treatments respectively. Root length density was significantly related (Figure 3.20) to root biomass ($P<0.001$) in R_{fed} ($R^2= 0.88$) and I_{sub} ($R^2= 0.90$) and I_{surf} ($R^2= 0.93$) treatments.

Table3.9 Proportional root length density (%) at various soil depths for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Depth (cm)	Rfed	I_{sub}	I_{surf}
Feb 2000			
20	43	32	44
40	24	26	28
60	22	24	20
80	8	15	6
100	2	3	2
Oct 2000			
20	43	40	42
40	22	25	23
60	23	17	21
80	8	11	8
100	4	4	5
120	1	2	2
July 2001			
20	48	47	46
40	30	22	25
60	14	16	16
80	5	7	10
100	1	3	2
120	1	3	1
160	0	2	1

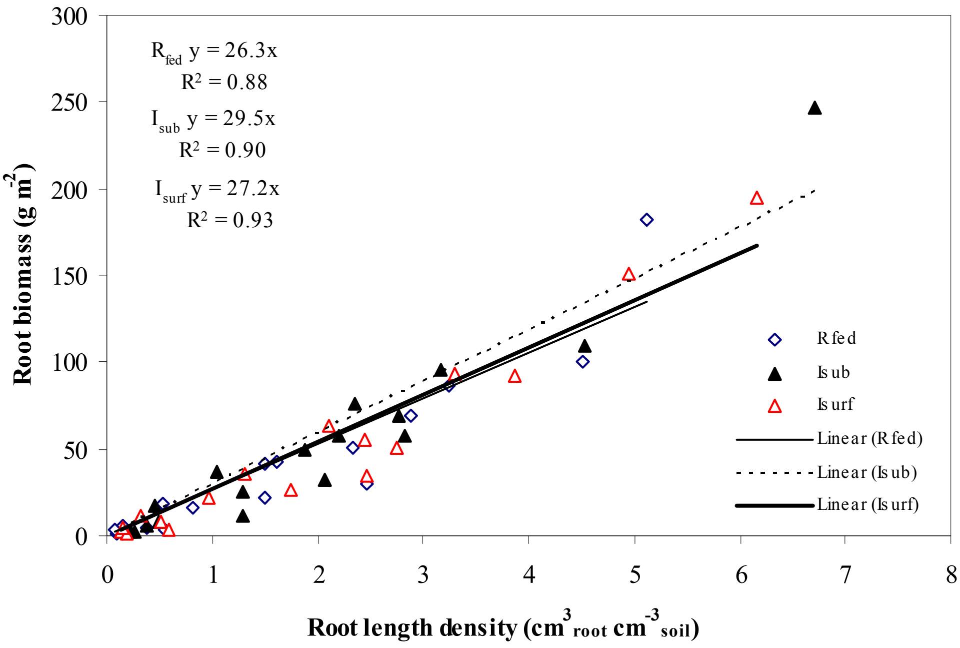

Figure 3.20 Root length densities in relation to root biomass in different treatments and in different sampling times during Dec1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

3.3.3.2 Root:shoot ratio

Lucerne root:shoot ratio for the R_{fed} treatment in summer 2000 was significantly ($P<0.001$) higher (1.53) than for both the summer irrigation treatments where root:shoot ratios for I_{sub} and I_{surf} were 0.50 and 0.46 respectively (Table 3.10). Towards the end of the 2000 winter-spring season the root:shoot ratio for the R_{fed} treatment was 1.08, much lower than during the summer and similar to that for I_{sub} (1.03), but still significantly higher ($P<0.05$) than the root:shoot ratio for I_{surf} (0.81).

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

Treatments	**Feb 2000**	**Oct-2000**
Rfed	1.53	1.08
I_{sub}	0.50	1.03
I_{surf}	0.46	0.81
LSD (α=0.05)	0.12	0.15

3.3.4 Total Non-structural Carbohydrates (TNC)

TNC varied significantly ($P<0.05$) between treatments and within the treatment over time although no distinct seasonal trends were observed (Figure 3.21). Overall means showed TNC was lowest for the R_{fed} treatment (36.3%) and also lower (($P<0.05$) in the I_{surf} treatment (39.61%) than I_{sub} (42.3%). In Jan 2000, the I_{sub} treatment was still at the highest level of TNC compared with the R_{fed} and I_{surf} treatments. The lowest level of TNC (28.5%) was recorded in the R_{fed} treatment near the end of summer (Feb 2000) compared to both the summer irrigated treatments. TNC was also low in the measurement taken in Mar 2000 in this treatment but differences were significant between R_{fed} and I_{sub} treatments only. During the 2000 growing season (May and July) the I_{sub} and I_{surf} treatments maintained greater TNC levels compare with the R_{fed} treatment. At the final sampling during April 2001 the TNC level was higher in the I_{sub} treatment than the R_{fed} and I_{surf} treatments, however, differences were significant only among R_{fed} and I_{sub} treatments.

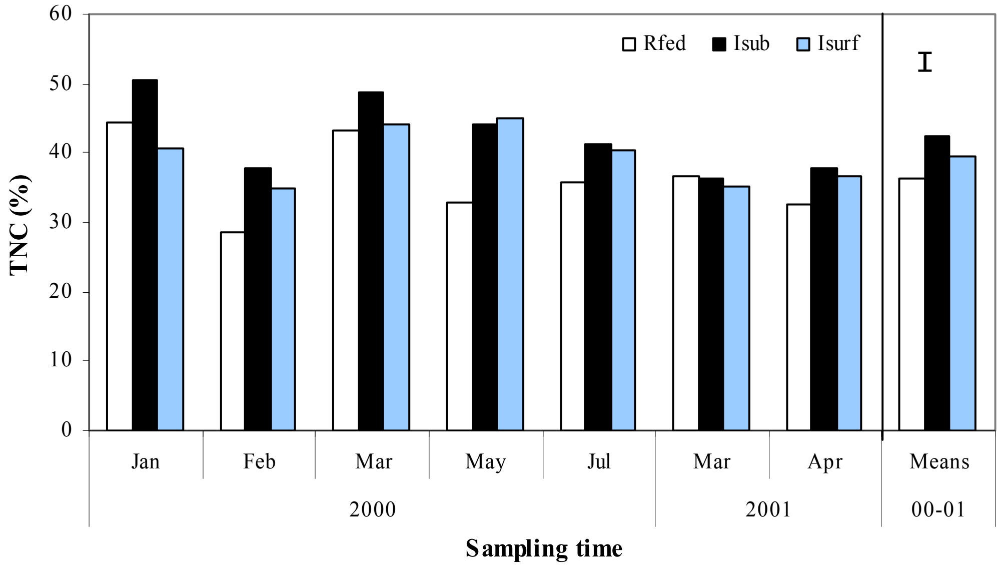

Figure 3.21 Total non-structural carbohydrates level (%) in taproots of rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation, during 2000-2001.

Error bars represent LSD (α=0.05) between treatments and *error bar is for comparison of a single set of treatment means over time.

3.4 Discussion

Integration of the results from this study enables a detailed insight into the growth, and to some extent the development of a lucerne crop grown on a duplex soil under Mediterranean climatic conditions in southern Australia. The following discussion will primarily focus on the major differences observed over a two-year period in the growth and yield of rainfed (dryland) lucerne compared with lucerne receiving various amounts of supplemental water over summer. The contributions of individual shoot growth components as determinants of yield will be examined and trends in belowground biomass accumulation described. The role of LAI in relation to PARi and the relationship of biomass with cumulative PAR_i will also be explored. Edaphic and climatic constraints to the productivity of lucerne will be highlighted, and the over-riding influence of water supply in determining yield in this particular study environment will be emphasized. The manner in which the water was supplied (i.e rainfall, sub-surface or surface irrigation) will, of course, have an important influence on subsequent availability to the plant; however, the details of this soil-plant water balance will be considered in the following chapter.

3.4.1 Lucerne dry matter yield and yield components

The lucerne stand had already been established for more than one year when the study commenced and had a relatively high plant density of 69 plants m^{-2} compared to the standard agronomic recommendation of 20-40 plants for this agro-climatic zone (Stanley and Christinat 1994). It was considered extremely likely that, at such high plant population, the lucerne had already exploited any stored soil moisture prior to the start of the study (Section 4.3.3.1-2). Since average rainfall during the study period was well below pan evaporation the rainfed crop-stand was assumed to be reliant on incident rainfall alone for production and survival. It appears that in the absence of required plant available water deep in the soil profile, rainfall events smaller than 20 mm d^{-1}, that are characteristic of this environment during the summer months, failed to cause a growth response in lucerne, and were presumably lost via soil evaporation. This was demonstrated by the very low productivity obtained in summer 2000 and a complete lack of shoot productivity during summer 2001 in the R_{fed} treatment in this study. Indeed, similar data supporting this lack of response over summer has been recorded for lucerne in the semi-arid Wimmera region of southern Australia (McCallum 1998, Lolicato 2000).

Furthermore, this study, particularly in the second summer season, demonstrated the compounding effect that high maximum air temperatures coupled with reduced water availability can have on plant growth and survival. During the first summer, total rainfall was above average (with one event of 74 mm) and maximum air temperatures were mostly average (28-30^{o}C), apart from in February when 34^{o}C was recorded. The number of stems, number of nodes and leaves per stem, and the maximum LAI ultimately achieved by the canopy was much lower over the summer than during the growing season (Apr-Nov) and resulted in yields less than 0.5 t ha^{-1}. Water stress is unanimously believed to have a detrimental effect on stem numbers per plant in lucerne (Cowet and Sprague 1962, Cohen *et al*. 1972, Perry and Larson 1972, Brown and Tanner 1983, Carter and Sheaffer 1983, Bolger and Matches 1990, Saeed and El-Nadi 1997), and there is some agreement that water stress also results in lower node and leaf numbers per stem (Perry and Larson 1974, Bolger and Matches 1990). However, Vough and Marten (1971) and Brown and Tanner (1983) have reported that soil moisture stress resulted in a greater number of smaller leaves, although this was not observed during this study. Unlike the negative response observed for many of the growth parameters, mean daily stem growth rates for the rainfed lucerne during this first summer were sometimes equal to, or greater than those achieved during the winter. This is a little surprising since it has often been reported that stem growth is more sensitive to moisture stress than leaf growth in lucerne (Brown and Tanner 1983, Carter and Sheaffer 1983a) and consequently causes an increase in leaf:stem dry weight ratio under low water availability (Whitfield *et al*. 1986, Halim *et al*. 1989). In this study leaf:stem dry weight ratio varied overall more widely for the rainfed lucerne, than in the treatments where water supply was more uniform, and, indeed, leaf:stem weight ratios were actually higher for the rainfed than for the irrigated treatments in late summer and early in the growing season in 2000. A contributory factor may be that leaf area expansion, enhanced by optimal temperatures, occurred in preference to stem growth at this time in response to the large single rainfall event in February. It has been reported for Australian rainfed conditions (McCallum 1998) that leaf:stem dry weight ratios in lucerne increased from 0.9-1.6 to 2.6-3.2 in summer under water stress conditions. Over the first summer there was also some reduction in plant population in the rainfed plots, from 69 to 50 plants m^{-2}, a similar decline to that reported by Latta *et al* (2001) for dryland lucerne during summer under Mediterranean climatic conditions in WA.

Rainfall was 30% below the long-term average in the second summer, with few effective rainfall events, and above-average temperatures were sustained for four months (Nov-Feb). Consequently, the low water availability interaction with high temperature caused a complete cessation of shoot growth and a large reduction in plant population to 20 plants m^{-2}. An even greater reduction in plant population from 60 to 7 plants m^{-2} over three years was reported (Bishop and Gramshaw 1977) for dryland lucerne in Australia. Similarly, Lloyd *et al.* (1985) also concluded that dry conditions contribute to poor plant survival. Since there was no evidence of disease on the shoots or roots of lucerne at any time during this study, these data suggest that air temperature sustained at 30°C or above, in conjunction with insufficient water, not only restricted growth and induced a temporary dormancy, but in some plants eventually triggers plant death, and hence a reduction in plant density. Key factors highlighted in the literature review (Chapter 2) as being associated with stand decline in lucerne are competition, disease, defoliation management and harsh environmental conditions (Bishop and Gramshaw 1977, Sheaffer *et al.* 1988, Lodge 1985, Lloyd *et al.* 1985), and clearly this last factor had a primary influence in this study. Although a contributory factor may have also been that the interval between defoliations for the rainfed treatment was slightly shorter than optimal due to a logistical requirement for synchronising cutting times for all three treatments.

Conversely, where water was supplied over summer, the high air temperatures had a positive effect on yield components such as stem density, stem growth rate, number of nodes and leaves per stem, and LAI. Plants were also taller, in agreement with reports by Vouge and Marten (1971) and Saeed and El-Nadi (1997). Shoot growth rate for irrigated lucerne was four times greater than that for rainfed lucerne, resulting in at least 5-6 times more dry matter production. There was an overall gradual decline in plant density in these treatments as a natural phenomenon of plant death over time (Heichel *et al.* 1984), but nothing as drastic as that which occurred in the rainfed treatment, even though much less irrigation water was supplied during the second summer. The observation in the 2nd year of the study that lucerne dry matter and growth under rainfed conditions was low, confirms reports by Melton *et al*. (1988) and Lolicato (2000), who found that when lucerne becomes rainfall dependent it can not perform to its potential, consequently production decreases drastically.

During summer 2000 where large quantities of water were supplied as surface (577 mm) or sub-surface (461 mm) irrigation, the potential for productivity of lucerne where water is not limiting was demonstrated. The surface irrigated lucerne yielded more than the sub-surface irrigated, probably because of the greater water supply and also the fact that the surface application might have encouraged earlier and quicker re-growth (Figure 3.4a). Although the quantity of irrigation water supplied was far less in summer 2001 (180 mm in I_{sub} and 195 mm in I_{surf}) it was sufficient to maintain a reduced level of shoot growth compared to the previous summer, whereas there was no growth at all in the rainfed.

Winter-spring productivity for the rainfed lucerne exceeded that for the summer periods and was about 4 t ha^{-1} which compares favourably with many other estimates (3-5 t ha^{-1}) for regions with Mediterranean climate (McCallum 1998, Latta *et al*. 2001 Hirth *et al.* 2001). Plants were taller, had faster stem growth rates, an increased number of nodes and leaves per stem, and achieved a higher LAI (~2.5-3), intercepted more light and transformed that light into dry matter better than those that grew over summer. Hirth *et al*. (2001) also recorded higher and less variable growth rates for lucerne during the growing season under Mediterranean climatic conditions in Australia and attributed this primarily to the increased quantity and reliability of rainfall. Although plant density was severely reduced in the rainfed lucerne following each of the summer periods, stem density in the rainfed treatment did not significantly decrease (over the entire two-year study period), and neither did leaf numbers per stem or TNC in taproots, which therefore demonstrated some compensation by the surviving plants for maintaining overall yield potential, and thus allowed the rainfed lucerne to achieve a similar LAI in winter 2001 as in winter 2000, despite the plant density being lower.

Nevertheless, comparison of growing season productivity between treatments clearly shows that water availability is a major limitation since lucerne that had received summer irrigation, particularly large amounts, demonstrated additional productivity in the growing season above that of the rainfed lucerne. There was therefore a residual effect probably due to storage of water in the soil profile where irrigation had exceeded plant demand (again, this will be quantified in the next chapter).

The highly positive linear relation observed in this study between quantity of water supplied (either as irrigation or rainfall) and lucerne dry matter yield is in accordance with reports by McCallum (1998), Sammis (1981), Sheaffer *et al.* (1988), Bolger and Matches (1990), Grimes *et al.* (1992), Saeed and El-Nadi (1997), and highlights the over-riding importance of water for plant production in these Mediterranean climates.

3.4.1.1 Phyllochron thermal time and development

Plant development was strongly driven by thermal time, but there was also a significant interaction between thermal time and photoperiod. There was a linear increase in main stem node appearance with accumulated thermal time (T_{b5}) in both the irrigated treatments in most of the regrowth cycles, with a high R^2>0.90 value indicating that thermal time is the main driver of this developmental process (Brown *et al.* 2005b). Further, greater number of nodes per main stem in summer regrowth cycles compared with winter also confirmed the above findings. There was some indication of water stress hastening plant development in the second summer in the irrigated treatments. Fewer nodes for most regrowth cycles in the R_{fed} treatment also confirmed an impact of water stress on node appearance (Grant and Barthram 1991) and consequently on phyllochron in this study.

Three distinct phyllochron 'seasons' could be identified; firstly a value around 31 ± 4 ^{o}Cd in winter and early spring, secondly a higher summer value, and thirdly a high value in autumn (~60 ^{o}Cd). An effect of photoperiod on phyllochron was also evident and has been reported in other studies (e.g. Robertson *et al.* 2002, Teixeira *et al.* 2007b). However, Brown *et al.* (2005b) reported a single phyllochron (37±7 ^{o}Cd) for winter spring and summer. The effect of photoperiod on phyllochron may be a function of highly variable treatment difference in terms of water regimes during the observational period, or perhaps may be a genetic factor. The use of a single T_{b5} value for all the seasons could be an over simplification. For example, Brown *at al.* (2005b) used two different base temperatures ($T_{b1/5}$). However, in a recent controlled environment study Brown *et al.* (2006) working with same lucerne cultivar 'Kaituna' using the same base temperature ($T_{b1/5}$), calculated a phyllochron of 30 ^{o}Cd compared to the earlier estimation of 37 ^{o}Cd, indicating the sensitivity of the relationship between environment and developmental mechanisms. The trend for phyllochron to increase during autumn was consistent with that reported by many others (Kahati and Lamire 1997, Moot *et al.* 2001, Brown *et al.* 2006, Teixeira *et al.* 2007b).

This phenomenon has been attributed to more assimilate being partitioned to root than shoot, leaving node appearance as source limited (Moot *et al.* 2001). The sharp decrease of phyllochron from ~ 60 ^{o}Cd at 13.21 hours photoperiod in autumn to ~ 40 phyllochron at 15 hours photoperiod points to a combined impact of photoperiod and season on the developmental process (Figure 3.11). Although only limited phenological data was collected in this study, the research points to the need for a better understanding of the interactions between temperature, photoperiod and water stress on developmental processes.

3.4.1.2 Shoot radiation use efficiency (RUE_{shoot})

RUE_{shoot} calculations are consistent with results reported elsewhere, but these data highlight the overriding influence of seasonal water stress on growth, light interception and RUE. Strong relationships between LAI and PAR_i and also PAR_i and shoot biomass within each growth cycle were demonstrated and concur with work by others (Avice *et al.*1997). This study reveals the full impact of the typical Mediterranean summer drought on lucerne. In general, RUE_{shoot} was always lower in R_{fed} treatments and it was also lower in irrigated treatments when reduced amounts of water (60-65 mm) were applied to both the irrigated treatments in summer 2001 (Figure 3.1). These results are consistent with Collino *et al.* (2005) and Whitefield *et al.* (1986b) who noted RUE_{shoot} tended to decrease under drought or limited water supply. The maximum RUE value of ~1.70 under non-limiting water condition was in close agreement with those reported by early workers (Goose *et al.*1984, Avice *et al.* 1997) and recently (Teixeira *et al.* 2008). It also confirmed that under non-limiting water conditions, radiation and temperature variability constitute the main influences on shoot biomass (Collino *et al.* 2005). The reduced RUE_{shoot} in autumn in both the years of the study also supports results of other workers (Kahaiti and Lemaire 1992, Varella 2002, Chen *et al.* 2003, Brown *et al.* 2006, Teixeira *et al.* 2008). However the observed reduction of RUE in late spring 2000 is not in agreement with other worker and it can be attributed to the reduced LAI in response to water stress (Brown and Tanner 1983) that caused rapid senescence and an exponential reduction in LAI at the 3rd measurement compared to the 1st and 2nd measurements (Figure 3.12). This is due to the typical characteristics of Mediterranean climate (rainfall pattern and temperature) prevailing in southern Australia in late spring where temperature increases and accelerates plant growth, combined with terminal water stress. Thus, demand for soil water increases and as is typical, there is no or little rainfall or stored soil moisture resulting in dramatic reductions in RUE_{shoot}. The detrimental effect of drought has already been documented by (Collino *et al.* 2005, Whitefield *et al.* 1986b). In general, the seasonal variation in RUE_{shoot} was not closely related to air temperature or vapor pressure deficit (VPD). Excluding the summer irrigation treatments, there was only a weak relationship (R^2 <0.35) between temperature and RUE indicating temperature has some influence (Teixiera *et al.* 2008), but is not a strong predictor under Mediterranean conditions. These results contrast with those of Collino *et al.* (2005) working in a much more benign climate in Argentina, who reported that lucerne RUE_{shoot} declined with temperatures below 21.1 ^{o}C. Differences in climate, particularly the severity of water stress, may explain these different findings.

3.4.2 Lucerne roots

It was only possible in this study to obtain intact cores for sampling lucerne roots to a maximum depth of 1.6 m, although in some plots roots were observed to a depth of 1.80 m. Reports for the maximum rooting depth of lucerne vary widely (Section-2.2.2), but there are several reports for southern Australia where rooting depths for lucerne range from 2-4.5 m (McCallum 1998, Douglas 1984, Kennett-Smith *et al.* 1990, Walker *et al.* 1992). It is highly likely that root growth and distribution have been limited by the nature of the duplex (texture-contrast) soil in this study, caused by the structural, textural and chemical changes inherent in the soil. Increases in soil bulk density, such as those recorded below 60 cm (Table 3.1), present a physical barrier to root penetration (Dardanelli *et al.* 1997). Other physico-chemical barriers to roots will also be presented by a pH in excess of 8.0 at 60 cm and below, the high calcium carbonate content of the soil and concentrations of boron greater than 15 mg kg^{-1} below 1 m depth. Furthermore, since lucerne reputedly has a moderately low tolerance of salinity (Stanley and Christinat

1994) the moderate to highly saline conditions below 60 cm (Table 3.1) may also have restricted root exploration. Indeed, although early in the study (Feb. 2000) roots in the rainfed treatment were present at least to 1 m depth, the majority (82%) were in the top 60 cm of the soil, with both root biomass and root length density declining sharply, in all treatments, with depth. Clarification of root activity at depth, inferred from soil water content changes, will be provided in the following chapter.

Root biomass was essentially lower in the R_{fed} treatment in Feb 2000 probably due to lower soil moisture availability and high summer temperature. Lou *et al.* (1995), studying the seasonal pattern root distribution of fine roots in lucerne, confirmed that root mass was generally greatest in the spring and autumn when mild soil temperatures (range 5-15 ^oC) and moisture were not limiting, and root mass was least during the summer under dry conditions. Whereas increased root mass in (0-20) cm soil depth in I_{surf} and (20-40) and (40-60) cm soil depth in I_{sub} can be associated with more soil water available in these depths (Abdul-Jabbar *et al.* 1982), and also higher leaf area with the potential for greater investment of photosynthate to roots (Klepper 1987, Lou *et al.* 1995).

Overall, relatively more root biomass was obtained in winter-spring sampling times (Oct 2000, and July 2001) rather than summer (Feb 2000) in all treatments. This may be due to sustained periods for growth in winter compared to summer as more frequent harvests and high soil temperature reduced root mass in summer (Lou *et al.* 1995). Root biomass will also be partially influenced by age of the lucerne stand (Pietola and Smucker 1995) and reduced plant populations over time.

RLD was also affected by soil moisture availability, seasonal variations and age of the lucerne stand. These results are not in accordance with those of Luo *et al.* (1995) who reported that soil moisture had little influence on root dynamics, and also with those of Knock *et al.* (1957) and Jodari-Karimi (1983) who concluded that lucerne roots grow deeper and became more fibrous under limited soil moisture regimes compared to irrigated conditions. Generally RLD data over time showed an increasing trend in RLD from Feb 2000 to Oct 2000 and July 2001 in upper soil depths of (0-20) and (20-40 cm) and was also likely to be related to the age of the lucerne stand (Pietola and Smucker 1995).

Clearly a sub-surface irrigation system, which delivers water deep in the soil profile, will be considered more efficient at supplying water for plant-use than an irrigation system which delivers water at the soil surface where it is more prone to evaporative (17-70%) losses (Kohl and Kolar, 1976, Ayars *et al.*1999). Indeed, sub-surface supply of water should be suited to lucerne which is well-renowned for the ability to exploit water at depth (Scott and Sudmeyer 1993), and in this study the sub-surface supply of water did encourage a greater proportion of roots at depth. However, this was only in the first summer when large quantities of water had been supplied, so that in February 2000, 27% of the roots present to 1 m were below 40 cm, compared to 20-21% for the R_{fed} and surface irrigated lucerne. The large amount of water supplied did have a residual effect over the 2000 growing season and an assessment of the roots in October 2000 revealed that an even higher proportion (33%) were below 40 cm in the lucerne that had been sub-surface irrigated over summer, whereas proportional distribution in the other treatments had not changed.

The results confirmed the findings of Paltridge (1955) who found that lucerne root distribution usually reflects the pattern of available soil water. Indeed lucerne root density following rewatering was found to be greater than it had been prior to the period of soil dryness. It seem that root growth is not essentially completely a permanent structure rather a dynamic one and a rapid flush of new fine roots growth in response to extra available water was an essential feature of this phenomenon in each growing season.

3.4.2.1. Root:shoot ratio

Higher root:shoot ratio in dry treatment in summer (Feb 2000) further confirmed the findings of Brown and Tanners (1983) and Whitfield *et al.* (1986) who had reported that lucerne diverted more assimilates to root growth under water stress resulting in a high root: shoot ratio. Further, the root:shoot ratio (1.5) found in this study, higher than many reported in the literature, is in-accordance with the results of McCallum (1998), indicating the severity of stress prevailing in dryland lucerne in South Australia during summer. When stress was removed as result of rainfall in the growing season the root:shoot ratio was much decreased in the rainfed treatment during winter (Oct 2000) compared to summer. However the higher root:shoot ratio in both the irrigated treatments can be attributed to cooler temperatures when lucerne partitioned more of assimilates to roots thus increasing root:shoot ratio (Smith 1962).

3.4.3 Total Non-structural Carbohydrates (TNC)

The results demonstrated that generally the TNC level was significantly lower in the R_{fed} treatment compared with both the irrigated treatments. Further it was higher during the first year compared to second year in all treatments. This can be attributed to the lower LAI, frequent harvesting under limited soil moisture, and the number of times that LAI was well below the critical level (~3.6) necessary to replenish the root reserves of TNC. These findings are consistent with Ritchie and Burnett (1971), Robison and Massengale (1968) and Klepper (1987), who established that a sustained LAI in the range ~3-4.5 for two weeks before the onset of flowering is necessary for growth, plant maintenance and replenishment of carbohydrate reserve in lucerne. This LAI (3-4.5) was observed in both the irrigated treatment for most of the sampling times in 2000. However, the lower quantity of TNC in all the treatments in March 2001, could mainly be caused by the response of lucerne to the reduction in photoperiod in autumn with more assimilate investment towards perennial organs like taproots for survival (Cunningham and Volence 1997, Brown and Tanners 1983) suppressing all other factors. The generally low TNC in the R_{fed} treatment can be attributed firstly to the long periods of water stress when replenishment of carbohydrate reserves was not possible, and secondly to the relatively frequent cutting regime that led to reduced TNC (Smith 1962, Brouwer 1983).

3.5 Conclusion

The following main points were concluded from the work reported in this chapter:

- Shoot growth and yield of dryland lucerne in the Roseworthy environment was severely limited, primarily by incident rainfall, but temperature interactions were also important.

- Plant population was influenced by water and temperature, and under rainfed conditions declined rapidly, although the plants partially compensated by increasing stem density.

- Under irrigated conditions lucerne was able to exhibit higher RUE_{shoot} (~1.7 g DM MJ^{-1}) in agreement with maximum RUE values established by earlier researchers.

- The phenomenon of autumn reduced RUE_{shoot} reported by other workers was also apparent under non-limiting water regimes, although there was a large degree of variability in RUE across seasons.

- Phyllochron was shown to increase from 31 to ~60 ^{o}Cd as autumn progressed, indicating a variable phyllochron under Mediterranean environmental conditions.

- Temperature is the main driver of developmental processes in this environment, but water stress can also influence development to a small extent.

- TNC in lucerne was severely affected by LAI and environmental factors and under stress conditions lucerne invests more in TNC in the taproot for survival.

- Root growth was restricted by subsoil constraints, the majority of biomass being in the top 40 cm soil, this was due to more than just low water availability and reflected other constraints associated with this duplex soil type.

Chapter 4

4 Water use and water use efficiency of lucerne on a duplex soil under semi-arid Mediterranean climatic conditions in response to varying water supply during summer

4.1 Introduction

Lucerne has demonstrated a potential to dry the soil profile to depth and combat the menace of deep drainage in Australia because of its deep and extensive root system, perennial nature and adaptation to a wide range of climatic conditions (Section 2.3) However, the depth and extent to which lucerne roots can grow in a duplex (texture contrast) soil and extract soil water will vary, depending primarily on the soil characteristics and on factors that influence plant canopy and water-use. How efficiently the extracted water can be transformed into plant biomass needs to be assessed and the measure of this is usually termed water use efficiency (Tanner and Sinclair 1983) which for a rainfed system is sometimes called precipitation use efficiency (Hatfield *et al.* 2001). Lucerne water use has been called profligate since often seasonal evapotranspiration rates are higher compared to other crops (Blad and Rosenberg 1976). Indeed, values reported for WUE also support this argument although it varies widely from 2 to 26 kg ha^{-1} mm^{-1} depending upon climatic factors like temperature, radiation, vapour pressure deficit (VPD) and seasonal conditions, soil water availability, soil fertility, cultivar potential and management (Section 2.3.3). Higher VPD during the day can cause a considerable reduction in water use efficiency (Tanner and Sinclair 1983). Lucerne, being perennial, undergoes a number of cutting and regrowth cycles and is thus exposed at different times of the year to varied combinations of solar radiation, temperature and soil moisture regimes, which makes it more prone to being affected by changing climatic factors (Collino *et al.* 2005). The extreme variability in amount and distribution of rainfall and the high VPD in summer that are characteristic of Mediterranean climate can further compound this issue and ultimately, decreased growth and water use of lucerne may lead to recharge (Zhang *et al.* 1999). Thus, the performance of lucerne for decreasing recharge will always be specific to site and season, and potential benefits may change from year to year depending on the prevailing climate (Ridley *et al.* 1997, Lolicato 2000, Ward 2006).

Clearly, it is therefore very important to compile detailed local data for the water balance of any lucerne-soil system, thus enabling a greater degree of confidence in application of predictive models to assess the long-term effects of growing lucerne in particular situations. Although there have been some field studies of lucerne under Mediterranean climatic conditions in southern Australia (McCallum *et al.* 2001, Ward *et al.* 2001 and Latta *et al.* 2001, Ward 2006, Dolling *et al.* 2005), data specifically describing the performance of lucerne in South Australia is insufficient for testing models such as APSIM, and in particular data for variable summer rainfall periods for the widespread region of duplex soils is lacking.

Therefore, the major focus of the research reported in this chapter was to characterise the duplex (texture contrast) soil at Roseworthy in terms of plant-available water and to describe the temporal pattern of extraction of that water by lucerne so that seasonal water use and conversion of that water into shoot biomass over a period of two years could be quantified. Further the effects of simulated summer rainfall events on the soil-plant water balance, water use and productivity in lucerne was also assessed.

4.2 Materials and methods

4.2.1 Experimental site – climate, soil, treatments and design

Details of the experimental site, climate, management, soil type, treatments and design are presented in Chapter 3.

4.2.2 Soil bulk density, total porosity and saturation

At the start of the study samples of soil for bulk density were taken mechanically using a hydraulic rig with a core of 70 mm diameter for soil depths from 0-70 mm and 50 mm diameter for the remaining depths up to 1800 mm. Sampling depths for bulk density corresponded to the soil layers to be measured for soil water content. Soil at 900 mm depth and below exhibited shrink-swell properties and therefore calculated bulk density (CBD) for the lower layers was determined using the following equation given by Dalgliesh and Foale (1998):

Calculated Bulk Density = (1-0.08)/(1/2.65 + gravimetric water content) (Eq. 4.1)

To describe the soil water holding characteristics and identify potential periods of water logging or drainage, total porosity (PO) and saturation (SAT) were also calculated using the following equations:

$$\text{PO } (\%\text{v/v}) = (1 - \text{BD or CBD}/2.65) \times 100 \qquad \text{(Eq. 4.2)}$$

$$\text{SAT } (\%\text{v/v}) = (\text{PO} - e) \times 100 \qquad \text{(Eq. 4.3)}$$

Where "e" ranged from 0.03 for the heavy clay soil layers of the B horizon to 0.07 for the sandier A horizon soils (Dalgleish and Foale 1998).

4.2.3 Soil water content (SWC) measurement

A steel access tube with a sealed lower end was installed in each plot in December 1999, to a depth of 3 m. During most of the study soil water content (SWC) was measured fortnightly using a neutron moisture meter (NMM, Campbell Pacific Nuclear Corps, Martinez California Model 503) except for the period January-April 2001 when it was measured weekly. Measurements, using the NMM were made at 10 points in the soil profile to a depth of 3 m: ie. at 150, 300, 500, 700, 900, 1200, 1600, 2000, 2400, 2800 mm. A polycarbonate sheet was used to reduce the emission losses in upper layer of 150 mm. The NMM was calibrated by simultaneous measurement of NMM and gravimetric water content; the latter was estimated from soil cores taken using the automatic drill rig as described earlier (Section 4.2.2) on five separate occasions so that the profiles ranged in water content from very wet at the drained upper limit (DUL) to extremely dry at the crop lower limit (CLL). Gravimetric water contents were converted to volumetric using appropriate bulk density values and linear regression relationships were determined between count ratio (x value) and volumetric water content (y value) for each soil depth. Different calibration equations were determined by using linear regression for different sections of the soil profile depending on soil characteristics, and are listed below:

(0-400 mm soil depth) $y = 0.4949\,x - 0.0022$ $R^2=81$ (Eq. 4.4)

(400-1000 mm soil depth) $y = 0.6373\,x - 0.0255$ $R^2=85$ (Eq. 4.5)

(1000-2800 mm soil depth) $y = 1.0924\,x - 0.1978$ $R^2=78$ (Eq. 4.6)

A decline in plant density during the study period in all treatments (Section 3.4) resulted in a reduction in the numbers of plants in the vicinity of the NMM access tubes; this was particularly evident in the R_{fed} treatment where there were no plants left close to the access tube in one replicate by the end of the study and therefore average data for three replications was used for this period.

4.2.4 Plant available water content (PAWC)

Determination of plant available water required measurement of bulk density (BD), drained upper limit (DUL) and crop lower limit (CLL) for the soil profile. DUL or field capacity is also important for determination of the water holding capacity of the soil, and thus for deep drainage estimates. DUL was measured using the 'ponding' method (Dalgliesh and Foale 1998). Briefly, for this purpose a circular soil bund of 1.5 metre radius and 30 cm height was constructed around an access tube and filled with water twice daily for 5 days. NMM monitoring was carried out regularly until saturation was observed and then the area was covered with plastic. Three days later soil core samples were taken up to 2 metres depth for gravimetric water content measurement; due to the slow drainage in the clay textured soil at depth another sampling was done three weeks later for determination of gravimetric water content. Gravimetric water contents were converted to volumetric water contents as described previously. Crop lower limit (CLL) for the 3 m soil profile was determined from the mean of the lowest recorded NMM measurements.

Volumetric soil water content measured for each depth was converted to soil water content (SWC mm) using the following equation (Lolicato 2000):

$$\text{SWC (mm)} = \text{Volumetric SWC} \times \text{depth of soil layers (mm)} \qquad \text{(Eq. 4.7)}$$

Profile water content was thus calculated as the sum of the soil water contents at each depth. Plant available soil water content (PAWC) or extractable soil water content was defined as the difference between the DUL and minimum observed profile or crop lower limit (CLL).

4.2.5 Evapotranspiration (ET)

Potential evapotranspiration (ET_p) was calculated from weather data using the following approaches:

(a) The Priestly-Taylor (1972) equation:

$$ET_p = \alpha\ (s/(s+\gamma)) * (Rn-G) \qquad \text{(Eq. 4.8)}$$

Where α is a constant (1.26), γ is the latent heat of vaporisation, Rn = net radiation, s = slope of the saturation vapour pressure curve at temperature T (°C) and G = ground heat flux (usually ignored as it is a small term).

(b) Modified Priestley-Taylor equation (Dunin– pers. Comm) where, based on a number of measurements for these drier environments, it is assumed that Rn-G, viz. net radiation minus ground heat flux, is constant at 60% of radiation, so Rn-G = 0.6 Rn. Actual evapotranspiration (ET_a) was calculated for each growth period, using the water balance equation, according to Ward *et al*. (2000).

$$ET_a = P+I \pm \Delta SW-R-D \qquad \text{(Eq. 4.9)}$$

Where P is rainfall, I is irrigation and ΔSW is the change in soil water storage or depletion for that specific growth period. Runoff was considered negligible due to (a) the flatness of the landscape and (b) the fact that it was never observed during the study even when a large quantity of water was applied as surface irrigation during the first summer. Drainage, inferred from soil water content change below the effective rooting depth (Section 4.2.7) was also minimal (Section 4.3.7).

The estimates of ET_a from the water balance method were compared with those calculated using the composite approach (ET_c) introduced by Ward and Dunin (2001) for shallow duplex soils in Mediterranean environments, where it is assumed that $ET_a = ET_p$ for times when the soil surface remains fairly wet i.e. from the break of season until rapid decline in soil moisture content in early spring. The assumption, therefore, also has been used in this study for estimating ET_c during the irrigated summer period in 2000 where water was applied to keep the soil surface moist only for surface irrigation. These different approaches to estimating ET were evaluated to compare ET under variable water supply and to suggest which approach is simple and workable for areas with a duplex soil in South Australia.

4.2.6 Soil evaporation (E_s)

Microlysimeters (Boast and Robertson 1982, Yunusa *et al.* 1993) were used to determine soil evaporation (E_s) pattern under lucerne in different treatments for short periods during the summer (February 2001). These observations for E_s were made immediately after cutting the lucerne, when soil was relatively bare. Briefly, PVC tubes 70 mm internal diameter 100 mm in height were inserted into the soil immediately following irrigation, these were then excavated, the lower end sealed with a cap and then the microlysimeter replaced in the ground (8 per treatment). The microlysimeters were weighed at the same time every day until there were no recorded further changes in weight. The amount of moisture lost daily via evaporation was calculated from the change in microlysimeter weight. Although these limited observations provided some actual data for evaporation from lucerne over summer in this location, the information was not as comprehensive as determined by other workers (e.g. Johns 1982 a, b) and also insufficient to extrapolate for this study. Therefore, E_s for each of the growth cycles during the study period was also estimated using APSIM.

4.2.7 Drainage (D)

Drainage beyond the estimated rooting depth of 1800 mm was inferred from changes in soil water content of the 1800-3000 mm soil depth for those treatments and time periods where potential evapotranspiration (ET_p) was higher than actual evapotranspiration (ET_a). Similarly drainage, for those treatments and time periods was also calculated using the water balance equation, as follows:

$$D = (P+I) - ET_p - \Delta SW \qquad \text{(Eq. 4.10)}$$

Where D is drainage, P is rainfall, I is irrigation, ET_p is potential evapotranspiration and ΔSW is the change in soil water storage for a specific time period. Runoff was assumed to be negligible as stated previously.

4.2.8 Water use efficiency (WUE, WUE_n) and transpiration efficiency (TE)

WUE was calculated as the ratio of harvested dry matter produced (kg) to water use (ET_a mm) estimated using the water balance equation for each regrowth cycle. A normalized water use efficiency (WUE_n (Kg DM ha^{-1} mm^{-1}.kpa) was also calculated for each regrowth cycle as the increased VPD can cause increase in ET_a with no added effect on dry shoot biomass (Tanner and Sinclair 1983). Therefore first, ET_a was normalized by dividing it by average daylight VPD of the regrowth cycle (Brown *et al*. 2005a). The VPD used for WUE_n were estimated daily as the difference between the average daily saturated vapour pressure and the actual vapour pressure using daily maximum and minimum temperature and daily maximum and minimum relative humidity (Allen *et al*. 1998). Since evaporation occurs during the day, the sum of the VPD at daily minimum and maximum temperature was multiplied by 0.7 to give more weighting to daylight hours (Tanner and Sinclair 1983, Howell 1990). TE was calculated as the ratio of cumulative dry matter produced to cumulative water transpired (i.e. ET_a-E_s) at each harvest. APSIM estimates of Es were used in these calculations and the same values of Es were used for R_{fed} and I_{sub} since the microlysimeter experiment demonstrated no measured difference in evaporation between the two treatments (Section 4.3.6).

4.2.9 Statistical analysis

Analysis of variance was performed on data for profile SWC and PAWC, for each growing season separately, using a split plot design (Genstat) by considering treatment as main plot and date as sub plots. Means were separated using least significant differences LSD ($\alpha = 0.05$) for each growing season. Analysis of variance was also carried out for volumetric SWC in each depth for different growing seasons, water use, WUE and WUE_n by considering treatment as main plot and date as sub-plots over the whole study period. Regression analysis was performed to determine any relationship between cumulative dry matter obtained in single growing cycles and water transpired during that period. Microlysimeter data was analysed using one-way ANOVA (in randomised blocks) and means were separated using LSD at ($\alpha = 0.05$).

4.3 Results

4.3.1 Climate

Characteristics of the Mediterranean type climate at the site have been described in (Section 3.2.1). The total quantity of water applied/received between each harvest did not exceed pan evaporation for the same period, apart from in February 2000 when the 283 and 266 mm of irrigation water applied in I_{surf} and I_{sub} treatments respectively, matched pan evaporation (Figure 4.1). Average monthly VPD values (Figure 4.2) ranged from 0.24 kpa in winter to 1.76 kpa in summer. Daily value ranged from 0.14 kpa on the coldest day (-0.1°C) on 12th August 2000 to 5.73 kpa on the warmest day (>45°C) on 12th January 2001.

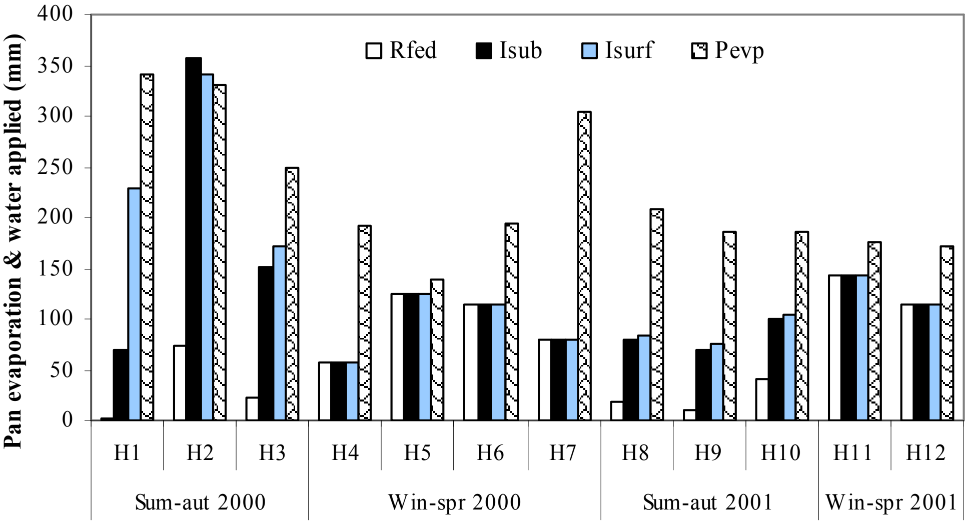

Figure 4.1 Pan evaporation and water received (mm) through rainfall or applied as irrigation for each harvest (H1-H12) during the study in rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the two year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

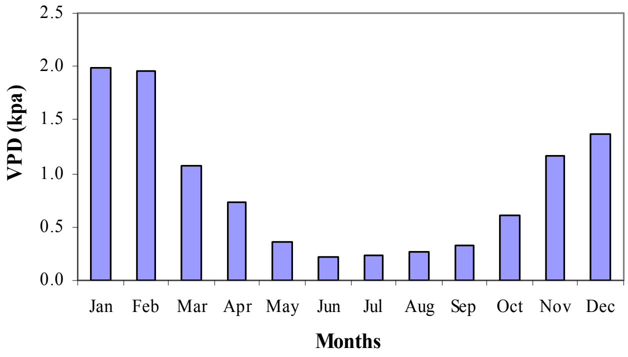

Figure 4.2 Monthly average vapour pressure deficit experienced at Roseworthy experimental site during the two year study period (Dec 1999 to Sep 2001).

4.3.2 Soil physical characteristics

Mean calculated bulk density for the upper soil profile (0-700 mm) was 1.26 Mg m^{-3}, ranging from 1.23-1.30 Mg m^{-3}, increasing below 700 mm to 1.41 Mg m^{-3} where the soil exhibited shrink-swell characteristics (Table 4.1). Porosity was greater in the upper soil profile (0.51-0.54 m^3 m^{-3}) due to the greater proportion of sand and decreased to 0.47 in the heavier clay of the lower profile (Table 4.1).

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

Depth	OBD	CBD	θv CLL	θv DUL	θv sat	ρ	PAWC
mm	Mg m^{-3}		----------------------		m^3 m^{-3}		-------------------
100	1.30	1.30	0.11	0.26	0.44	0.51	30
300	1.23	1.23	0.11	0.25	0.47	0.54	28
500	1.24	1.24	0.13	0.26	0.46	0.53	26
700	1.26	1.26	0.15	0.26	0.45	0.52	22
900	1.41	1.41	0.18	0.26	0.42	0.47	16
1200	1.49	1.41	0.20	0.28	0.43	0.47	32
1600	1.56	1.41	0.25	0.30	0.44	0.47	20
2000	1.59	1.41	0.31	0.33	0.44	0.47	08
2400	1.59	1.41	0.37	0.39	0.44	0.47	08
2800	1.59	1.41	0.38	0.39	0.44	0.47	04

Where OBD is for observed bulk density, CBD is for calculated bulk density, θv CLL is for crop lower limit, θv DUL is for drained upper limit, sat is for saturation, ρ is for porosity and PAWC is for plant available water content.

4.3.3 Soil water content (SWC) to rooting depth (0-1800 mm)

Observations of the difference in SWC between the beginning of the study (Dec 1999) and at the end of a relatively dry period in early April 2000 demonstrated that lucerne, regardless of the treatment, was extracting water to a depth of approximately 1800 mm (Figure 4.2) and this corresponded to the measured presence of active lucerne roots (Section 3.2.5). There was no difference in SWC (mm) throughout the rooting depth profile (0-1800 mm) under any of the designated treatments (Figure 4.3c) at the commencement of the study in December 1999. However, a steady decrease in SWC was observed for the R_{fed} treatment over the first summer-autumn period (2000) and SWC was significantly lower ($P<0.001$) compared to both irrigated treatments for the last measurement time in this period and into the winter 2000 period (Figure 4.3c). SWC of this profile in the R_{fed} treatment was lowest (318 mm) on 10th February 2000 and highest (400 mm) on 3rd September 2001. SWC of the rooting depth profile increased with onset of irrigation, regardless of whether it was surface or sub-surface, and the highest SWC for this profile (485 mm for I_{sub} and 349 mm for I_{surf}) was recorded in Feb-Mar 2000 (Figure 4.3b&c), but these amounts of water were less than the determined value for the DUL (490 mm) for this soil profile indicating that maximum water holding capacity was not reached. A residual effect of summer 2000 irrigation treatments resulted in the SWC to the depth of rooting of the irrigated treatments being significantly greater than the R_{fed} up to October during the 2000 growing season.

Due to the texture change that occurs within the rooting depth profile it is useful to discuss SWC of the upper part of this profile (0-600 mm) separately to that in the lower part (600-1800 mm), as in the following sections.

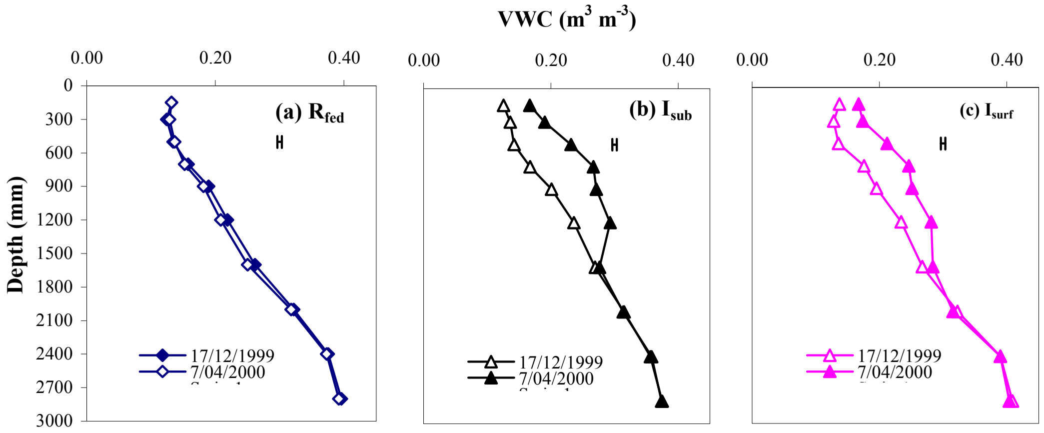

Figure 4.3 Volumetric soil water content (m^3 m^{-3}) on 17/12/1999 and 7/4/2000 for soil profiles indicated by Neutron meter ata under (a) rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via (b) surface (I_{surf}) or (c) sub-surface (I_{sub}) irrigation during the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

4.3.3.1 0-600 mm soil profile

The minimum recorded SWC i.e the crop lower limit (CLL) in the 0-600 mm soil profile was 69 mm, recorded for the R_{fed} treatment in February 2000 and March 2001 (Figure 4.4a). There was a rainfall event of 72 mm at the end of February 2000 (Figure 3.3) that increased SWC from 69 to 119 mm in the 0-600 mm soil profile (Figure 4.4a) in the R_{fed} treatment. This had no impact on SWC of the 600-1800 mm soil profile (Figure 4.3b), and a large proportion of this water in the upper profile was either used by the crop or had been evaporated by the next measurement time. After the onset of growing season rainfall, in 2000, the SWC increased in the 0-600 mm soil profile for all treatments over the winter and, although the SWC in the R_{fed} treatment in this profile was lower than that of the irrigated treatments, there were no significant differences by spring 2000.

Residual effects of irrigation on SWC in the 0-600 mm profile were clearly evident in the 2000 winter growing season (Figure 4.4a) but by spring 2000 a continuous decrease in SWC was observed in this profile. After limited application of irrigation (Figure 3.3) in both irrigated treatments in summer 2001 SWC was again significantly higher at some measurement times in I_{sub} and I_{surf} treatments than the R_{fed} treatment ($P<0.001$) but the profile quickly dried-out so that there were no residual effects on SWC in this 0-600 mm soil profile and during winter 2001 there was little variation in SWC content for different treatments (Figure 4.4a). The highest SWC in this 0-600 mm profile for the R_{fed}

treatment (141 mm) was observed in September 2001. Despite the supplemental irrigation and above average rainfall, during summer (2000) as well as in the growing seasons of years 2000 and 2001, SWC for the 0-600 mm profile never exceeded the calculated DUL (154 mm) in any treatment.

4.3.3.2 600-1800 mm soil profile

The SWC of the 600-1800 mm soil profile (Figure 4.4b) fluctuated less than the upper part of the soil profile in response to irrigation or rainfall events. However it was consistently lower in the R_{fed} treatment compared to both the irrigated treatments, with no differences between I_{sub} and I_{surf} throughout the study period. The initial large increase in SWC observed after irrigation in 2000 was similar to that observed for the 0-600 mm soil profile and there was significantly ($P<0.005$) greater SWC in I_{sub} and I_{surf}, compared to the R_{fed}, from February until mid-July 2000. The lowest value for SWC (CLL) in this profile, 243 mm, was observed in spring 2000 in the R_{fed} treatment. Generally there was little variation in SWC in the R_{fed} treatment during the two years of the study period (Figure 4.4b) and it was close to the CLL at most of the measurement times.

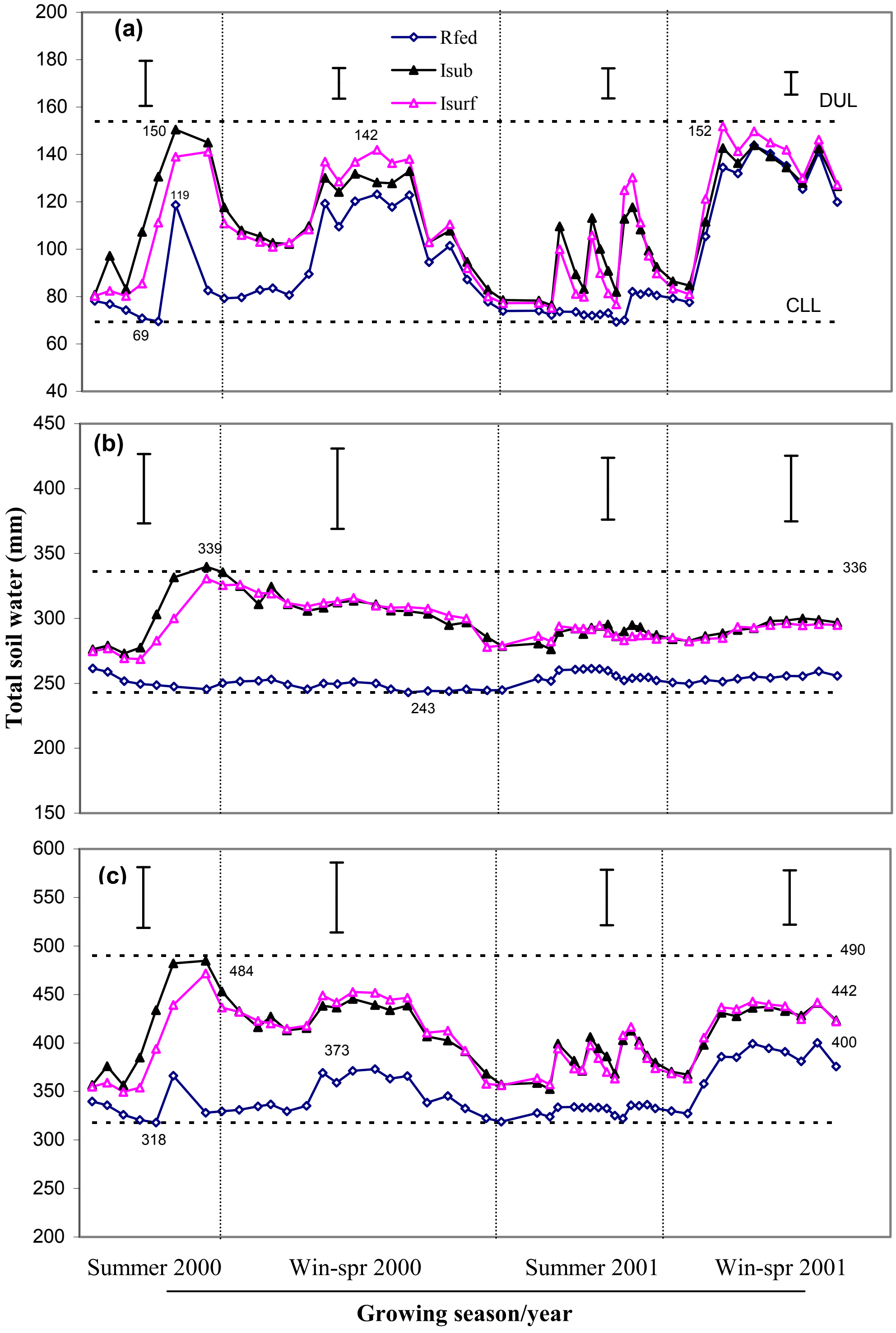

Figure 4.4 Total soil water content (mm) in (a) 0-600, (b) 600-1800 and (c) 0-1800 mm soil profiles under rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the two year study period (Dec 1999 to Sep 2001).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

4.3.4 Plant available water content (PAWC)

During the whole study period PAWC in the R_{fed} treatment was lower, in both 0-600 and 600-1800 mm soil profiles, compared to treatments where irrigation, even small amounts, was applied during the summer (Figure 4.5). On average, across summer 2000 significantly ($P<001$) less water was available for plants in the 0-600 mm soil profile under lucerne in the R_{fed} treatment, 12mm compared to 44 and 34 mm respectively in I_{sub} and I_{surf} treatments. PAWC in the R_{fed} treatment was zero in this 0-600 mm profile in the mid-summer 2000 and after the onset of rainfall it increased gradually to a maximum (54 mm) in mid-growing season 2000 (Figure 4.5b). A further decrease in PAWC in the R_{fed} treatment was observed during the next summer (2001) and PAWC was only 6 mm in the 0-600 mm soil profile, reaching zero by mid-summer 2001. Across growing seasons more water was available in 2001 than 2000 in all treatments in the 0-600 mm soil profile (Figure 4.5a).

A steady decrease in PAWC from 18 to 2 mm was recorded in the lower soil profile (600-1800 mm) over summer-autumn 1999/2000 in the R_{fed} treatment (Figure 4.5b). During the growing season of 2000 rainfall had very little effect on PAWC in this profile and therefore by spring 2000 PAWC was zero for the R_{fed} treatment. However in 2001 PAWC responded differently in this profile (600-1800 mm) and was higher in summer 2001 than 2000.

Despite the fact that more water was applied in the I_{surf} than the I_{sub} treatment during summer 2000 (Figure 4.1) mean PAWC in the I_{sub} treatment (~ 46 mm in the 0-600 mm soil profile and ~ 63 mm in the 600-1800 mm soil profile) was higher than the I_{surf} treatment (Figure 4.5a). A residual effect of irrigation on PAWC during the growing season 2000 (Figure 4.5) was also evident in both the irrigated treatments. Even though a relatively limited amount of water, 180 and 195 mm in I_{sub} and I_{surf} respectively, was applied through three irrigations in summer 2001 the PAWC in the irrigated treatments was greater than the R_{fed} treatment, in summer and in winter 2001 (Figure 4.4a&b). The maximum PAWC for the rooting depth soil profile (0-1800 mm), calculated from the difference between when it was at its lowest (10th Feb 2000) and highest (3rd Sep 2001), was 82 mm for the R_{fed} treatment; whereas it was 122 and 132 mm in I_{sub} and Isurf treatments respectively, representing 70-76% of the estimated PAWC content at field capacity (Figure 4.4c).

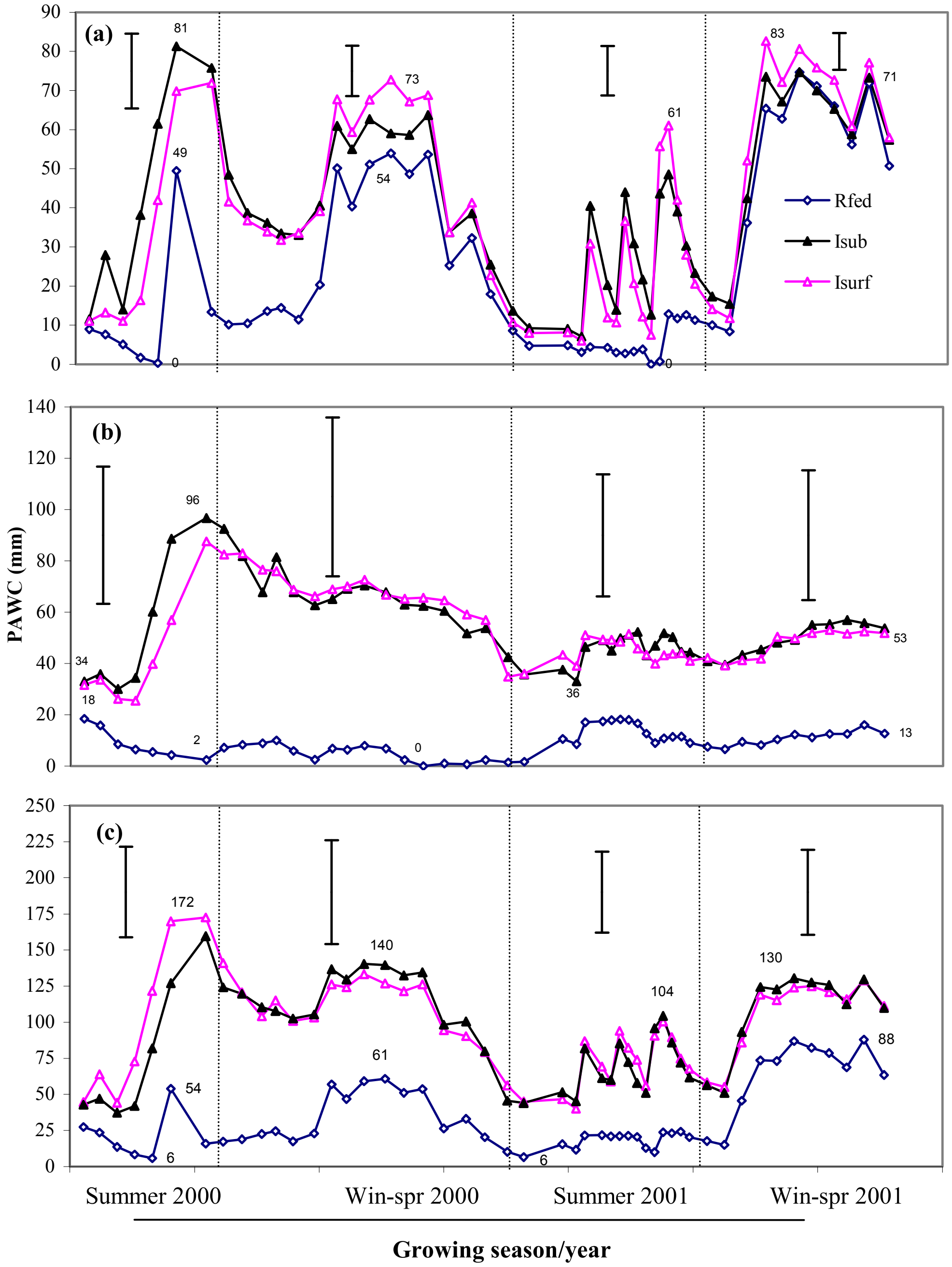

Figure 4.5 Plant available water content (mm) in (a) 0-600, (b) 600-1800 and (c) 0-1800 mm soil profiles under rainfed (R_{fed}) lucerne and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the study period (Dec1999 to Sep 2001). Error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

4.3.5 Evapotranspiration (ET)

4.3.5.1 Actual evapotranspiration (ET_a)

During both summer periods in the study ET_a or total water use, determined from Equation 4.9 was significantly lower ($P<0.001$) for the R_{fed} treatment than the irrigated treatments (Table 4.2). ET_a in the R_{fed} treatment exceeded rainfall during the 2000 summer period (Figure 4.1) indicating extraction of stored soil water from the profile (Figure 4.3a). There were no treatment differences in total water use at harvests 6-8 during the growing season 2000 but ET_a was significantly lower at H4 in the R_{fed} treatment than the I_{sub} and I_{surf} treatments and significantly higher in I_{sub} than R_{fed} at H7 (Table 4.2). Although the R_{fed} lucerne produced no shoot growth in summer 2001 (Section 3.3.2.1) ET_a was similar to that in summer 2000 indicating water losses through Es, whereas in the irrigated treatments, where less water was applied than in the previous summer, ET_a was lower (Figure 4.1). Despite the significant decrease in the plant population in the R_{fed} treatment during summer 2001 (Section 3.3.2.4), there were no significant differences in ET_a between any of the treatments during the following 2001 growing season (Table 4.2). Total water use was similar in irrigated treatments in 11 out of the 12 harvests, the exception being H1 when ET was higher ($P<0.001$) in I_{surf} than I_{sub} (Table 4.2).

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

Treatment	Summer 2000			Win-spr 2000				Summer 2001			Win-sp 2001	
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12
R_{fed}	18	31	59	48	90	147	95	20	10	40	75	139
I_{sub}	55	245	164	98	107	153	117	107	55	106	86	128
I_{surf}	231	253	156	90	92	156	132	106	77	101	73	136
LSD (0.05)	27.65											
SLT*	28.76											

*Same level of treatment

There was a strong relationship (R^2=0.99) between cumulative ET_a calculated using the water balance equation and estimated using the composite approach (Ward and Dunin 2000) for the irrigated treatments (Figure 4.6). This suggests that the composite approach can also be used under supplemental water supply during summer, as well as under rainfed conditions during a growing season, provided that sufficient water is applied to maintain a moist surface during that period. However, the composite approach overestimated ET_a in the R_{fed} treatment, especially in the 2001 growing season (Figure 4.6).

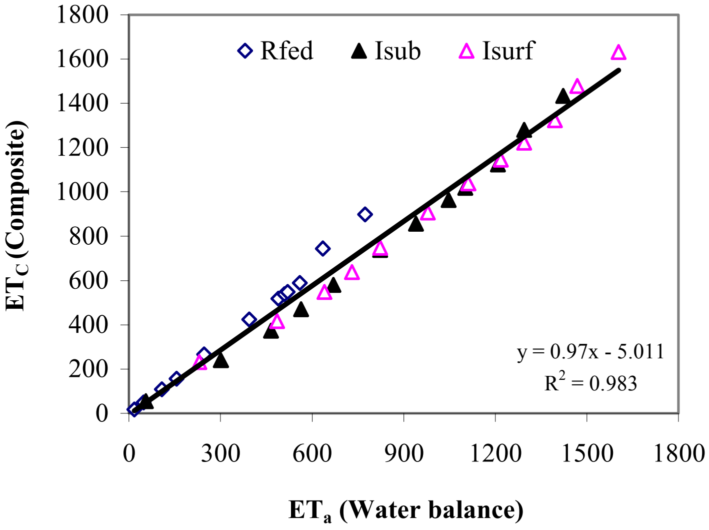

Figure 4.6 Comparison between cumulative ET_a estimated during the period Dec 1999 to Sep 2001 by using the water balance equation and the modified composite approach (Ward and Dunin 2001), for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or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

4.3.5.2 Potential evapotranspiration (ETp)

Potential evapotranspiration (ET_p), regardless of the method used for estimation, was always higher than ET_a in the R_{fed} treatment during the entire study (Figure 4.7). ET_p was also higher than ET_a for most of the measurement periods in both the irrigated treatments, except for the period Dec 15, 1999 to Mar 31, 2000 when ET_a was higher than ET_p in the I_{sub} and I_{surf} treatments. Estimates of ET_p using the Priestley-Taylor method were always higher than those using the modified method.

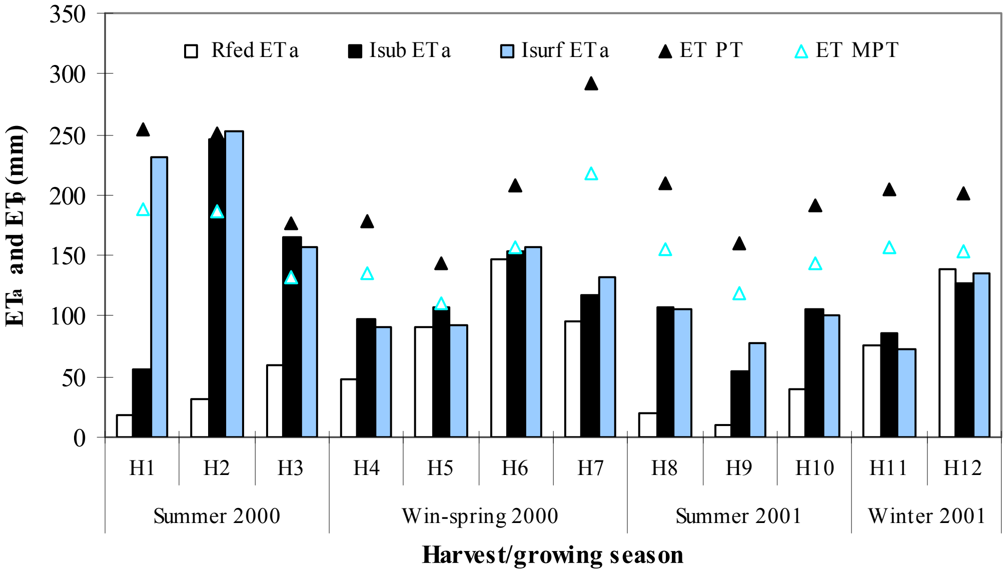

Figure 4.7 Actual evapotranspiration (histogram bars, ET_a) calculated using the water balance equation and potential evapotranspiration (symbols, ET_p) estimated by (a) Priestley Taylor equation (ET_{PT}) or (b) Modified Priestly Taylor (ET_{MPT}) for rainfed lucerne (R_{fed}) and lucerne supplied with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

4.3.6 Soil evaporation

Soil evaporation (E_s) from the surface soil (top 100 mm) measured over four days during the summer 2001 was 5.36 mm for the first day after application of surface irrigation and whilst it might be operating in stage-1 conditions (energy dependent) in I_{surf} treatment it cannot be in the other two treatments since there was no rainfall during this time and water was applied 400 mm below the soil (Figure 4.8). On the first measurement day, evaporative loss was higher in I_{surf} than in the R_{fed} (0.987 mm) and I_{sub} (0.928 mm) treatment. E_s losses decreased sharply afterwards and on the second day E_s was 1.95 mm in the I_{surf} treatment, still higher ($P<0.001$) than that of the other treatments. Generally more than 50% of the total loss occurred in soil moisture through evaporation during the first day in all treatments prior to regrowth.

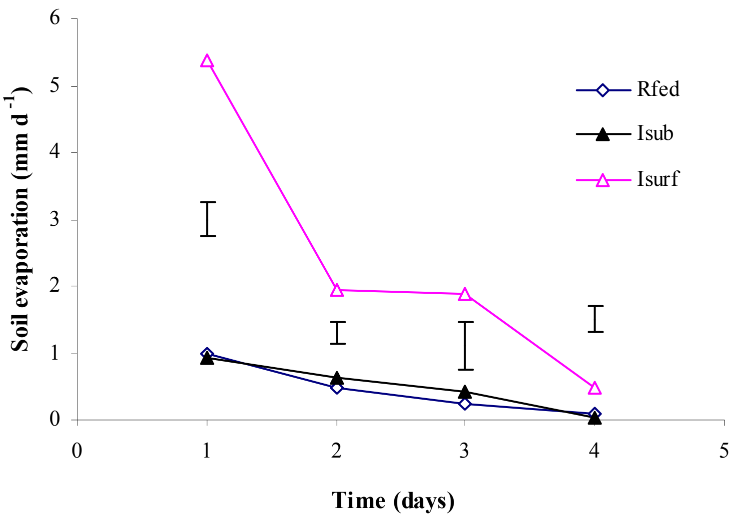

Figure 4.8 Measured soil evaporation (E_s) from the surface 0-100 mm soil during 15-19 Feb 2001 in rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water in summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation

Estimates of E_s soil evaporation for each growing period over the study from APSIM suggest that 50% of the total water used (ET_a) is likely to be lost via E_s in the R_{fed} treatment compared to 30-33% in I_{sub} and I_{surf} treatments respectively (Table 4.3). The model suggested E_s losses would be lowest in the summer seasons in I_{sub}, from 10-19% of ET_a whereas in the growing seasons it ranged from 47-49% of ET_a. A similar trend was noted in the I_{surf} treatment in summer and growing seasons but losses were predicted to be about 8% higher than I_{sub} in every growing-season. The model also suggested that in the R_{fed} treatment Es was very variable e.g. in summer 2000 nearly 34% of the total water use would be lost through E_s while during the extremely hot summer of 2001 it would be 66% as E_s. Whereas, during growing seasons of year 2000 and 2001 the model predicted water lost through evaporation would be 56 and 49% respectively in this treatment (Table 4.3). Water loss via soil evaporation was related to water applied (Figure 4.9a) and more strongly related to total water used (Figure 4.9b) for the R_{fed} and I_{surf} treatments, but not for the I_{sub} treatment.

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

Growing seasons and year	**Treatments**																	
	Rfed						**Isub**						**Isurf**					
	WA	**ET**	**Es**	**Tr**	**DMY**	**TE**	**WA**	**ET**	**Es**	**Tr**	**DMY**	**TE**	**WA**	**ET**	**Es**	**Tr**	**DMY**	**TE**
	-----------mm----------				**kg**	**kg/ mm**	**-----------mm-----------**				**kg**	**kg/ mm**	**-----------mm-----------**				**kg**	**kg/ mm**
Summer 2000	97	108	36	72	1149	16	577	465	49	416	6903	17	739	639	186	453	8001	18
Water use (%)		111[1]	34[2]	66[3]				81	10	90				86	29	71		
Win-spr 2000	374	381	212	169	3710	22	374	475	222	253	7721	31	374	471	174	297	7198	24
Water use (%)		102	56	44				127	47	53				126	37	63		
Summer 2001	69	71	46	24	143	6	249	268	51	217	3131	14	264	284	94	191	2769	15
Water use (%)		102	66	34				108	19	81				108	33	67		
Win-spr 2001	257	214	104	110	1621	15	257	213	105	108	4407	41	257	209	77	132	3846	29
Water use (%)		83	49	51				83	49	51				81	37	63		
1999-2001	797	773	399	374	6623	18	1457	1422	427	995	22162	22	1635	1603	531	1072	21814	20
Water use (%)		97	52	48				98	30	70				98	33	67		

[1] Means Et % of water applied

[2] Means Es% of ET

[3] Means Tr%

4.3.7 Drainage

The NMM data indicated there were some changes in SWC of the 1800-3000 mm soil profile that suggested potential extraction by lucerne roots or drainage of water beyond the specified rooting depth (Figure 4.9). However, the largest of these changes was 15 mm, many were less than 10 mm, close to the accuracy of a NMM, and all values were smaller than the experimental error terms for the soil water contents (Figure 4.3). Thus it was deemed likely that water movement in the 1800-3000 mm zone was insignificant and drainage below rooting depth negligible in all treatments.

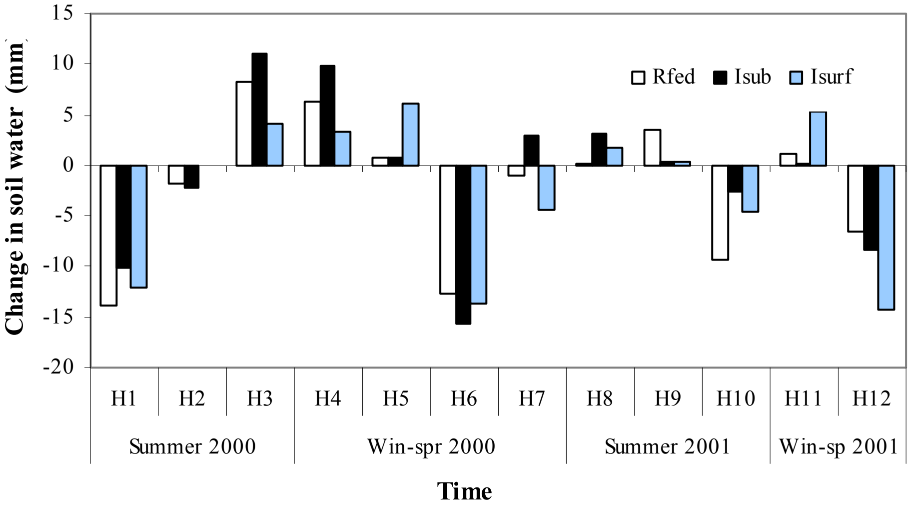

Figure 4.9 Measured changes in SWC at 1800-3000 mm soil profile for different measuring times from Dec 1999 to Sep 2001 for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water via surface (I_{surf}) or sub-surface (I_{sub}).

Using ET derived from Priestly-Taylor the estimated drainage using a water balance approach was also zero (Figure 4.10a). However, it was noted that using ET from the modified Priestly-Taylor approach 92 mm deep drainage was estimated for I_{sub} and 135 mm for I_{surf} during the first summer (Figure 4.10b). APSIM also predicted no deep drainage for the same first summer-spring I_{surf} treatments (Section 6.3.3.1).

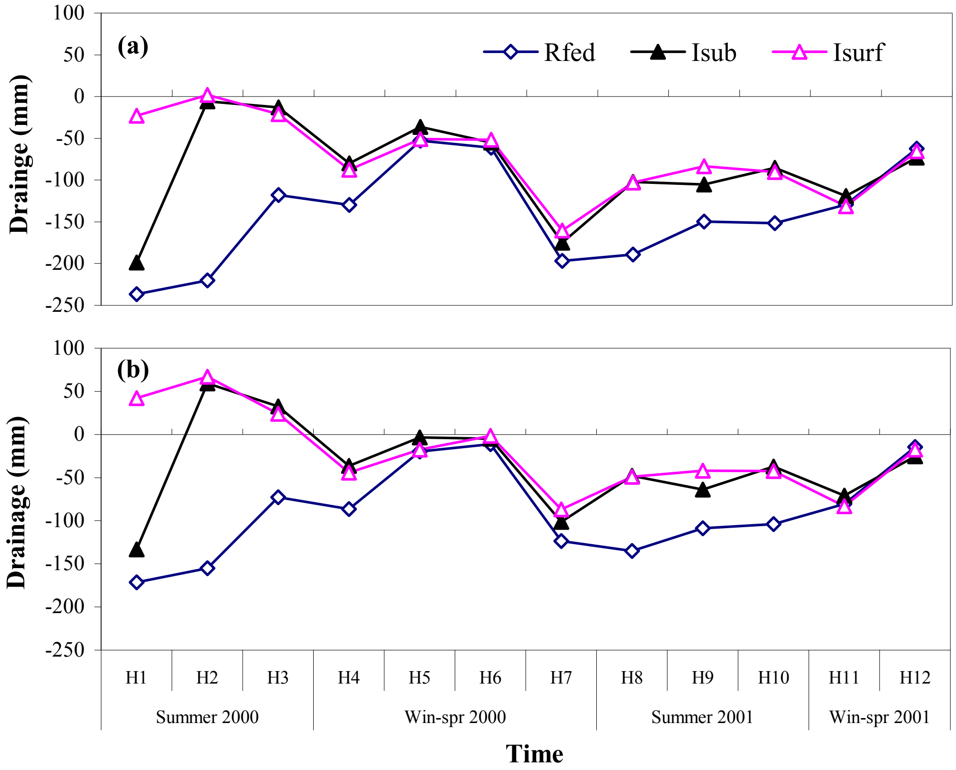

Figure 4.10 Deep drainage (positive values) calculated using a water balance with ET estimated using Priestly-Taylor and for rainfed lucerne (R_{fed}) and lucerne supplied supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation during the study period (Dec 1999-Sep 2001).

4.3.8 Water use efficiency WUE, WUE_n and transpiration efficiency

Water-use efficiency (WUE) was different ($P<0.001$) between treatments at a single time, and also varied between harvests in a single treatment (Table 4.3). The same applied to WUE_n (Table 4.4)$^{.}$ Overall WUE for the study period, determined from the cumulative total water use (ET) and dry matter production (Figure 4.11), was greatest for the I_{sub} treatment (15 kg DM $ha^{-1}mm^{-1}$) and similar for the I_{surf} (14 kg DM $ha^{-1}mm^{-1}$) but lowest for the R_{fed} treatment (9 kg DM $ha^{-1}mm^{-1}$). WUE and WUE_n were significantly lower in the R_{fed} treatment than both the irrigated treatments at most harvests, except for H2 where WUE was identical in all treatments, and H1 and H7 where WUE for I_{surf} and R_{fed} treatments were similar. WUE in the R_{fed} treatment was higher in summer 2000 (8-13 kg DM ha^{-1} mm^{-1}) than in summer 2001 (0-4 kg DM $ha^{-1}mm^{-1}$). In summer 2001 WUE was lower than in winter 2001 in all treatments, but not in 2000. However, for

WUE_n values were higher in all treatments during summer (Table 4.5) indicating the weighting factor may be less appropriate for lower temperature regime.

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

Treatment	**Summer 2000**			**Winter-Spring 2000**				**Summer 2001**			**Winter 2001**	
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12
R_{fed}	8	13	11	10	10	9	11	0	0	4	10	6
I_{sub}	26	11	17	19	22	12	15	11	14	12	21	20
I_{surf}	6	13	16	17	20	15	11	9	9	12	19	18
LSD (0.05)	3.79											
SLT*	3.72											

*Same level of treatment.

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

Treatment	**Summer 2000**			**Win-spr 2000**				**Summer 2001**			**Win-sp 2001**	
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12
R_{fed}	14	23	13	4	2	3	8	0	0	4	2	2
I_{sub}	47	20	21	9	5	4	11	30	24	12	5	5
I_{surf}	11	24	25	8	4	5	8	25	15	11	5	4
LSD (0.05)	3.79											
SLT*	3.72											

The relationship between total dry matter production and transpiration for each treatment is presented in Figure 4.12 and is linear (R^2 >0.98) with transpiration efficiency (slope of the regression) being 19 kg DM $ha^{-1}mm^{-1}$ in the R_{fed} treatment and 22 kg DM $ha^{-1}mm^{-1}$ in the irrigated treatments. Like WUE, TE was higher in the winter-spring than summer in all treatments (Table 4.3). TE was similar over summer 2000 in the all treatments (16 -18 kg DM $ha^{-1}mm^{-1}$) and in the growing season 2000 TE value ranged from 22-31 kg $ha^{-1}mm^{-1}$ in all treatments. The lowest TE (6 kg DM $ha^{-1}mm^{-1}$) was obtained in the R_{fed} treatment during summer 2001, compared with 14 and 15 (kg DM $ha^{-1}mm$) respectively in I_{sub} and I_{surf}, treatments and the highest TE value (37 kg DM $ha^{-1}mm^{-1}$) was recorded for the I_{sub} treatment.

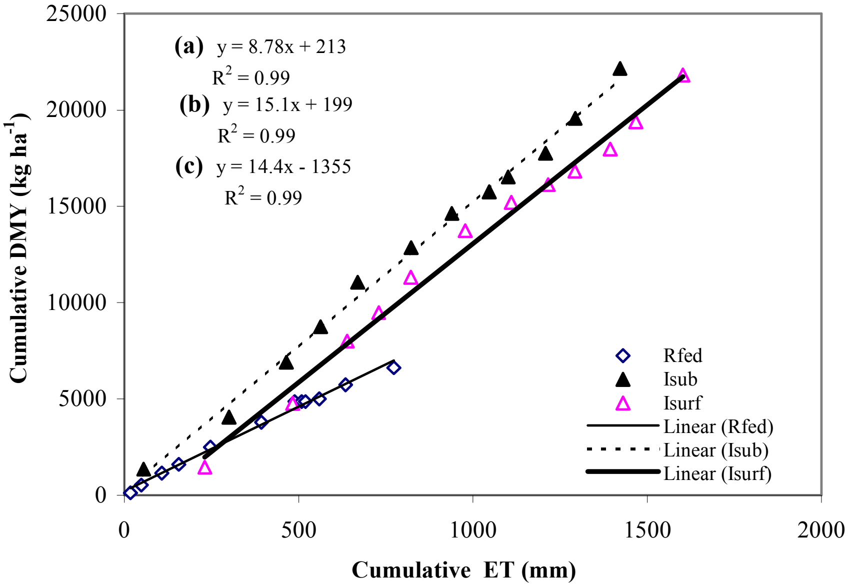

Figure 4.11 Relationship between cumulative amounts of water used with cumulative dry matter yield produced (a) R_{fed} (b) I_{sub} and (c) I_{surf} treatments of lucerne during Dec 1999 to Sep 2001.

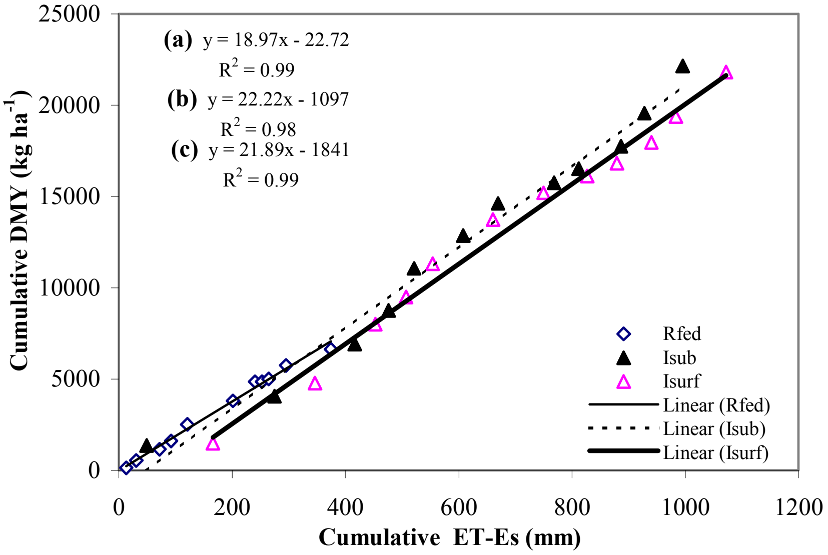

Figure 4.12 Relationship between cumulative amounts of water transpired with cumulative dry matter yield produced in (a) R_{fed} (b) I_{sub} and (c) I_{surf} treatments of lucerne during Dec 1999 to Sep 2001.

4.4 Discussion

The focus of this chapter was to describe seasonal patterns of water use and WUE by lucerne in a Mediterranean climate on a duplex soil in response to different amounts of water applied or received during the summer periods within two years of study. The major findings from this work are discussed below:

4.4.1 The duplex calcareous red chromosol at Roseworthy stored water in the 600-1800 mm soil profile

The 0-1800 mm soil profile of the duplex soil at Roseworthy, a typical example of the calcareous red chromosol common across much of South Australia, has a high water holding capacity and can potentially store 77% of average annual rainfall at field capacity. Further, it was also highlighted that the PAW capacity of the 0-600 mm soil profile, considered the important water extraction zone for annuals (Gregory *et al*. 1992, Weston *et al*. 1997, Ward and Dunin 2001), was 84 mm; this represented only 20% of average annual rainfall indicating that the majority of potential plant available water storage is in the 600-1800 mm soil profile and therefore probably not fully accessible to annuals due to their root system and growth pattern. The relatively low water holding capacity of the upper horizon is presumably related to the texture of the soil and hydraulic conductivity of the sand whereas the high clay content in lower profile retains water for a longer time (Hillel and Talpaz 1977). Although, in general, high clay content increases the storage capacity of soil for water it should be noted that it may also decrease aeration, essential for good root growth, development and functioning. However lucerne roots in this study were observed up to 1800 mm and appeared to function at this depth in terms of water extraction.

4.4.2 Lucerne, in the Roseworthy environment, was able to dry the soil profile to 1800 mm

Continuous and extended soil water extraction by lucerne round the year kept the soil profile dry to a depth of 1800 mm in the R_{fed} treatment and prevented deep drainage, therefore confirming the reported potential to reduce the risk of secondary salinity. These results reinforce the findings of Ward and Dunin (2001), Lolicato (2000) McCallum *et al*. (2000) who found similar water extraction patterns and dry profiles under lucerne in rainfed conditions on duplex soils in other regions of Australia. Furthermore, under rainfed conditions in this study lucerne dried the whole soil profile to the lower limit during both years in the summer, and in the spring season in the second year of the study, indicating a water limitation for lucerne growth during those periods. These observations concur with those of Ridley *et al.* (2001) for rainfed lucerne on a duplex soil in eastern Australia where all available water was extracted down to the lower limit in each year.

The observed depth of soil water extraction (1800 mm) in all treatments in this study was similar to the 1.8 to 2 m reported by Lolicato *et al.* (2000), Ward and Dunin (2001) and McCallum *et al.* (2001) for lucerne on duplex soils in Mediterranean environments, but less than the 2.8 to 4 m reported by others (Ridley *et al.* 2001, Douglas 1984, Kennett- Smith *et al.* 1990 and Walker *et al.* 1992) in environments with a slightly more even distribution of rainfall across the year and more favourable soils. The very deep rooting patterns for lucerne reported overseas, for example 6 m (Halvorson and Reule 1980), are likely to be for soils without any subsoil constraints to root growth and water use.

4.4.3 Irrigated lucerne in this environment also extracted water to 1800 mm

The soil water extraction patterns in the irrigated treatments also showed that lucerne has the potential to scavenge extra water if it is available deeper in the profile up to 1.8 m. A consistent decrease in soil and plant available water content in the 600-1800 mm soil profile (Figure 4.3 & 4.4) confirms the ability of lucerne as soil water and nitrate scavenger from deep in the soil. The heavy irrigation in the first year (summer 1999-2000) resulted in an initial depletion of soil water in 0-600 mm surface profile, followed by a period of fluctuating soil water due to rainfall received and plant water use, and finally by extraction of soil water and nitrate below 600 mm. These results conform with those of some researchers (Snaydon 1972, Kelner *et al.* 1997, Lolicato 2000) for irrigated lucerne, but are contradictory to others (Taylor and Marble 1986) who reported that on a red-brown earth duplex soil under irrigated conditions lucerne did not use water deeper than 1.2 m in the soil profile and also left 16% of PAWC in 0-1.2 mm soil profile and 89% in the 1.2-1.8 mm soil profile unused. The difference in these observations might be due to differences within duplex soil types, as soil structure and salinity level can result in differences in PAWC; or possibly differences in irrigation scheduling (timing and amounts), since in the present study water was supplemented only in summer. Also, lucerne was grown under rainfed conditions for 20 months prior to the start of this study, and that might have implications for subsequent root distribution and soil water extraction patterns.

4.4.4 Actual ET driven by stored soil moisture use in this environment

Actual ET_a for lucerne was mainly dependent on soil water availability regardless of weather, indicating lucerne has the potential to use water throughout the year. It also confirms that some extra water extraction from deeper in the soil profile was used during different intervals e.g. in H1 in R_{fed} treatment during summer 2000, 18 mm of soil water was used whereas only 1.2 mm was received from rainfall during that period. During this time about 6 mm of soil water was available in the 0-600 mm soil profile and the remaining 12 mm of soil water was extracted from 600-1800 mm soil profile. Limited dry matter production during summer period is consistent with the water use results (Section 3.3.2.1). Generally 15% more water was used in summer 2000 and 2001 than water received in R_{fed} treatment and these findings are in agreement with those of (Ridley *et al.* 2001, Latta *et al.* 2001). It is likely that lower water use versus amount of water applied in 2001 might be due to early termination of experimental measurements, since most of the additional water extraction occurs in spring and summer (Ward and Dunin 2001, Ward 2006). Despite the plant population losses in summer 2001 there were no significant differences in estimated water used as ET_a between all three treatments (Table 4.2) in winter 2001, confirming that 20 plants m^{-2} was sufficient to prevent recharge (Kipnis *et al.* 1989, Virgona *et al.* 2003). However, higher lucerne plant population may be required for high levels of production.

The estimated ET_a during summer 2000 for different irrigated treatments was considerably lower than the water applied indicating some storage. This stored water was used later during the growing season in 2000 when total water use was 126-127% of rainfall, with most of the extraction of this stored water occurring prior to the onset of rainfall or later in spring 2000; similar results have been reported by Snaydon (1972) for irrigated lucerne in a temperate region of Australia. In summer 2001, after a limited amount of water was supplied in irrigated treatments, water use was 8% higher than water application indicating some stored soil water extraction. In general, extraction from stored soil moisture indicated a period when plant water use exceeded water received through irrigation and/or rainfall (Ridley *et al.* 2001).

4.4.5 Potential ET in this environment was consistently greater than actual ET under rainfed conditions but not necessarily under irrigation

This study highlights that potential ET_p was consistently higher than ET_a (Figure 4.10) in the R_{fed} treatment even when rainfall was above average. These results contrast with those of Ward and Dunin (2001) who found that for much of the growing season on a shallow clay duplex soil in Western Australia ET_p was close to ET_a. The difference may be due to the specific soil environment at Roseworthy or a difference in the climatic conditions that prevailed during the study (Undersander 1987). An important difference between this study and the study by Ward and Dunin (2001) was that surface soil was generally wetter in their study. They reported that the A horizon of their duplex soil was at >20% soil moisture level during most of the measuring times in the growing season, whereas in this Roseworthy study the upper profile (0-600 mm) was rarely at 20% soil moisture value. The surface soil in this study was a comparatively deep sandy soil and therefore it might not be able to hold as much soil moisture in the root zone to enable ET_a to equal ET_p during the growing season. Further, for most of summer and some periods during the growing season the lucerne shoots in the R_{fed} treatment were observed to be under severe or moderate stress higher VPD ~ 1.90 (Section 3.3.2.1). In addition to this the rainfall pattern (probability per event) might have some implications since this type of discrepancy in moisture holding pattern has already been reported in a study conducted on a duplex soil in Western Australia (Anderson *et al.* 1998). However, in irrigated treatments ET_a paralleled ET_p when the quantity of water supply was about 80% of pan evaporation in summer 2000 and later in July-Sept in growing season of year 2000. In summer 2001 where water supplementation was limited, ET_a was lower again than ET_p for most of the measuring times.

4.4.6 Drainage below the effective rooting depth of 1.8 m was negligible even under irrigation

Estimated drainage was negligible under the R_{fed} treatment, further confirming the role of lucerne to prevent leaching and subsequent soil degradation in this environment. These results corroborate the findings of Abbs and Littleboy 1998, Lolicato 2000, McCallum *et al.* 2001, Ward and Dunin 2001, Ridley *et al.*, 2001, Dilling 2005, Ward 2006, Verburg 2007). The finding also supports Latta *et al.* (2001), who proposed the inclusion of lucerne in rotation to minimize drainage on duplex soils under a Mediterranean environment.

However, under irrigated treatments when water application was relatively high estimated drainage losses were in the range of 25-91 mm in I_{sub} and 28-133 mm in I_{surf}, depending on use of ET_p for the period of study when drainage was recorded in summer 2000. No drainage losses were recorded later on in the growing season as well as in summer 2001 when irrigation was limited. Further if water extraction from 2000-3000 mm (below the estimated root zone) was taken into account, drainage losses were further reduced to 60 mm in I_{sub} treatment and 84 mm in I_{surf} treatments.

4.4.7 WUE was lowest under rainfed conditions and increased under irrigation

Water use efficiency in any crop is a function of water use and growth which is extremely influenced by environment. The results from the three different treatments uniformly demonstrated the strong relation (R^2 >0.98) between dry matter yield and water use in this study (Figure 4.11), irrespective of amount of water applied and method of water application, indicating the main driving force in determining the yield was amount of soil water. These results are in agreement with several earlier reports (Sammis 1981, Bauder *et al.* 1987 Grimes *et al.* 1992, Saeed and El-Nadi 1997, Brown *et al.* 2005). The different slopes of regression equations however, represent different water use efficiency in various treatments (Figure 4.11). Generally R_{fed} treatment gave significantly lower WUE (9 kg DM $ha^{-1}mm^{-1}$) compared to treatments where water was supplemented in summer, having about 17 kg DM $ha^{-1}mm^{-1}$ in I_{sub} and 14 kg DM $ha^{-1}mm^{-1}$ in I_{surf} (Table 4.4). These differences in WUE can be mainly explained in terms of different water supply and consequent water use (Figure 4.1). The value for WUE in the rainfed treatment in this study (9 kg) was towards the lower end of the range reported for dryland lucerne in Australia (Hirth *et al.* 2001, Snaydon 1972, Dunin, et al 2001) which could be attributed to differences in radiation, temperature and the pattern of rainfall (Sheaffer *et al.* 1988). The lower water-use efficiency for the rainfed treatment suggests that this particular system at Roseworthy is constantly operating below potential irrespective of season, limited by one or more constraints, which may be soil related or climatic factors. The data concur with the view that WUE can be significantly higher under irrigation (Bauder *et al.* 1978, Cater and Sheaffer 1983, Saeed and El-Nadi 1997) but contradict the suggestion by some researchers that WUE may be greater under low water regimes (Jodari-Karimi 1983, Benz *et al.* 1984). Significantly higher water use efficiency values in the I_{sub} treatment compared to the I_{surf} treatment indicates more water losses through E_s in I_{surf} than I_{sub}. The sandy texture of the surface soil is likely to have promoted evaporation losses in this duplex soil (Gregory *et al.* 1992). The lowest water use efficiency during summer 2001 in R_{fed} treatment might be the interaction of high temperature and lowest water availability during that period (Figure 4.1). The deleterious effects of high temperature and moisture deficit on efficiency of water use have been documented by other researchers in Australia (Snaydon *et al.* 1972) and overseas (Kipnis *et al.* 1989, Collino 2005).

To consider WUE across seasons WUE_n was also determined for all the regrowth cycles. Values supported the finding that water used is linearly related to shoot dry matter and values estimated (~26 kg DM ha^{-1} mm^{-1}. kpa) were comparable to other worker like Brown *et al.* (2005). However, a considerable decrease in estimated WUE_n during the growing season may be attributed to the greater weighting given to high daylight maximum temperature in winter under the southern Australian Mediterranean conditions. Whereas, it may not be valid to allocate the same weighting to winter daylight hours since conditions are wet and there is relatively uniform VPD (<0.28 kpa) from June to August. Furthermore, the variety used in this study was winter-active (>8 activity level) and therefore very responsive to the winter-spring temperature regime.

A linear relationship with high coefficient of determination (R^2 >0.98) between dry matter yield and transpiration (plant water use), regardless of amount of variability in water application in all treatments, emphasized the importance of water for yield in this environment (Figure 4.12). Similar relationships have been found between yield and TE in lucerne (Rachel *et al.* 1991, and Grimes *et al.* 1992). Another important finding of this study was higher TE in the winter-spring growing seasons than summer seasons in all treatments could be due to more favorable radiation, temperature and possibly the use of the carbohydrates in root reserves, promoting growth at the expense of lower water use (Daiger *et al.* 1970, Saeed and El-Nadi 1997, Heichel *et al.* 1988). Further, Brown *et al.* (1972), Fick *at al.* 1988 have established that optimum temperature for accumulation of dry matter in lucerne ranged from 15-25°C. Production of the lowest level of biomass (6 kg DM $ha^{-1}mm^{-1}$) in R_{fed} treatment during summer 2001 further reinforce the implications of water and higher temperature in the process of dry matter accumulation in lucerne (Snaydon *et al.* 1972, Kipnis *et al.* 1989).

Total quantity of water lost via soil evaporation was highest in the I_{surf} treatment followed by the I_{sub} and R_{fed} treatments. However, as a percentage of total water received as rainfall or irrigation, losses were highest in the R_{fed} treatment (52%) compared to 33% in the I_{surf} treatment. The high soil evaporation in the R_{fed} treatment is consistent with the generally low LAI in this treatment that allowed greater radiation to reach the soil surface. Figure 4.11 provides an interesting comparison of E_s in the I_{surf} and I_{sub} treatments. The slope for these two treatments is similar (14.4 for I_{surf} and 15.1 for I_{sub}) indicating a similar WUE. The point where the two lines cross the x-axis indicates the difference in E_s, 94 mm for I_{surf} and 13 mm for I_{sub}. This difference can be explained in the greater period of time for stage-1 evaporation under the surface irrigation compared to the I_{sub} treatment when surface soil was wet only in response to rainfall. This conclusion is further supported by the lysimeter data where E_s losses were far less under I_{sub} compared to I_{surf} during summer (Figure 4.8).

4.5 Conclusion

The key findings from this study were:

- The duplex calcareous red chromosol at Roseworthy was found to be storing water in the 600-1800 mm soil profile potentially beyond the rooting depth of annual crops or pastures but accessible to lucerne.
- Both rainfed and irrigated lucerne in this environment dried the soil profile to 1800 mm but the majority of roots (~70%) were in the top 0-40 cm soil depth. These two observations lead to the conclusion that soil constraints were restricting lucerne roots from fully exploiting the subsoil.
- Actual ET appeared to be driven by stored soil moisture. Potential ET was consistently greater than actual ET under rainfed conditions but not necessarily greater under irrigation in this environment.
- Drainage below the effective rooting depth of 1800 mm was negligible in this environment, even under irrigation, highlighting the ability of lucerne to intercept and utilize all available water.
- Water use efficiency was lowest under rainfed (9 kg DM $ha^{-1}mm^{-1}$) conditions and increased under irrigation (14-15 kg DM $ha^{-1}mm^{-1}$), emphasizing the limitation to growth commonly encountered by lucerne growing under these Mediterranean climate rainfed conditions.
- Transpiration efficiency was similar in all three treatments, 19-22 kg DM $ha^{-1}mm^{-1}$ of water transpired. This similarity in TE across treatments indicates that the major source of difference in WUE is due to differences in soil evaporation.
- Sub-surface irrigation was a more efficient method for supplying water to lucerne in this environment, partly because of the sandy nature of the A-horizon. The main advantage of sub-surface irrigation was through reducing losses via soil evaporation.
- Under both rainfed and irrigated conditions a considerable reduction in transpiration efficiency for lucerne was observed during summer compared to winter-spring. High mean daily maximum temperatures in both summer periods (32-36°C) were possibly responsible for this lower TE given that the optimum temperature for growth in lucerne is around 15-25 °C.

Chapter 5

5 Soil-plant N dynamics for lucerne on a duplex soil under semi-arid Mediterranean climatic conditions & response to varying water supply during summer

5.1 Introduction

Dry matter production and amount of N_2 fixed by annual and perennial pastures are positively related and 25 kg N (range 22-31) has been reported for every tonne of legume dry matter produced (Section 2.4.1). Major climatic and edaphic factors that influence lucerne shoot growth (viz. water, temperature, radiation and nutrition) will certainly have an effect on N_2 fixation too, since supply of carbohydrate from the shoot is a key determinant for this process. In addition, edaphic conditions will affect lucerne root growth and function and the activity of the nodules, and regulate the supply of mineral N in the system. For example, soil moisture stress directly affects N_2 fixation by reducing activity of the nodule bacteroids (Section 2.4.1.1) and indirectly influences N_2 fixation via it's effect on root and shoot growth. There are few field data reports concerning these effects although some aspects of seasonal dynamics of N_2 fixation in dryland lucerne, in relation to soil water, have been described (McCallum *et al.* 2000). However, it is uncertain whether information from these studies is directly transferable or applicable to the Mediterranean climatic conditions on duplex soils (texture contrast) of South Australia. The presence of high concentrations of mineral N in soil has been reported to reduce N_2 fixation (Section 2.4.1.3), although the extent to which N_2 fixation is depressed is extremely variable between species and sites. Indeed, the regulatory mechanisms underlying N acquisition from different sources are not fully elucidated for lucerne (Blumenthal and Russelle 1996). Utilisation of excess nitrate from deeper in the soil profile by lucerne is also thought to be another useful feature to reduce the potential threat of acidity (Section 2.4.2.2). However, data concerning soil NO_3^- uptake by lucerne in Australia is sparse and insufficient for extrapolation, and more studies are warranted especially in relation to the interaction between growth, N_2 fixation and soil NO_3^- uptake in lucerne.

The study described in this chapter aimed to quantify N inputs by lucerne growing on a duplex soil in the Mediterranean climate of South Australia, and to investigate any potential limitations imposed by lack of rainfall over summer. To achieve these aims measurements were carried out on rainfed plots and those irrigated over summer to quantify total shoot N productivity by lucerne and to estimate proportional dependence on N_2 fixation (Ndfa) and thus reliance on soil N uptake. Soil mineral N to depth was monitored at intervals, in conjunction with root distribution (Chapter 3) and soil water content (Chapter 4), to assess the likelihood of leaching losses of N.

5.2 Materials and Methods

5.2.1 Experimental site, climate and soil details

Details of the experimental site, climate, management, soil, treatments and design are presented in Chapter 3.

5.2.2 Shoot biomass and N accumulation

Details of total aboveground shoot biomass determination from samples taken using a quadrat technique are given in (Section 3.2.4). N content for these samples was calculated using the corresponding measured N concentration for lucerne shoots and residues (taken from the same plot and at the same time) from the paired sampling technique described in the next section

5.2.3 Estimation of dependence on N_2 fixation (Ndfa) and amount of N fixed

Proportional dependence on N_2 fixation or Ndfa (%) at each of the 12 harvests during the study period for all the treatments was estimated using the $\delta^{15}N$ natural abundance method (Unkovich *et al.* 1997, Peoples *et al.* 1998). A basic assumption of the technique is that the $\delta^{15}N$ of a non-legume 'reference' plant is a representative measure of the $\delta^{15}N$ for the soil mineral N pool. It is also well-established that atmospheric N_2 fixed by the legume has a $\delta^{15}N$ value of zero and therefore by comparing the $\delta^{15}N$ values obtained for a legume with those for a non-legume it is possible to estimate the extent to which the legume has been accessing the soil N pool. In this study paired sampling, of at least five lucerne plant shoots and adjacent (about 1 m distant) non-legume reference plant shoots, was carried out in each plot prior to each shoot biomass harvest. A range of different dicotyledonous species were utilised as reference plants (Table 5.1). There were no available reference plants in summer 2001 (Feb & Mar) and the monocotyledonous weed species ryegrass was the only reference plant available in November 2000. The efficacy of the method relies heavily upon selection of reference species because the δ^{15}N value has a significant influence in determination of Ndfa (Unkovich *et al*. 1997), and even more so for a perennial such as lucerne (McCallum *et al*. 2000, Peoples *et al* 2001). The major criteria for selection of a reference plant are that it has a root system and a life cycle similar to the legume, and thus for lucerne (a deep-rooted perennial) this is extremely difficult, so any choice represents a compromise. Nevertheless, despite some reservations, the technique has been evaluated and widely applied in Australia for lucerne (Peoples *et al*. 2001, McCallum *et al*. 2000, Unkovich *et al*. 1997).

Shoot samples were dried at 60^{o}C in an oven to constant weight and coarsely ground using a 2 mm sieve. Sub-samples of these coarsely ground samples were further finely ground using a Spex mixer mill (Spex Industries Inc, Metuchen N. J.) and the material was analysed for N concentration (%N) and natural abundance δ^{15}N using continuous flow mass spectrometry.

Ndfa was estimated (Unkovich *et al*. 1997) using the following equation:

$$\text{Ndfa} = \frac{\delta^{15}\text{N reference plant} - \delta^{15}\text{N lucerne}}{\delta^{15}\text{N reference plant} - \text{B}} \times 100 \qquad \text{(Eq. 5.1)}$$

B is the designated δ^{15}N value for a lucerne plant entirely dependent on N_2 fixation. The B value for this study was assigned using the same approach as that of McCallum *et al*. (1998) and it was taken as -1.27, i.e. the lowest mean value recorded for δ^{15}N from all the lucerne shoot samples.

The amount of N fixed by lucerne was then calculated as:

$$\text{N fixed (kg N ha}^{-1}) = \text{Shoot N content (kg ha}^{-1}) \times \text{Ndfa (\%)}/100 \qquad \text{(Eq. 5.2)}$$

Table 5.1 Species used as reference plants for estimation of proportional dependence on N_2 fixation (Ndfa) by lucerne using the $\delta^{15}N$ natural abundance technique

Sampling date	Common name	Botanical name
Jan 2000	Potato weed	*Heliotropium europaeum* L.
Feb 2000	Potato weed	*Heliotropium europaeum* L.
Mar 2000	Potato weed	*Heliotropium europaeum* L.
May 2000	Wild mustard	*Sinapis arvenisis* L.
July 2000	Cape weed	*Arctotheca calendula* (L.) Levyns
Oct 2000	Milk thistle	*Lactuca Serriola L.*
Nov 2000	Ryegrass	*Lolium rigidum* Gaudin
Feb 2001	No Weed	
Mar 2001	No Weed	
Apr 2001	Wire weed	*Polygonum aviculare* L.
July 2001	Milk Thistle	*Lactuca serriola* L.
Sep 2001	Milk Thistle	*Lactuca serriola* L.

5.2.4 Soil mineral N measurement

Soil samples were taken from all three treatments for determination of mineral N (NO_3-N and NH_4-N) on four occasions during 2000 following H1, H2, H4 and H6 and twice in 2002, following H10 and H12 (Table 3.2). The first sampling was carried out with a manual augur (diameter 70 mm) to a depth of 0.4 m and samples were divided into two equal sections (0-200 and 200-400 mm). The second sampling was carried out mechanically up to 1 m with a core of diameter 60 mm, and 200 mm sections were sampled for analysis. Sampling at the other times was carried out mechanically to 1.5 m and the cores were divided into seven segments (0-200, 200-400, 400-600, 600-800, 800-1000, 1000-1300, 1300-1500 mm). Samples were sieved (4 mm mesh) to remove gravel and big stones, thoroughly mixed and then sub sampled. A portion of sub-sample (about 20g) was used to determine water content by drying in an oven at 105°C. Mineral N was extracted from a further portion (about 40 gm) using 200 ml of 0.5 M K_2SO_4 in the case of samples from the first two sampling occasions and 2 M KCl for the remaining samples. It is less than ideal to have two different extractants but was, in this case, unavoidable, and thus restricted the validity of comparison across the entire study period. Extracts were stored frozen prior to analysis for nitrate and ammonium using Continuous Flow Analysis (Alpkem two-channel auto-analyser). Results are reported as concentration of nitrate-N or ammonium-N per gram of dry soil and converted to field units (kg N ha^{-1}) using measured bulk densities (g cm^{-3}) for each plot at every depth.

5.2.5 Statistical analysis

Data were analysed using split plot design (General analysis of variance) in GenStat 6 Release 6.1 (Lawes Agricultural Trust, 2003). To compare soil inorganic N at different depths between treatments and interaction between treatment and date (time) analysis of variances was performed for each soil depth separately, with treatment as main plots and time of sampling as sub-plots. The interaction was also computed between treatments and depth at a single sampling time. Treatment differences in Ndfa, amounts of N fixed and N uptake were computed by considering treatment as main plot and date as sub-plots. Separation of means was performed using least-square differences (LSD) at the 5% level of significance, and use of the term significant difference in the text implies this level of significance unless otherwise indicated. Regression analysis was carried out to establish the relationship between the amount of fixed N and either shoot biomass, water received as irrigation and/or rainfall, or Ndfa.

5.3 Results

5.3.1 Shoot N accumulation

There was no difference in total shoot N accumulation for the study period between the two irrigation treatments (Figure 5.1) although over the 2000 summer period shoot N accumulation for the I_{surf} treatment was higher ($P<0.05$) than for I_{sub} (Table 5.2). Total shoot N accumulation for the rainfed treatment was about 40% that of the irrigated treatments with two-thirds of its total N accumulated during the first year of the study. Generally, for all the treatments N accumulation in shoot biomass was greater in the first year of the study than the second and for the winter-spring periods than for the summer periods (Table 5.2).

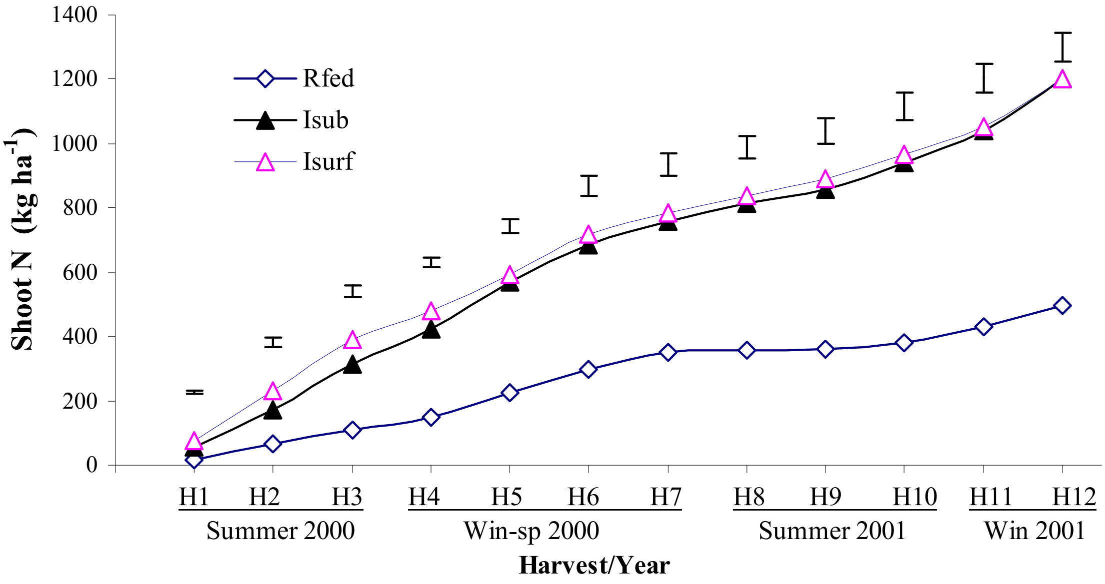

Figure 5.1 Cumulative shoot N content for the two year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD at $\alpha=0.05$.

Table5.2 Seasonal shoot biomass production (total), shoot nitrogen content, Ndfa (%) N_2 fixed, N uptake from soil, shoot N_2 fixed per tonne of dry matter and per mm of total water use (ET), during four growing seasons in the study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Treatment	2000			2001			LSD (α=0.05)
	Summer	Win-Spr	Yr. Total	Summer	Win-Spr	Yr. Total	
			Shoot dry matter (t ha^{-1})				
R_{fed}	2.40	5.86	8.26	0.64	2.57	3.21	0.77^{*}
I_{sub}	9.02	10.67	19.69	5.12	5.84	10.96	0.64^{**}
I_{surf}	10.04	10.21	20.25	4.84	5.27	10.12	
			Shoot N (kg ha^{-1})				
R_{fed}	110	242	352	29	114	143	31.79
I_{sub}	315	445	760	179	263	442	29.86
I_{surf}	391	395	786	180	236	417	
			Ndfa (%)				
			Yr. Mean			**Yr. Mean**	
R_{fed}	49	58	53	48	41	45	10.52
I_{sub}	78	55	67	52	46	49	10.16
I_{surf}	62	61	62	60	55	57	
			Shoot N_2 fixed (kg ha^{-1})				
			Yr. Total			**Yr. Total**	
R_{fed}	55	151	205	12	47	59	26.26
I_{sub}	243	248	491	91	124	215	27.78
I_{surf}	255	242	498	107	128	234	
			Shoot N uptake (kg ha^{-1})				
R_{fed}	55	92	147	16	68	84	31.33
I_{sub}	72	197	269	88	139	227	29.67
I_{surf}	135	153	288	73	109	182	
			Shoot N_2 fixed per tonne dry matter (kg N/t)				
			Yr. Mean			**Yr. Mean**	
R_{fed}	22	25	23	20	18	19	3.34
I_{sub}	27	23	25	18	21	19	3.36
I_{surf}	24	24	24	22	24	23	
			Shoot N_2 fixed per mm total water use (kg mm^{-1})				
R_{fed}	0.512	0.396	0.454	0.273	0.233	0.253	0.108
I_{sub}	0.653	0.551	0.602	0.398	0.573	0.486	0.118
I_{surf}	0.459	0.459	0.459	0.439	0.628	0.534	

* For comparison between treatments. ** For comparison with same level of treatment at different time

5.3.2 Nitrogen Fixation

5.3.3 Natural abundance ($\delta^{15}N$) of reference species and lucerne

There was significant variation over time in $\delta^{15}N$ of reference species with values ranging from -0.79 to 4.20 (Figure 5.2a). The $\delta^{15}N$ of reference species cape weed sampled in July 2001 ranged from 7.14 to 8.05 in all the treatments (Appendix C), yet there was no corresponding increase in the $\delta^{15}N$ of lucerne at this time of sampling, whereas at all other times both the reference plants and lucerne followed a similar trend pattern (Figure 5.2a,b). Therefore, since the $\delta^{15}N$ appeared anomalously high (potential reasons discussed later in section 5.4.3) it was removed from the analysis and the averaged values of the references species collected atn adjacent sampling times (i.e immediately before and after) were used to determine Ndfa at this time. There were some significant treatment differences in $\delta^{15}N$ values for reference species, particularly in the first year of the study when large amounts of irrigation water were supplied.

The reference plant $\delta^{15}N$ value was significantly lower in I_{sub} than R_{fed} and I_{surf} in the first sampling taken in Jan 2000 (Figure 5.2a), whereas $\delta^{15}N$ was significantly higher in I_{surf} than R_{fed} and I_{sub} in Feb 2000. There was no significant variability in reference plant $\delta^{15}N$ between the two irrigation treatments for the other nine sampling times. After the termination of irrigation and onset of rainfall in May 2000 reference plant $\delta^{15}N$ for both the irrigated treatments was higher ($P < 0.001$) than for the R_{fed} treatment (Figure 5.2a), but this trend was reversed for the next two sampling times (Sep and Oct 2000).

The $\delta^{15}N$ values for lucerne ranged from -1.27 to 1.22 across all the treatments and were more variable over time in the first year of the study. Apart from during the first irrigation phase in summer 2000 there were no other significant differences in $\delta^{15}N$ for lucerne between the irrigated treatments at each of the sampling times during the study period. $\delta^{15}N$ of R_{fed} lucerne was higher ($P < 0.001$) than I_{surf} in March and May 2000 and lower in July 2000 than both the irrigated treatments (Figure 5.2b).

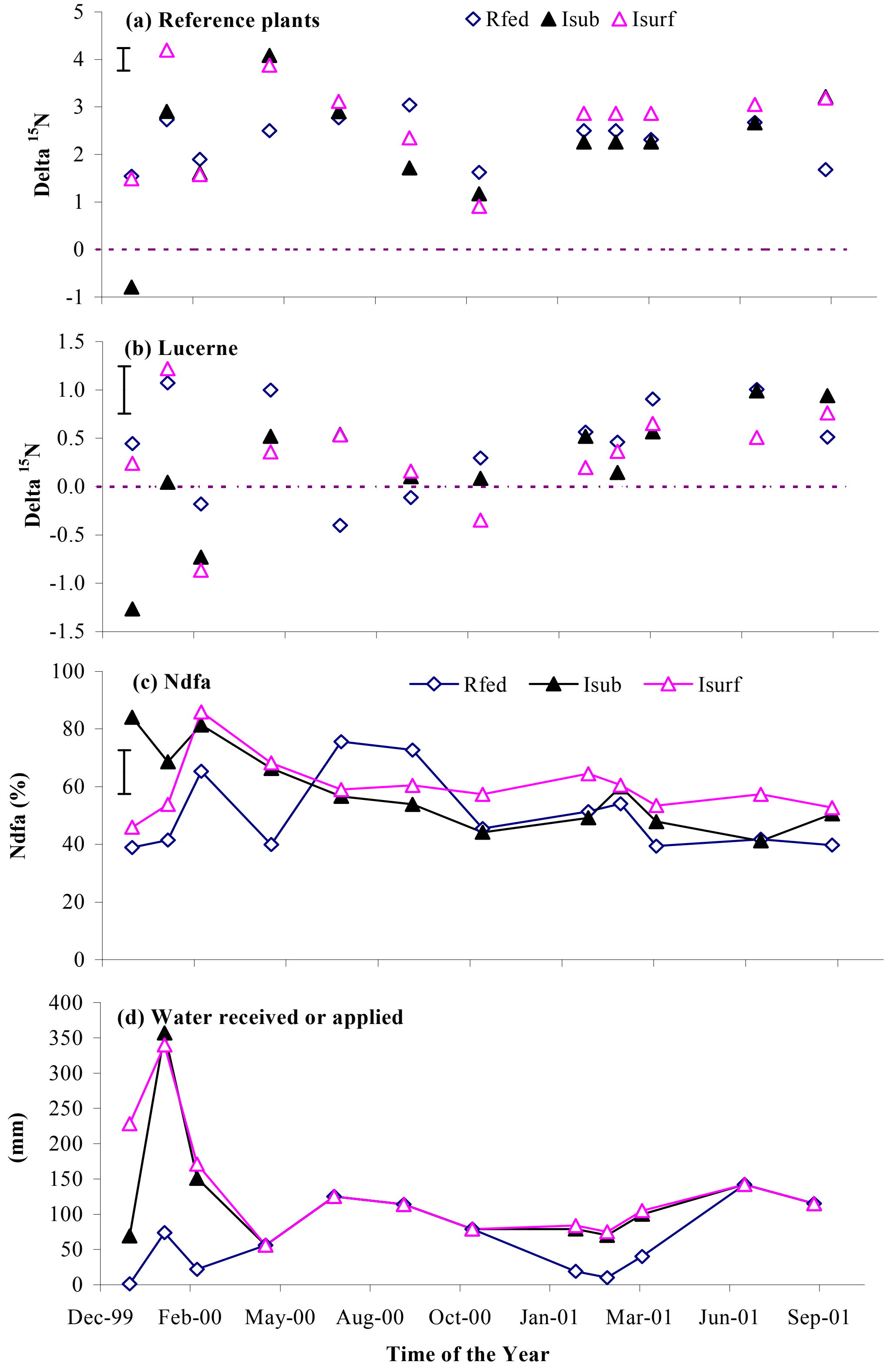

Figure5.2 Measured δ15N of (a) reference plants (b) lucerne (c) estimated Ndfa (%) and (d) amount of water (mm) applied and/or received as rain fall in Rfed, Isub and Isurf treatments during the study period (Dec 1999-Sep 2001) for the 12 sampling times. Error bars represent the LSD at (α=0.05)

5.3.3.1 Lucerne Ndfa

Lucerne Ndfa varied significantly between sampling times in summer and in the growing seasons (Figure 5.2c), although the overall pattern from the study corresponded reasonably well to the amount of water being applied or received as rainfall (Figure 5.2d). Ndfa (84%) was highest for the I_{sub} treatment at the beginning of the study and the start of the first irrigation season (Figure 5.2c); significantly higher than that for both the I_{surf} (45%) and the R_{fed} (38%) treatments. At the second sampling time (Figure 5.2c) there was no difference between I_{sub} and I_{surf} treatments and both were higher than the R_{fed} treatment. Ndfa for the R_{fed} treatment was also lower ($P<0.001$) than both the irrigated treatments in the subsequent (3rd and 4th) harvests taken in March and May 2000, although Ndfa in March (in all treatments) increased in response to a 60 mm rainfall event (Figure 5.2c,d), but subsequently declined again in May. Following termination of irrigation and more than 100 mm of opening season rains (Figure 5.2d) Ndfa for the R_{fed} treatment increased significantly to values of 75% and 72% at the 5th and 6th harvests taken in July and Sept 2000, respectively (Figure 5.1c), whereas the irrigated treatments declined to Ndfa values between 50-60%. Ndfa values for the I_{surf} treatment for the remainder of the study period were slightly, but not significantly higher than the other two treatments (Figure 5.1c), and there was no apparent increase in Ndfa in response to either the relatively small amounts of irrigation in summer 2001 or to rainfall in the 2001 growing season.

Seasonally, Ndfa did not differ significantly across the two years of the study period for the I_{surf} treatment, ranging from 55-62%. Ndfa was higher for the I_{sub} treatment in the first summer period (78%) than the other seasons where it ranged from 46-55%. Ndfa for the R_{fed} treatment was not significantly lower for the summer than the growing season but was significantly higher in the winter-spring of 2000 than 2001 (Table 5.2).

5.3.3.2 Shoot N: amounts derived from fixation and soil uptake

The R_{fed} treatment fixed significantly lower amounts of N_2 (kg ha^{-1}) in each of the growing seasons than both the summer-irrigated treatments but no significant differences in amount of N_2 fixed (kg ha^{-1}) were found between I_{sub} and I_{surf} (Table 5.2, Figure 5.3). Amounts of N_2 fixed (kg ha^{-1}) were higher in the winter-spring growing seasons than the summer periods for the R_{fed} treatment in both years of the study and all treatments in the second year of the study (Table 5.2). The large amounts of irrigation water (550-750 mm) applied in the first summer season (Figure 5.2d) resulted in similar amounts of N_2 being fixed for that period, and the subsequent 2000 growing season, in both the irrigated treatments (Table 5.2).

Cumulative N_2 fixed for the R_{fed} treatment was 264 kg N ha^{-1} and N uptake from the soil was similar (231 kg N ha^{-1}) over the study period (Figure 5.3). The mean cumulative N_2 fixed for the irrigated treatments (719 kg N ha^{-1}) was 2.7 times greater than the R_{fed} treatment whereas N uptake from the soil (483 kg N ha^{-1}) was only double that of the R_{fed} treatment and thus represented a lower proportion of the total shoot N accumulation (Figure 5.3)

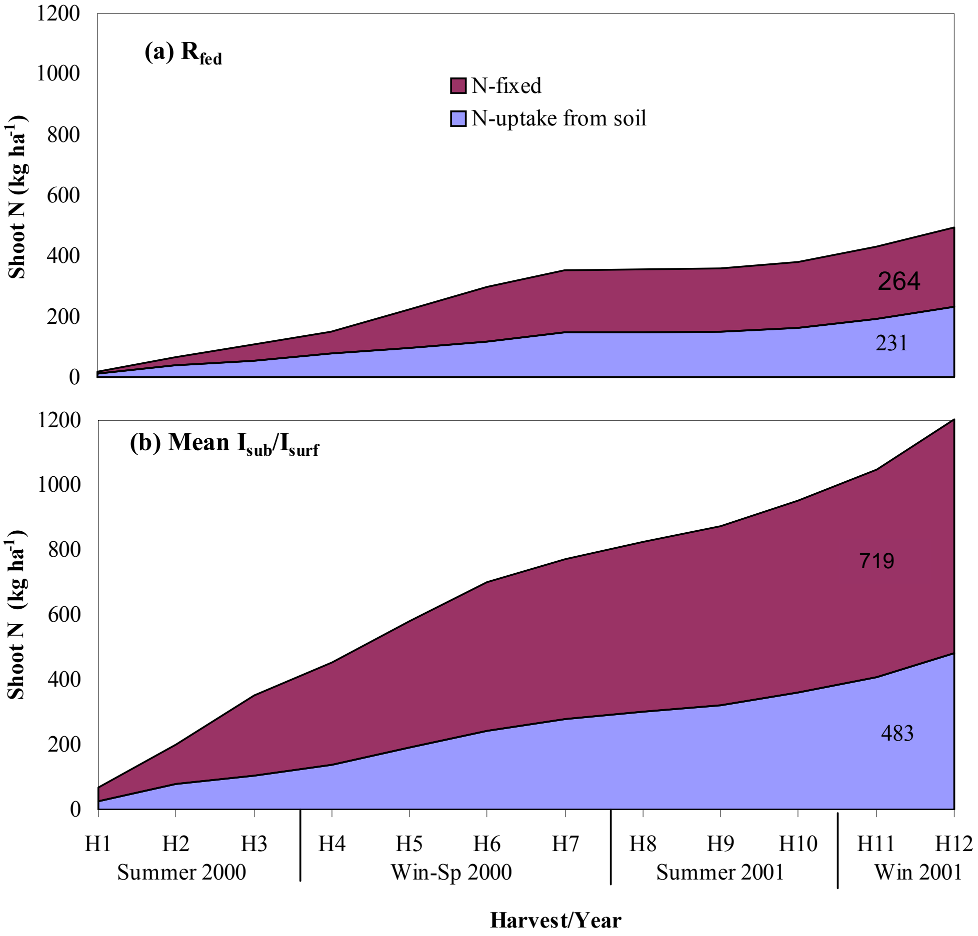

Figure 5.3 Cumulative shoot N_2 fixed and N uptake from soil for the two-year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation

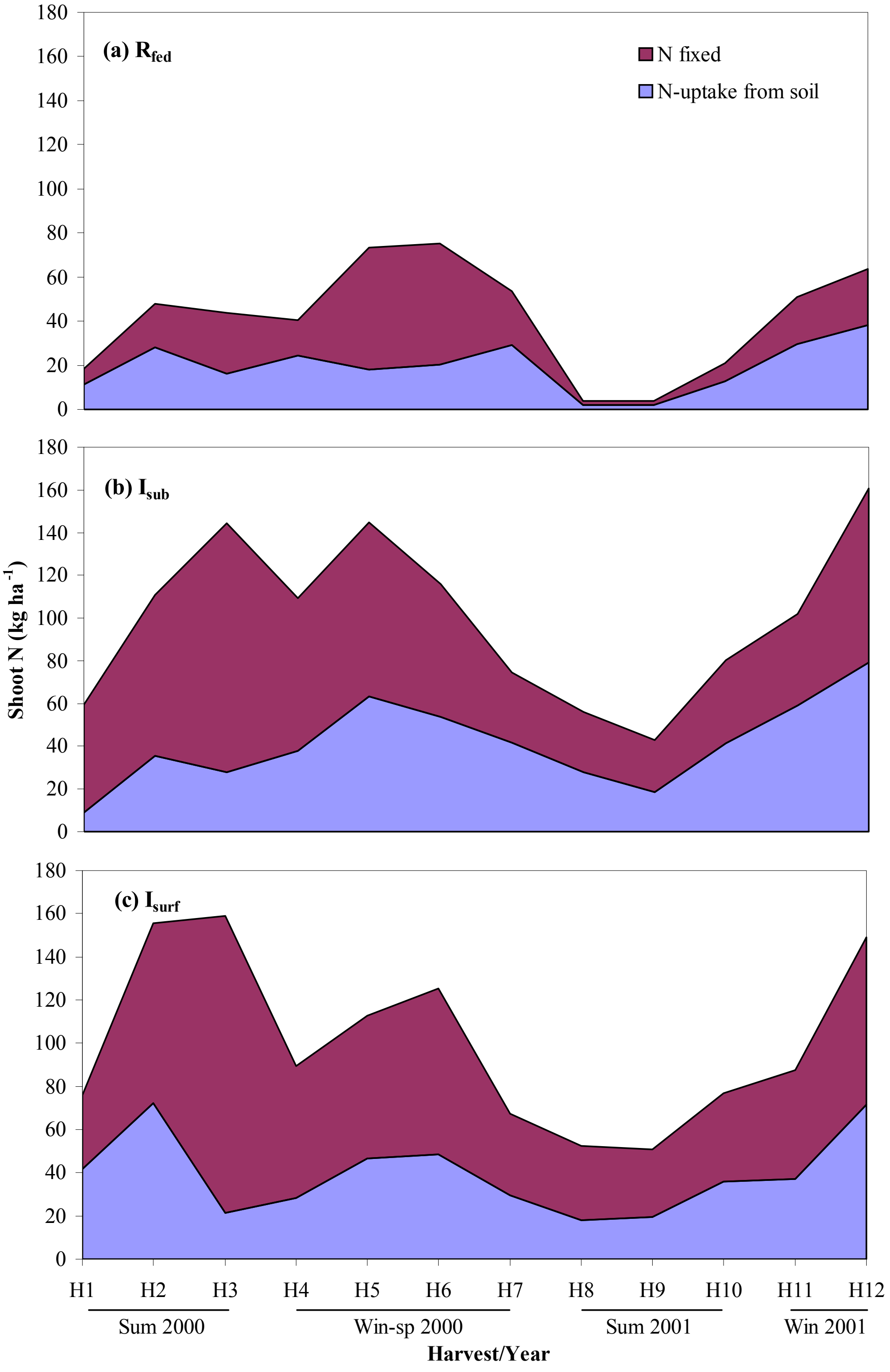

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Figure 5.4 Shoot N (fixed + uptake from soil) in 12 harvests during the two-years study period (Dec 1999-Sep 2001) for rainfed lucerne (Rfed) or lucerne supplied with supplemental water over summer via surface (Isurf) or sub-surface (Isub) irrigation.

Soil N uptake was greater in the winter-spring growing seasons than the summer periods in both years and in all treatments (Table 5.2, Figure 5.4). During the first irrigation period the I_{sub} treatment took up significantly less soil N (72 kg ha^{-1}) than I_{surf} (135 kg N ha^{-1}), although greater soil N uptake by the I_{sub} treatment in the subsequent 2000 growing season resulted in soil N uptake for the two treatments being similar for the first year of the study (Table 5.2, Figure 5.4). Soil N uptake in the second year of the study was lower than the first year for all treatments, and in each of the seasons, apart from the I_{sub} treatment in summer 2001 where soil N uptake was similar to that in summer 2000 (Table 5.2, Figure 5.4)

5.3.4 Relationships between shoot biomass, N_2 fixed, Ndfa and water applied/received

There was a strong linear relationship ($P<0.001$, $R^2 = 0.84$) between the amount of N_2 fixed (kg ha^{-1}) and biomass accumulation (Figure 5.5a). Since biomass accumulation was highly dependent on water applied or received (Section 3.3.2.1) N_2 fixed was therefore also very closely related ($R^2 = 0.95$) to water applied/received (data not shown). However, the amount of N_2 fixed showed only a weak linear relationship with Ndfa ($R^2 = 0.40$) although it was significant $P<0.001$ (Figure 5.5b). There was no relationship between total shoot N and Ndfa (Figure 5.5c).

The amount of N_2 fixed expressed as kg of shoot N_2 fixed per tonne of shoot biomass (Table 5.2), ranged from 18-27 kg N t^{-1} and differed between the treatments and years. It was significantly lower for the R_{fed} treatment in summer 2000 (22 kg N t^{-1}) than the I_{sub} (27 kg N t^{-1}) and I_{surf} (24 kg N t^{-1}) treatment but no significant differences were observed between the treatments in the 2000 winter-spring growing season. These values were higher in 2000 overall than in 2001 and averaged over two-years were 21, 22 and 23 kg N_2 fixed t^{-1} shoot biomass in R_{fed}, I_{sub} and I_{surf} treatments, respectively.

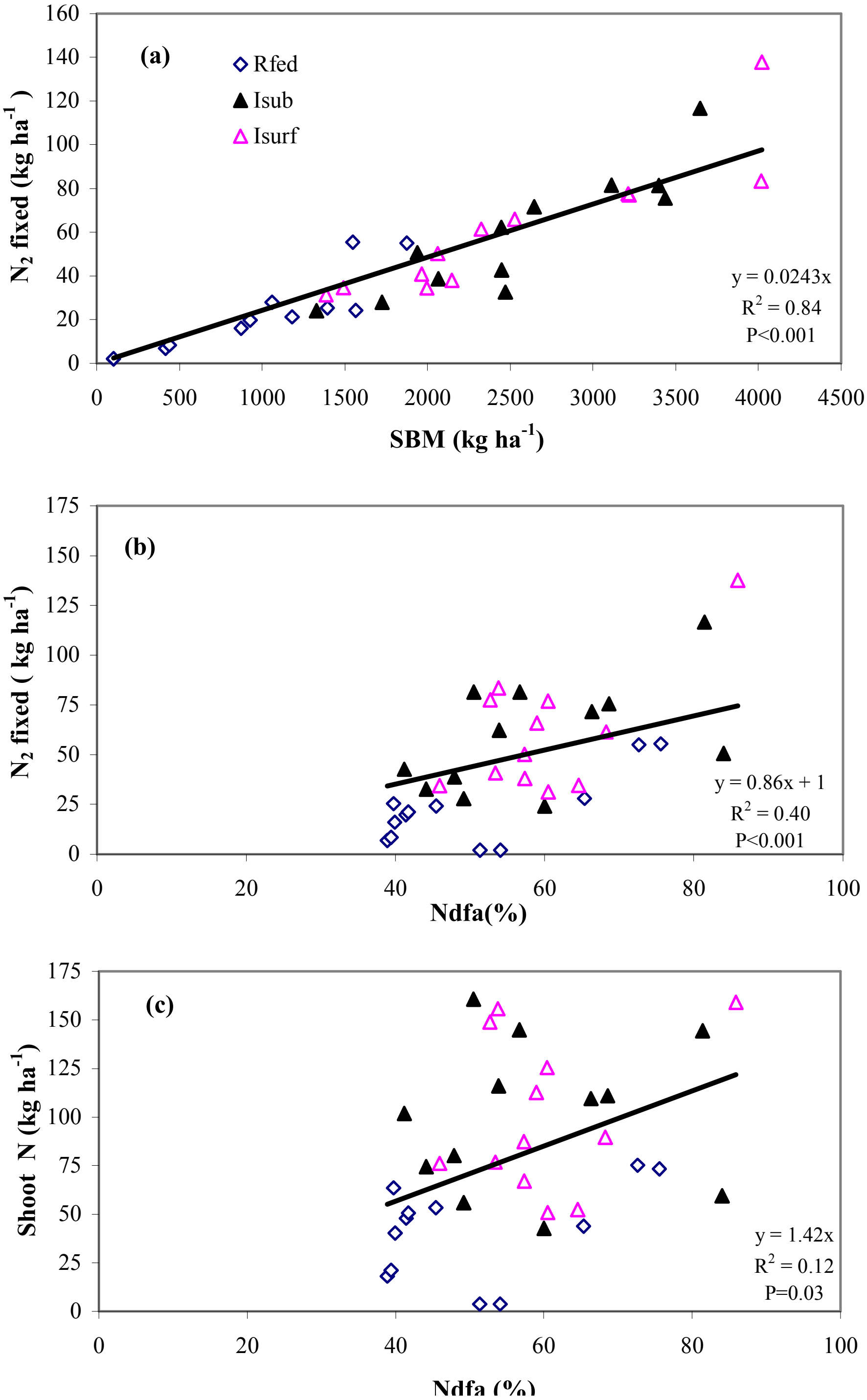


Figure 5.5 Relationships between (a) shoot dry matter and N_2 fixed (b) Ndfa and N_2 fixed and (c) Ndfa and shoot N for the study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

N_2 fixed in the different treatments expressed per mm of total water use followed the same trends as was seen for those based on shoot biomass, but with an opposite seasonal pattern (Table 5.2). The values were significantly higher ($P< 0.05$) in I_{sub} (0.653 kg N_2 fixed mm^{-1}) than I_{surf} (0.459 kg N_2 fixed mm^{-1}) and R_{fed} (0.512 kg N_2 fixed mm^{-1}) during summer 2000, and in the following year I_{sub} was again the highest, but there were no significant differences between treatments (Table 5.2).

5.3.5 Soil mineral N

5.3.5.1 Seasonal depth distribution of mineral N

Mineral N was mainly detected as nitrate, apart from the first two sampling times when ammonium N, at concentrations ranging from 0.3-1.88 mg kg $^{-1}$, representing 28% of the total mineral N measured in the 0-400 mm soil depth in January 2000 and 7% in February 2000 (Appendix D). The NH_4-N mainly present in the I_{sub} treatment early in the study is likely to be associated with concentrations of animal (deer) excreta (section 3.2.1), since animals were seen preferentially 'camping' in the areas where sub-surface irrigation had been installed prior to the start of the experiment; it also could be a function of altered soil N processes due to the mixing and disturbance that accompanied the irrigation installation. In January 2000 mineral N in the top 0-400 mm soil depth (Figure 5.6a) was significantly higher for the I_{sub} treatment (81kg N ha^{-1}) compared to the R_{fed} (43 kg N ha) and I_{surf} (41 kg N ha^{-1}) treatments, probably as a result of increased mineralisation caused by the soil disturbance that occurred when installing the sub-surface irrigation equipment in late 1999. At the second sampling in Feb 2000 mineral N in the 0-400 mm soil profile (Figure 5.6a) was significantly lower (11 kg N ha^{-1}) for the I_{surf} treatment compared to R_{fed} (38 kg N ha^{-1}) and I_{sub} (45 kg N ha^{-1}) treatments, corresponding to higher uptake of soil-derived N by the lucerne in the I_{surf} treatment (Table 5.2). During the growing season for 2000, as soil-derived N uptake by lucerne increased in all treatments (Figure 5.4), the mineral N had decreased to 6-8 kg N ha^{-1} by October 2000 (Figure 5.6a). In May 2001, for the 0-400 mm soil profile, 54 kg N ha^{-1} for the I_{surf} and 55 kg N ha^{-1} for the R_{fed} treatments were observed being significantly higher than 43 kg N ha^{-1} for the I_{sub} (Figure 5.6a). These amounts, by the final sampling in October 2001, were reduced in all treatments to 8-12 kg N ha^{-1} (Figure 5.6a).

Mineral N in the 400-1000 mm soil depth did not differ over the five sampling times or between treatments (Figure 5.6b), and was less than 20 kg N ha^{-1}, apart from at the final sampling (Oct 2001) when the amount in the R_{fed} treatment significantly increased to 33 kg N ha^{-1}. Consideration of the concentration of mineral N for the soil profile clearly demonstrates apparent leaching in the R_{fed} treatment with nitrate present in the top 400 mm soil depth in May 2001 (Figure 5.7d) being recovered in the 400-1000 mm soil depth in October 2001 (Figure 5.7e). A similar trend, but less marked, is noted for the I_{surf} treatment but not for the I_{sub}, and this may be correlated with the higher observed root biomass (Chapter 3, Figure 3.13) and root length density (Chapter 3, Table 3.8) at depths for this treatment. This apparent leaching contrasts with the fate of mineral N measured in Feb 2000 (Figure 5.7a) that was not observed to move down the profile but was presumed to contribute to plant uptake, and thus was not present at any measured depth in June or October 2000 (Figure 5.7b,c). Mineral N in the 1000-1500 mm soil depth consistently decreased throughout the study period in all the treatments from 35 to 6-11 kg N ha^{-1} between June 2000 and May 2001 in both the irrigated treatments and from 28 to 12 kg N ha^{-1} in the rainfed, indicating some extraction of nitrate by lucerne from this lower profile.

5.3.5.2 Seasonal patterns for soil mineral N and N2 fixation

Despite substantial seasonal fluctuations in soil mineral N (Figure 5.8b) for all treatments these were not paralleled by similar fluctuations in Ndfa (%) (Table 5.2, Figure 5.8c). Furthermore, although the quantity of N_2 fixed did vary seasonally for the various treatments (Figure 5.8a) the trends were not consistently related to those observed for mineral N. For example, soil mineral N in summer 2000 in the 0-1000 mm soil profile for the I_{sub} treatment (Figure 5.8b) was relatively high (65 kg ha^{-1}), as was Ndfa (78%) and shoot N_2 fixed at 243 kg ha^{-1} (Figure 5.8a,c). Whereas under I_{surf} in the same growing season there was less mineral N in 0-1000 mm soil profile (31 kg ha^{-1}), yet Ndfa was still relatively high (62%) and shoot N_2 fixed was the highest of the treatments (256 kg ha^{-1}). Furthermore, in winter 2000, all the treatments were at lower levels of soil mineral N but Ndfa and shoot N_2 fixed were not significantly lower ($P<0.001$) than in the summer 2000 (Figure 5.8). Similar trends were observed in the summer and winter-spring growing seasons 2001 (Figure 5.8). Overall there was no positive relationship between soil mineral N and amount of N_2 fixed or Ndfa.

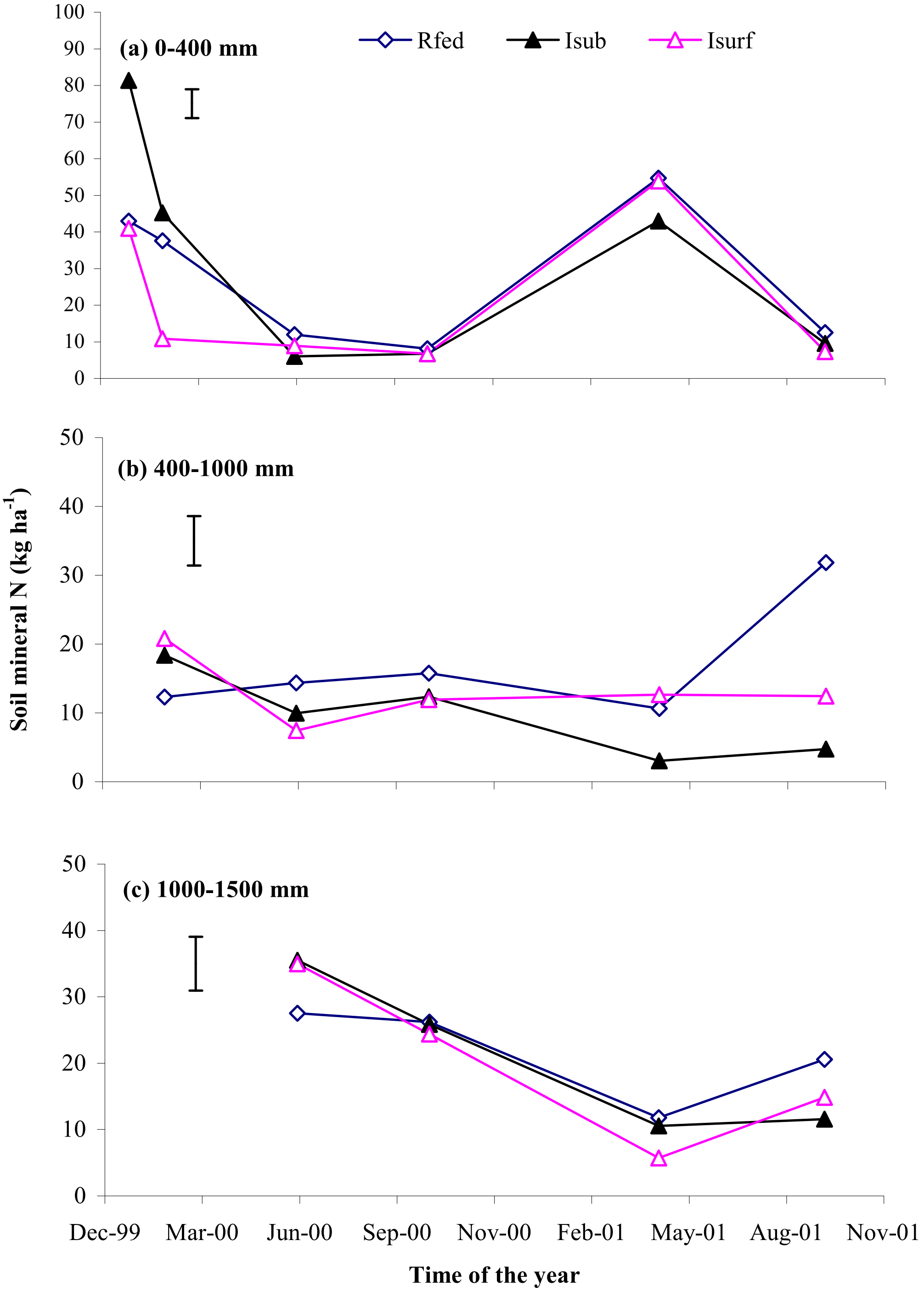


Figure 5.6 Amounts (kg ha^{-1}) mineral soil N (a) 0-400, (b) 400-1000 and (c) 1000-1500 mm soil profiles for the two year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface ($_{Isub}$) irrigation.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

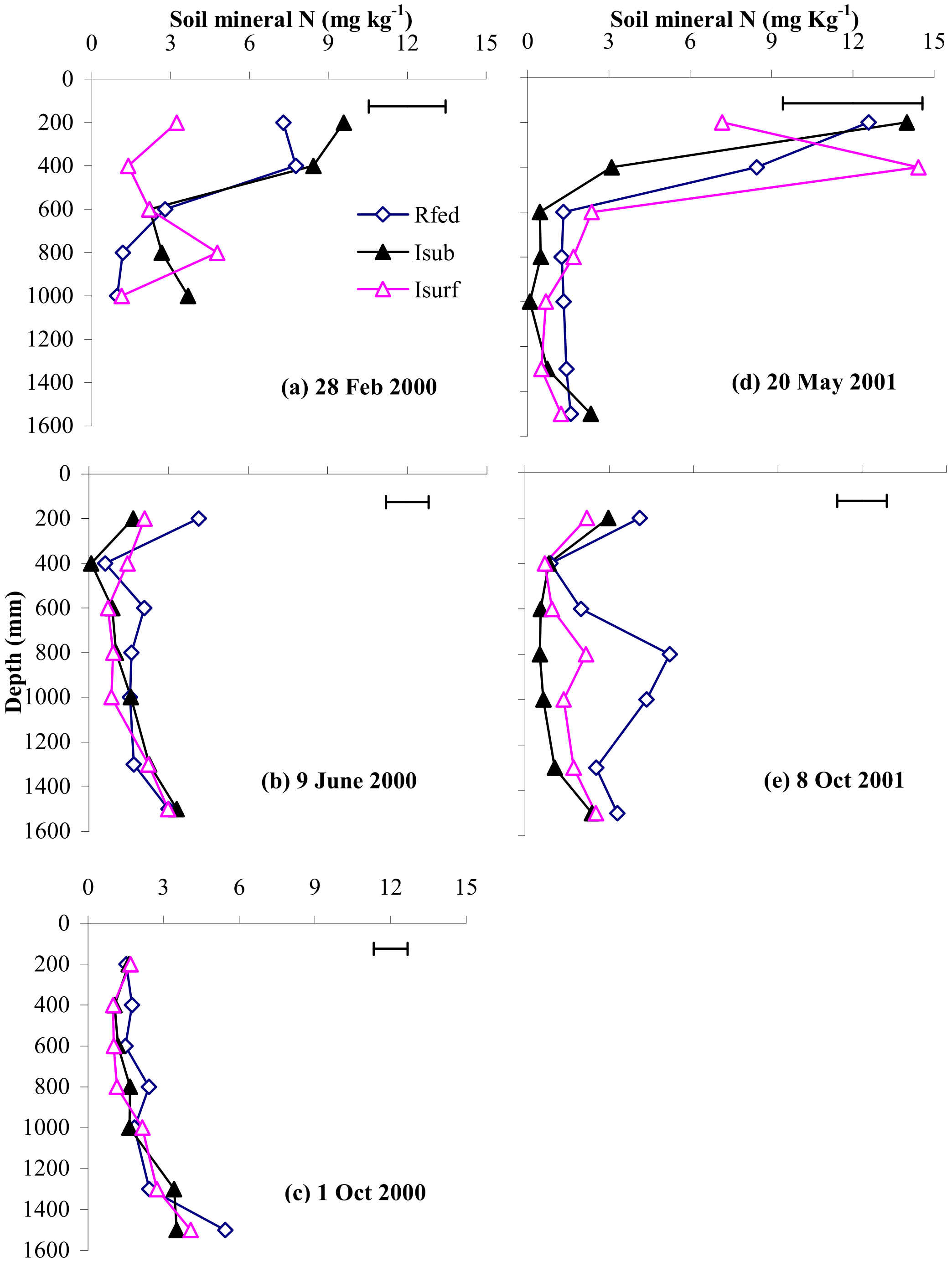


Figure 5.7 Soil profile mineral N concentrations (mg kg^{-1}) measured (a) 28 Feb 2000, (b) 9 June 2000 (c) 1 Oct 2000 (d) 20 May 2001 and (e) 8 Oct 2001 for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error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

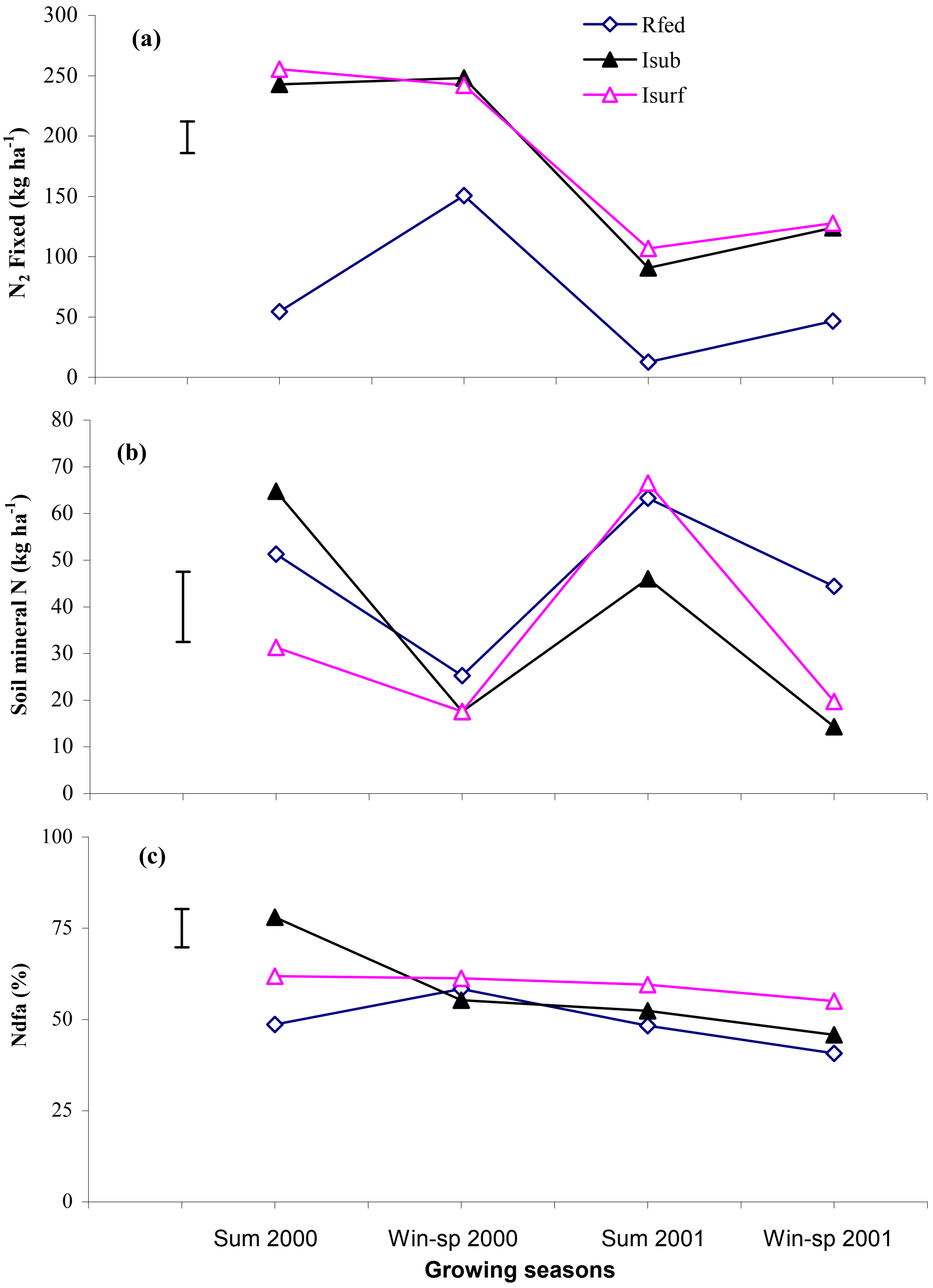


Figure 5.8 (a) Seasonal N_2 fixed and (b) amounts of soil mineral N in 0-1000 mm soil profile and (c) Ndfa (%) for the two year study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation. Error bars represent LSD at (α=0.05)

5.4 Discussion

The results of this study present an insight over two years into the soil-plant N dynamics of lucerne, in relation to spatial and temporal variation of water supply, for a lucerne crop growing on a duplex soil in a Mediterranean climate in South Australia. Amount of shoot N_2 fixed by lucerne in this study was largely related to the amount of accumulated shoot biomass and therefore, any strategy that enhanced the growth (such as irrigation) also caused a positive impact on the amount of N_2 fixation. Similar relationships between shoot biomass and shoot N_2 fixed for other legumes, both annuals and perennials have been reported for environments in southern and eastern Australia (Peoples *et al.* 1998, McCallum *et al.* 2000, McDonald *et al.* 2001).

5.4.1 Seasonal N_2 fixation

The greater shoot biomass and N production in the winter-spring growing seasons in this study (Table 5.2) is due to the cooler temperatures and higher rainfall in winter (Peoples *et al.* 1998, Kelner *et al.* 1987) for this Mediterranean climate favouring growth of this highly winter-active variety (Sceptre) of lucerne, compared to the stresses imposed over summer. The amounts of shoot N_2 fixed by the R_{fed} treatment in 2000, 55 kg N ha^{-1} in summer and 151 kg N ha^{-1} in the growing season, with a yearly total of 205 kg N ha^{-1}, are greater than reported results under similar rainfed conditions of southern Australia, such as 47-167 kg N ha^{-1} (Peoples *et al.* 1998), 14-138 kg N ha^{-1} (Dear *et al.* 1999) and 19-90 kg N ha^{-1} (McCallum *et al.* 2000).

This may largely be that in this study total above-ground shoot biomass was used to calculate amount of N_2 fixed rather than shoot dry matter yield (DMY) harvested at 5 cm height. Indeed, values for shoot N_2 fixed using the latter approach are more in agreement with those of the aforementioned researchers (Appendix E). During the second year (2001) total shoot N_2 fixed by rainfed lucerne was 13 kg N ha^{-1} in summer and 47 kg N ha^{-1} in the growing season with a yearly total of 60 kg N ha^{-1}. The reason for this substantial reduction in the quantity of shoot N_2 fixed during 2001 compared to the previous year was the reduction in plant population in summer 2001 (Chapter 3, Figure 3.7) as a result of prolonged drought in hot weather conditions (McCallum *et al.* 2000). Further, subsoil hostility causing restricted access to soil water (Chapter 4) may also have compounded this issue. Peoples *et al*. (1998) and Dear *et al*. (1999) have observed a similar reduction in shoot N_2 fixed in response to lower plant populations under rainfed conditions in eastern Australia.

Regardless of the type of irrigation used lucerne fixed similar amount of total shoot N, 491-498 kg N ha^{-1} in 2000 and 215-234 kg N_2 ha^{-1} in 2001 (Table 5.2); based on DMY these values were 365-375 kg N ha^{-1} and 149-154 kg N_2 ha^{-1} in 2001 (Appendix E) which are comparable with the findings under irrigated conditions in eastern Australia (Gault *et al*. 1996), as well as internationally in Canada (Kelner *et al*. 1987) and Sweden (Wivstad *et al*. 1987). In summer 2001, a very limited amount of water (60-65 mm per harvest) was applied and there was a drastic reduction in the amount of shoot N_2 fixed, principally reflecting the strong influence of climatic constraints (specifically water) either indirectly on shoot growth and subsequently N_2 fixed, or directly on root and nodule function (Wivstad *et al*. 1987 Peoples *et al*. 1998, Dear *et al*. 1999, McCallum *et al*. 2000).

5.4.2 Proportional dependence on N_2 fixation

The range of values for Ndfa for the R_{fed} treatment in this study (39-76%) was wider than other ranges reported for lucerne under rainfed conditions in other areas of Australia, for example, 73-77% (McCallum *et al*. 2000), 57-71% (Peoples *et al*. 1998), and 59-60% (Dear *et al*. 1999). The observed lower range in Ndfa for the R_{fed} treatment (39-51%) in the second year of the study (2001) compared to the first was probably a combined effect of the extended period of soil water stress over the 2001 summer followed by a relatively low rainfall 2001 growing season. Other Australian researchers (Peoples *et al*. 1998, Dear *et al*. 1999, Bowman *et al*. 2002) have reported similar reductions in Ndfa over time due to adverse edaphic and climatic conditions. Overseas studies have reported that water stress can specifically affect nitrogenase activity in lucerne (Carter and Sheaffer 1983, Wery *et al*. 1986, Mohammed *et al*. 1996, Carranca *et al*. 1999).

In contrast to the rainfed situation, under irrigated conditions in North America Heichel *et al*. (1984) reported a consistent increase in Ndfa over a period of four years. The strong relationship between Ndfa and water supply is illustrated by the results from this current study where, for both the irrigated treatments, Ndfa ranged from 45-86% in summer and 44-68% in the growing season, and was generally greater at the time when plant available water was higher, irrespective of season. These values for Ndfa agree with those reported for lucerne grown under irrigated conditions in Australia (Gault *et al.* 1995, Brockwell *et al.* 1995, McDonald *et al.* 2001), and overseas (Wivstad *et al.* 1987, Kelner *et al.* 1997); although, due to summer irrigation only in this study the mean annual Ndfa was 16% lower than that reported by (Gault *et al.* 1995) where irrigation was applied all year round.

Observed variation in Ndfa between sampling times within a single growing season was most marked in the R_{fed} treatment. Clearly, factors such as shoot and soil temperature, mobilisation of root carbohydrate reserves, soil mineral N concentration and quantity of available soil water (Heichel *et al.* 1984, Wivstad *et al.* 1987, Kelnar *et al.* 1996, Peoples *et al.* 1998) all have the potential to be involved. However, the absence of any strong relationship between shoot N_2 fixed (derived from shoot biomass production) and Ndfa in all the treatments evaluated in the study suggests that there is not always a direct influence of climatic or edaphic factors on both shoot growth and N_2 fixed, and that some factors that directly affect root and nodule function (soil water and mineral N) may be operating independently of influences on the shoot.

Over the whole study period R_{fed} lucerne relied on N_2 fixation more than soil N uptake only during the first growing season (2000). Drought stress decreasing N_2 fixation much more than nitrate assimilation has previously been reported (Wery *et al.* 1986, Carter and Sheaffer 1983, Wery *et al.* 1986, Mohammed *et al.* 1996, Carranca *et al.* 1999). The concept of a dominant effect of water stress on N_2 fixed is further supported by the fact that in both the irrigated treatments during the first year of the study, when water supply was not considered particularly limiting, lucerne relied more on N_2 fixation than uptake. Wery *et al.* (1986) found that in lucerne, during periods of rapid plant growth, N_2 fixation and N uptake may function simultaneously, and this was clearly observed in all treatments for many of the sampling times during the second year in this study where there was almost equal dependence on soil N uptake and N_2 fixed. The lower reliance on soil N uptake by the I_{sub} treatment than the I_{surf} observed in the first part of the study could be due to the effect of placing water deeper in the soil profile versus shallow application, since the supply of mineral N and the uptake are more likely to have been initiated faster in the surface soil layers.

5.4.3 Comments on the ^{15}N natural abundance method

It is not clear why the $\delta^{15}N$ of cape weed was extremely high (7.14 to 8.05) compared to all others species used in the study (-0.86 to 4.04). Capeweed is reported to be a nitrate accumulator (Unkovich *et al.* 1998) but there is no obvious rationale why this would lead to a higher $\delta^{15}N$ value. Others have used capeweed and reported lower $\delta^{15}N$ values (Unkovich and Pate 2001). It is worth noting that at the time of measurement soil mineral N under all the treatments was 20-30 kg N ha^{-1} compared to earlier amounts of 30-60 kg N ha^{-1} and it has been reported that a reduction in amount of soil mineral N can induce changes in the $\delta^{15}N$ abundance of the pool (Bergersen *et al.* 1989), but, if this were the case one would expect to see an increase in the corresponding lucerne $\delta^{15}N$ value too.

Lucerne $\delta^{15}N$ values, and reference plant even more so, were relatively stable in the second year of the study but far more variable in the first year. The most likely reason for this may be that, as previously mentioned in the mineral N results (Section 5.3.5.1) prior to the trial being established there had been animals (deer) using the paddock and it is known that animal excreta can vary widely in $\delta^{15}N$ (Kerley and Jarvis 1996).

5.4.4 Relationship of amounts of N_2 fixed to growth and total water use

Despite seasonal differences in Ndfa and amount of N_2 fixed, variability in terms of kg of N_2 fixed per tonne of lucerne shoot biomass (SBM) was relatively small, ranging from 23-25 kg N_2 t^{-1} SBM in the first year of the study and 19-23 kg N_2 t^{-1} SBM in the second year, over all treatments, irrigated and rainfed. These values correspond closely to the "rule of thumb" for the estimation of legume N_2 fixed from shoot biomass established by researchers in Australia (People *et al.* 1998, Dear *et al.* 1999), McCallum *et al.* 2000).

The amount N_2 fixed per mm of total water use was far more variable, probably due to total water use (ET) being an integration of both soil evaporation and plant transpiration. The I_{sub} treatment had the highest values of N_2 fixed per mm water use due to the lower soil evaporation losses, although the surface treatment was reasonably similar. Even the values for the rainfed treatment were greater than that reported by McDonald *et al.*

(2001) of 0.270 kg N fixed per mm water use in a first year stand of lucerne under irrigated conditions in NSW Australia. The higher values in this study may have been due to the lucerne being 18 months old and having a more established root system for exploitation of water.

5.4.5 Soil mineral N dynamics under lucerne

The number of measurements made for mineral N limit, to some extent, detailed interpretation for dynamics of plant-available N under lucerne, however some broad conclusions can be suggested. There was no apparent relationship between the amounts of soil mineral N and dependence on N_2 fixation in this study, in any growing seasons under any treatment. Mean amount over the whole study in the top 0.4 m of soil, where the majority of nodules are likely to be located, was about 20 kg N ha^{-1} and the highest recorded amount in that profile over two years of measurement was 35 kg N ha^{-1}; these amounts may have been below the concentrations required to inhibit N_2 fixation. The data from this study support the view that N_2 fixation and N uptake occur in a complementary manner in lucerne. Others have also demonstrated that lucerne N_2 fixation is not correlated to presence of mineral N; e.g Lamb *et al.* (1995) reported that N_2 fixation in lucerne continued even under N fertiliser application rates as high as 840 kg N ha^{-1}, a view supported by the work of Blumenthal and Russelle (1996) and Kelner *et al.* (1997).

The amount of mineral N present in the soil was generally inversely associated with shoot growth (and thus N uptake) of the lucerne (Wery *et al.* 1986), and therefore soil mineral N accumulated following periods of low growth and decreased following rapid growth. In this regard there also appeared to be influences from soil water that were dominant in terms of driving N uptake rather than supply of N. For example, the larger quantity of water initially applied in the I_{surf} treatment up to the first sampling time resulted in less soil mineral N remaining in 0-1000 mm soil depth than under the I_{sub}. The decrease from Feb 2000 to Oct 2000 in soil mineral N observed in all treatments was greater for both the summer-irrigated treatments compared to the R_{fed}, a further indication of the inverse relationship to lucerne growth and soil water use. The observed high concentration of soil mineral N (50-70 kg N ha^{-1}) in 0-1000 mm soil depth in autumn and early winter, decreasing during peak periods of growth in spring to 20-30 kg

N ha^{-1} was a similar pattern to that reported under annual pasture (Peoples and Baldock 2001). The larger flux of mineral N in the 0-400 mm soil profile for the I_{surf} in autumn 2001, compared with the previous year, is likely to be due to supply of sufficient water over summer to stimulate mineralisation, but not for sustained plant uptake. The situation will have been exacerbated by death of plants over summer 2001 with decomposition of the above and belowground parts. However, during the 2001 growing season this mineral N flux, to different extents, was assimilated in all treatments, although some was leached deeper in the profile in the R_{fed}.

The overall observed pattern of initial exploitation of the upper soil profile for soil mineral N with subsequent extraction at depth is a common observation under lucerne in Australia (Catchpoole 1992, Dear *et al.* 2001,) and worldwide (Boawn *et al*. 1963, Schertz and Miller 1972, Mathers *et al*. 1975, Peterson and Russelle 1991, Blumenthal and Russelle 1996, Kelner *et al*. 1997, Martin *et al*. 2001). Proportional extraction from the lower profile was different between all the treatments with R_{fed} being less than the irrigated treatments and I_{sub} being better than I_{suf}. These observations are correlated with a higher RLD in the 1200-1400 mm soil profile for I_{sub} compared to I_{surf} and R_{fed} (Section 3.3.3.1). A similar relationship between soil N uptake and RLD or root distribution was reported for annual pasture legumes by Anderson *et al*. (1998).

5.5 Conclusion

The following major conclusions were derived from the work:

- Lucerne grown under Mediterranean climate on a duplex soil in South Australia fixed similar amounts of N_2 to lucerne grown in other dryland farming regions of Australia; estimates based on total shoot dry matter were 205 kg N ha^{-1} in the first year and 59 kg N ha^{-1} in the second year of the study.
- Proportional dependence on N_2 fixation varied widely over the two years of the study, ranging from 39% - 76% in the rainfed lucerne, a reflection of the extreme variability in soil moisture content, and possibly temperature, characteristic of the Mediterranean environment.
- The potential to overcome limitations to N_2 fixation by lucerne imposed by low rainfall and soil water supply in these environments using either large amounts of summer irrigation or with relatively small summer rainfall events (simulated), was demonstrated. The effect was primarily through an increase in shoot biomass production i.e. amounts of shoot N_2 fixed were increased to 495 kg N ha^{-1} in the first year and 235 kg N ha^{-1} in the second year. However, there was also a significant positive effect on proportional dependence on N_2 fixed during the first summer of the study, with mean Ndfa for the irrigated lucerne estimated to be 70% compared to 55% in the rainfed.
- Lucerne in this rainfed environment appeared equally dependent on both soil mineral N and N_2 fixation for the majority of the time, apart from the growing season in 2000 when soil moisture stress was reduced and reliance on N_2 fixed increased. There was no apparent relationship between soil mineral N and dependence on N_2 fixed but lucerne clearly demonstrated the ability to extract NO_3 from depth in the soil profile.

Chapter 6

6 Evaluation of the performance of APSIM-Lucerne in a Mediterranean climate on a duplex soil

6.1 Introduction

Crop simulation models have proven useful for increasing the quantitative understanding of how a crop system operates under different environmental and climatic conditions (Sinclair and Seligman 2000, Xie *et al.* 2001). However, validation of the simulation model against independent observed data is essential to assess its potential and credibility (Penning de Vries, 1977, *Dent et al.* 1997, Probert *et al.* 1998a). If a simulation model accurately predicts the experimental data under a range of soil, environmental and management practices, additional value can be gained from the experimental data, and the research results can be extrapolated to other conditions with greater confidence (Dolling *et al.* 2007). The Agricultural Production System Simulator (APSIM) is an advanced cropping system model and possesses the capacity for simulating both crop growth processes and soil processes including soil water, soil nitrogen, crop residues, and acidification in a range of scenarios under conditional management rules (Asseng *et al.* 2000, Keating *et al.* 2003).

The APSIM-lucerne module was developed in Queensland, Australia and is based on physiological processes and principles (Robertson *et al.* 2000). APSIM modules have been evaluated in phase farming systems dealing with soil water and nitrogen dynamics and model predictions were in satisfactory agreement with measured data (Asseng *et al.* 1998a, Robertson *et al.* 2002, Yunusa *et al.* 2004, Dolling *et al.* 2005, Verburg *et al.* 2007). APSIM-lucerne also demonstrated its robustness in accurately predicting experimental data in terms of lucerne growth under irrigated and rainfed conditions, in the areas where it was developed (Probert, *et el.* 1998a, Robertson *et al.* 2002). However, the performance of APSIM-lucerne requires evaluation under a range of locations having different environmental and climatic conditions. Further research is needed to assess the sensitivity of the model to a range of plant and soil parameters. Previous research has indicated that considerable effort is required to parameterise the model in order to obtain accurate predictions (Moot *et al.* 2001, Dolling *et al.* 2001, Dolling *et al.* 2005, Chen *et al.* 2003).

This study provides a detailed evaluation of the performance of APSIM-Lucerne in terms of growth, water balance, soil mineral N movement and N accumulation under lucerne in response to variable soil water regimes grown on a duplex (texture contraxt) soil in a Mediterranean type climate in South Australia. The performance of the model has been evaluated using several statistical tests.

6.2 Materials and Methods

6.2.1 Climate

This study was undertaken on a sandy loam duplex soil at Roseworthy Campus of The University of Adelaide located at (34°32′S, 138°45′E) north of Adelaide in South Australia. Daily climate data was sourced from SILO, Bureau of Meteorology for Roseworthy Campus (Station No 23020) in APSIM format. The weather data required for APSIM simulation consisted of daily radiation (MJ m^{-2}), daily maximum and minimum temperature (^{o}C) and daily rainfall (mm). A sample format is provided below (Table 6.1).

Table 6.1 Sample of SILO data used in simulation modelling

Year	Day	Radn	MaxT	MinT	Rain
2001	1	24	40.5	19.8	0
2001	2	26	40.3	26.5	0
2001	3	26	38.2	9.0	0
2001	4	24	38.4	24.1	0
2001	5	27	30.6	12.8	0
2001	6	27	30.9	10.8	0
2001	7	29	32.2	12.8	0
2001	8	24	34.3	15.6	0
2001	9	31	39.1	13.1	0
2001	10	29	42.2	21.5	0

6.2.2 Input data

As described previously (Section 3.3) three irrigation treatments (R_{fed}, I_{sub} and I_{surf}) were imposed on an 18 month old stand of lucerne variety ‘Sceptre’. Comparison of only two treatments (R_{fed} and I_{surf}) was included in this evaluation of APSIM, due to the complexity of simulation of water below ground in the I_{sub} treatment. The observed data for lucerne growth, phenology, soil water and soil nitrogen, (Chapters 3 to 5) were used to evaluate

APSIM-Lucerne performance. APSIM-Lucerne is linked with 3 other modules, SOILWAT2, SOILN2 and RESIDUE for simulating lucerne based farming systems (Keating *et al*. 2003).

6.2.3 Model parameterisation

6.2.3.1 Management and operation

Management rules and operations were specified as closely as possible to actual management practice in the field (Table 6.2, Appendix M provides a copy of the manager file). Since the experiment was initiated in an 18 month old lucerne stand, the original sowing date in model was specified according to Julian day (155) 1998 (Table 6.2). Actual seed rate and sowing depth were also specified in the lucerne manager file. Start and end of simulation day and year was specified under the clock parameters. APSIM considers the lucerne stem as a primary production unit (plant) and stem population is time invariant, unaffected by climatic conditions or management (Probert *et al*. 1998a). Stem population was initialised at 500 stems m^{-2} and then varied with observed values at the appropriate time for each treatment; since stem population varies the LAI. Irrigation amount in summer 2000 was reduced by 33% to account for apparent losses due to the often hot and windy conditions at the time of irrigation using an overhead sprinkler system, whereas it was retained at 100% for the summer 2001 irrigation period due to more careful (irrigating only when wind was low) and much lower irrigation amounts this year compared to the first summer.

Table 6.2 Details of actions and commands used in APSIM.

Action or command	Detail
Start date	5th June (155 Julian day)
Seed rate	5 (kg ha^{-1})
Sowing depth	40 mm
Harvest dates	12 harvests (See Table 2.1 for individual harvest date)
Cutting height	5 cm
Stem population	500 for R_{fed} and 500 for I_{surf}
Irrigation	Summer (1999-2000) amount (642 mm) Summer 2000-2001 amount (195 mm) For detail (See Appendix G)
End date	20th Sep 2001

6.2.3.2 Soil parameters

APSIM-Lucerne (version 3.6) simulates phenology, biomass, nitrogen and soil water use on a user-specified time step and is driven by daily values of temperature, radiation and irrigation or rainfall (Robertson *et al.* 2002). This particular simulation operated on a daily time-step and utilised several other modules including SOILWAT2, SOILN2 and RESIDUE for simulating a lucerne-based farming system (Keating *et al.* 2003). Detailed description of APSIM-Lucerne is provided in Robertson *et al.* 2002. The SOILWAT module determines plant available water capacity (PAWC) from drained upper limit (DUL) crop lower limit (CLL), bulk density and porosity. These parameters were derived by the ponding method (Table 4.1, 6.3) for the site and Neutron Moisture Meter observations (Dalgleish and Foale 1998). SOILWAT2 uses two parameters (u and cona) to specify a two-stage soil evaporation process. The parameter '*u*' determines the cumulative amount of water loss during the energy limiting stage-1 of evaporation, and the parameter '*cona*' determines the rate of soil evaporation during the water limited stage-2 phase.

The growth of lucerne roots, and therefore also the pattern of soil water extraction, is determined by three parameters, '*ll*' (the lower limit of soil water extraction), '*kl*' (the fraction of PAWC that can be extracted in a single day, and '*xf*' (the root exploration factor that determines how fast roots grow through a soil layer. Each of these three parameters must be specified for each soil layer (Table 6.3). Movement of soil water when soil water is below the Drained Upper Limit (DUL) is specified by two parameters (diffus_const and diffus_slope). Further detailed description of the processes involved in the models has been reported by (Asseng *et al.* 1998b, Probert *et al.* 1998b).

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

		Soil parameters			**Soil x plant parameters**		
Layer	Mid depth	L15	Dul	Sat	Ll[1]	Xf[2]	Kl[3]
No	mm	------------------mm/mm----------					
1	100	0.11	0.26	0.44	0.11	1.0	0.09
2	300	0.11	0.25	0.47	0.11	0.8	0.08
3	500	0.13	0.26	0.46	0.135	0.7	0.06
4	700	0.15	0.26	0.45	0.18	0.5	0.03
5	900	0.18	0.26	0.42	0.20	0.2	0.01
6	1200	0.20	0.28	0.43	0.20	0.2	0.01
7	1600	0.25	0.30	0.43	0.25	0.1	0.01
8	2000	0.31	0.33	0.43	0.31	0.1	0.01
9	2400	0.37	0.39	0.43	0.37	0.0	0.0
10	2800	0.38	0.39	0.43	0.38	0.0	0.0

[1] Ll is the lower limit for water extraction by lucerne

[2] Xf is the exploration factor that defines root extension rate for that soil layer.

[3] Kl is the fraction of PAWC that can be taken up from a layer in a day.

6.2.3.3 Model testing strategy

A series of steps were followed:

1. In collaboration with APSRU a new cultivar ‘Sceptre’ was created in the model based on observed phenology (see new parameters in Table 6.5). Observed flowering date was analysed with photoperiod and temperature data to determine the relationship between thermal time and photoperiod (Figure 6.1).
2. The model was run with the new ‘Sceptre’ phenology parameters. Observed and simulated plant response, soil water and soil nitrogen were compared. Where agreement between observed and simulated output was poor, a sensitivity analysis was conducted to evaluate possible improvements to the model.
3. The parameters ‘*k*l’, ‘*xf*’ were slightly modified on the basis of observed drying phases by lucerne and the presence of roots in the profile (Table 6.3).
4. Changes were made to RUE (Table 6.6), on the basis of observed data (Figure 3.16). RUE for ‘*regrowth’* was estimated by averaging RUE values in the irrigated treatment (I_{surf}) when water deficit was not limiting the growth in summer (2000), whereas the ‘*reduced’* value for autumn-winter was determined when growth was not limited by water deficit in the June to August periods in both 2000 and 2001 (Figure

6.18). '*Seedling'* RUE was not relevant in the current evaluation of already established lucerne and was left at the same values reported by Dolling (2005, Table 6.6). Specific leaf area was modified (Table 6.5b) according to field observed data. The fraction of stem to leaf ratio was also changed on the basis of observed data (Table 6.5c). Minor changes were also made to the transpiration coefficients '*trans_eff_coef'* (Table 6.5d), following (Dolling *et al*. 2005, Smeal *et al*. 1991).

5. The observed data for phyllochron (Figure 3.10) was within the range of published values presently being used in the model. Observed data were used to specify the phyllochron in the model but simulated results were not different so the standard phyllochron (51 and 34) was used in the final simulation.
6. A final assessment of model performance based on the final version of the model was carried out using a range of statistical tests.

6.2.3.4 Statistical analysis

Four different statistics were used for comparison of simulated and observed data. The Root Mean Squared Deviation (RMSD) was estimated (Wallach and Goffinet 1989, Gauch *et al*. 2003) for comparing observed and simulated biomass for 12 regrowth cycles in the R_{fed} and I_{surf} treatments separately. Similarly soil water data for two profiles (0-600, 0-2000 mm) was compared over the two-year study period using RMSD. Statistical analysis (RMSD) was also under-taken for amount of observed and simulated soil nitrate nitrogen at 5 times. Shoot N was also statistically compared over the 12 harvest cycles. RMSD was used to compare the absolute magnitude of the error between observed and simulated data. RMSD is considered a useful measure of model performance as it indicates the relative degree of model deviations from field observation and can be used to determine further statistical properties (Mayer and Butler 1993) and presented as:

$$\mathrm{RMSD} = \{[\Sigma O_n - S_n)^2])/N\}^{0.5} \qquad \text{(Eq. 6.1)}$$

Where O_n are the observed values, S_n are the simulated values, and N is the number of data pairs. Generally, the bigger the RMSD the greater the overall difference between simulation prediction and field observation. RMSD is the square root of the mean squared deviations (MSD).

$$\mathrm{MSD} = \Sigma(O_n - S_n)^2/N \qquad \text{(Eq. 6.2)}$$

MSD was further partitioned into 3 components following Gauch *et al.* (2003), SB (squared bias), NU (non unity slope) and LC (lack of correlation).

$$SB = (O_m - S_m)^2 \qquad \text{(Eq. 6.3)}$$

O_m and S_m are means of the observes and simulated values.

NU was determined as:

$$NU = (1-b)^2 \text{ x } (\sum(S - S_m)^2/N) \qquad \text{(Eq. 6.4)}$$

where b is the slope of the least-squares regression of simulated (y-axis) on observed (x-axis). The LC was calculated as:

$$LC = (1-r^2) \text{ x } (\sum(O-O_m)^2/N) \qquad \text{(Eq. 6.5)}$$

where r^2 is the square of correlation.

In addition to this, regression analysis was performed between simulated and observed data (Microsoft Office Excel 2003, SP2 Microsoft Corporation).

6.3 Results

6.3.1 Model Parameterisation

Unless described below, all parameters have been left unchanged in their ‘standard’ values. For example, ‘*kl*’ and ‘*xf*’ were slightly modified on the basis of observed drying phases by lucerne (Table 6.3) and the presence of roots in lower layers of the soil profile.

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

Stage code	Stage name	For regrowth crop
1	Sowing	
2	Germination	
3	Emergence	
4	End of Juvenil	End of Juvenil
5	Floral_initiat	Floral_initiat
6	Flowering	Flowering
7	Start_grain_fi	Start_grain_fi
8	Grain_fi	
9	Maturity	
10	Harvest_rpe	
11	End	

RUE was reduced for regrowth during autumn-winter-spring as APSIM does not dynamically simulate seasonal changes to shoot:root ratios and, in reality, lucerne partitions more assimilate to roots as autumn approaches and this process continues in winter (Figure 3.16). This lack of dynamic root:shoot partitioning can result in APSIM over predicting lucerne shoot biomass in autumn-winter. A solution to this recognised problem has been to reduce RUE for this period to better match predicted shoot biomass with observed (Robertson *et al*. 2002 Dolling *et al*. 2005, Table 6.6).

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

	(a) Genotypic parameters		
Tt/Pp vs stages	**Description**	**Standard** (Trifecta)	**Modified** (Sceptre)
tt_emerg_to_endjuv	Thermal time (Tt) from emergence to end of juvenile phase (^{o}Cd)	700	300
X_pp_endjuv_to_init	Sensitivity of thermal time requirement to photoperiod during vegetative growth (See Fig 6.2)	10.7 17.0	11.5 15.0
Y_tt_endjuv_to_init	-do-	300 300	240 140
tt_init_to_flower	Tt from initiation to flowering (^{o}Cd)	200	260
	(b) Spec. leaf area vs LAI		
	Delta LAI	**Standard**	**Modified**
	0	60000	60000
	1	40000	45000
	3	30000	35000
	5	30000	35000
	(c) Translocation fraction		
Stage code	**Stage name**	**Standard**	**Modified**
3	Emergence	0.55	0.55
4	Juvenile	0.55	0.60
5	Floral initiation	0.40	0.60
6	Flowering	0.10	0.60
	(d) Trans-eff-coef		
Stage code	**Stage name**	**Standard**	**Modified** (Dolling *et al*. 2005)
3	Emergence	0.0050	0.0050
4	Juvenile	0.0050	0.0050
5	Floral initiation	0.0050	0.0040
6	Flowering	0.0050	0.0025
7	Start grain fill	0.0050	0.0025

After sensitivity analysis, further changes were made to the following parameters, leaf fraction (frac_leaf) and specific leaf area (sla), and these are presented in (Table 6.5b) Maximum specific leaf area (sla_max) for delta LAI was increased in the lucerne-ini file to allow greater leaf area at LAI>1 on the basis of observations in leaf weight (Figure 3.14).

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

NOTE:
This table is included on page 163
of the print copy of the thesis held in
the University of Adelaide Library.

* After Dolling *et al.* (2005).

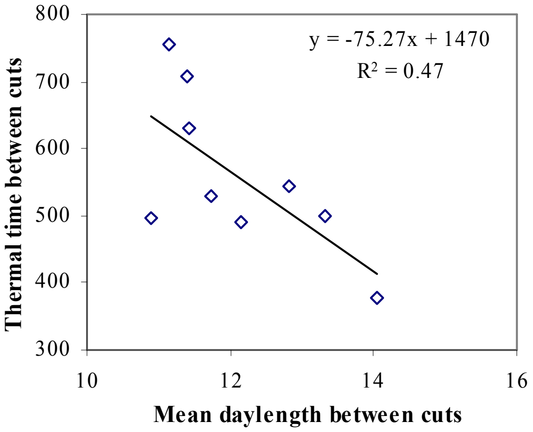


Figure 6.1 Relationship between mean day length and thermal time (Tt) during different harvests of lucerne from Dec1999-Sep 2001.

The following evaluation of model performance is based on the final parameters presented above.

6.3.2 Model performance

6.3.2.1 *Phenology*

This study comprised the results of 12 harvest cycles of lucerne taken during Dec 1999 to Sep 2001. Along with other growth parameters flowering time was also observed at each harvest cycle and is presented with simulated values (Figure 6.2). It indicates that flowering time was predicted within seven days on 11 of the 15 observed flowering times. The model failed to predict observed flowering time on the 5th March 2001 (harvest cycle no. 9), a period of severe moisture stress. Generally the model predicted flowering a few days earlier than the observed dates.

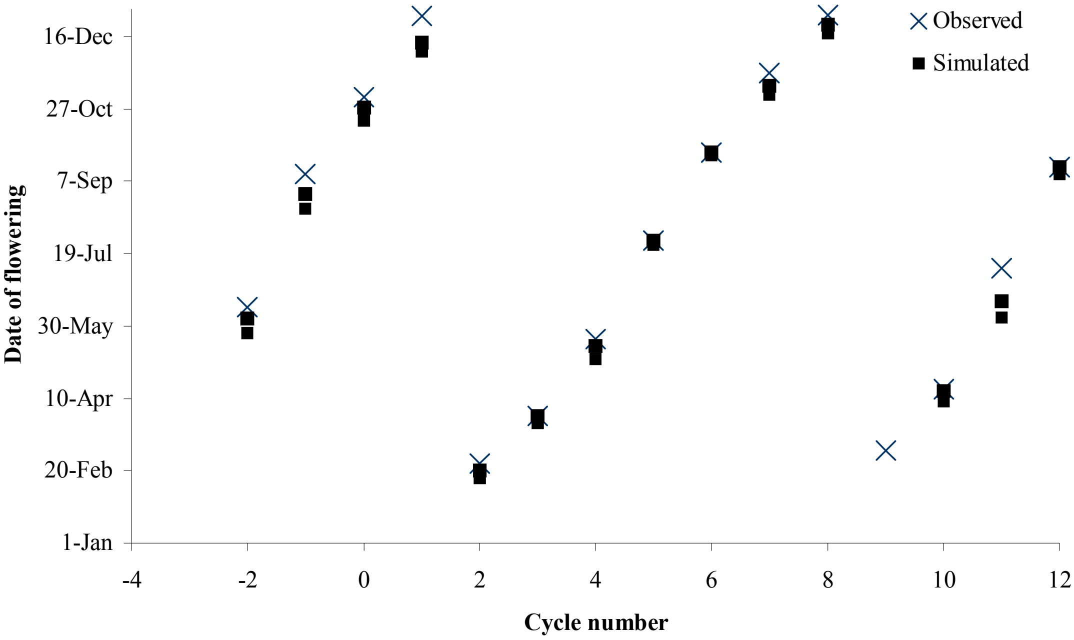


Figure 6.2 Comparison of observed and simulated date of flowering. Cycle number describes harvest cycle number; negative numbers refer to harvests prior to the main experiment commencing. Simulated values include start and finish dates of flowering.

6.3.2.2 Shoot biomass

Shoot biomass for individual harvests ranged from less than 500 to over 4,000 kg ha^{-1} (Figure 6.3). In the R_{fed} treatment simulated biomass was greater than observed in September 2001 and less (~24%) than observed during the late summer early autumn period in both years (Figure 6.3a). Due to this the estimated RMSD was high (~50% of the mean observed biomass (Table 6.8). The main components of the simulated deviations (65%) from the biomass observations in the R_{fed} treatment were LC (lack of correlation) and SB (square bias) (Table 6.8). The regression analysis (Figure 6.4a) also showed similar level of agreement between simulated and observed shoot biomass (SBM) with lower regression coefficients (R^2 = 0.68) and slope of 0.82 with intercept deviating from 0 with a value of -57. In the I_{surf} treatment (Figure 6.3b) simulation output closely agreed with observed data during the Apr-Nov growing periods in both years, although in both years the model under-predicted shoot biomass during the summer irrigation period (Figure 6.3b). For example, in summer 2000 the simulated biomass was 6106 kg ha^{-1} compared to the observed values of 10062 kg ha^{-1} over three harvests, resulting in a 39% under-prediction. Similar though smaller differences, (35%) between simulation and observed shoot biomass were recorded in summer 2001. The annual comparison of lucerne shoot biomass production (t ha^{-1} yr^{-1}, 7 harvests in 2000 and 5 in 2001) illustrated that under rainfed conditions lucerne produced 8.3 against the simulated production (7.1) in 2000 and 3.2 (3.4) in 2001 (Table 6.7). Under supplemental summer irrigation, the shoot biomass increased up to 20.3 (t ha^{-1} yr^{-1}) against the simulated value (16 ton ha^{-1}) in 2000 and 10.1 versus (8.5) in 2001.

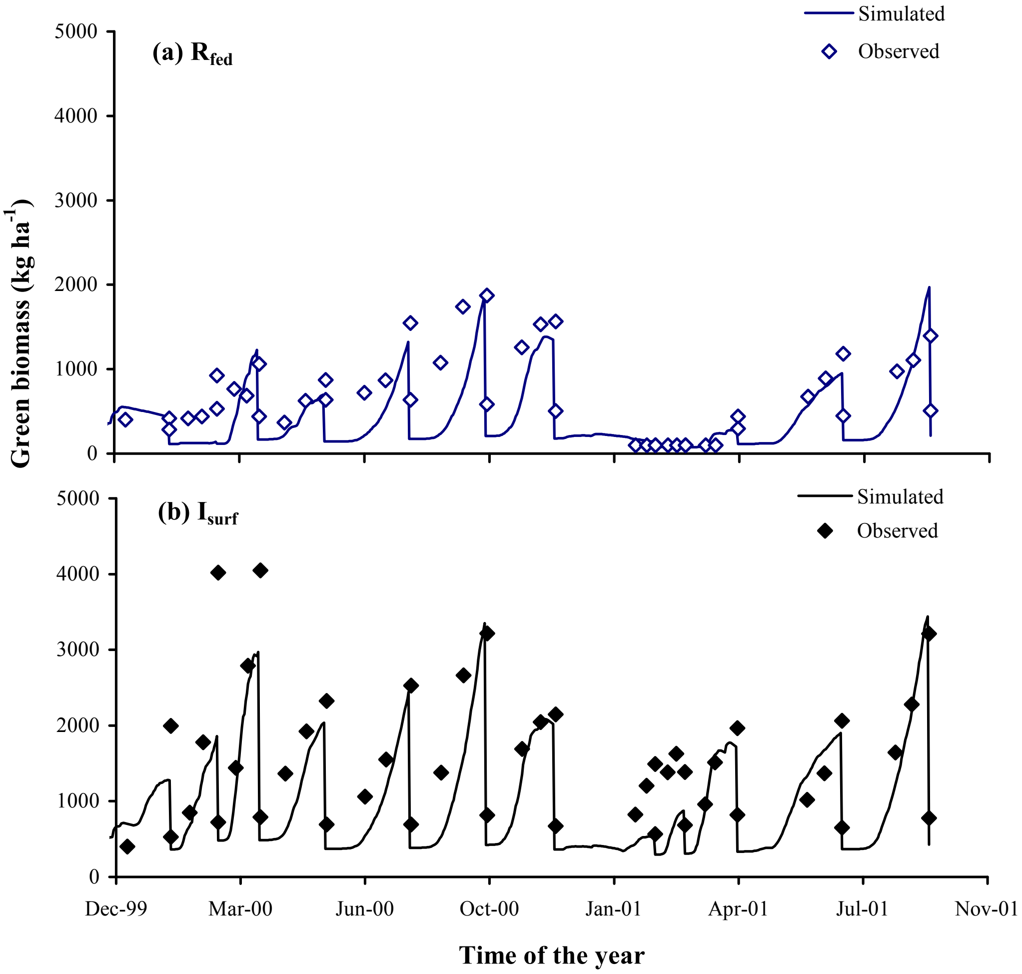


Figure 6.3 Observed (◊) and simulated (–) green shoot biomass (kg ha-1) over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) Rfed and (b) Isurf treatments.

Apart from the under-prediction of biomass under summer irrigation, there was close agreement between simulated and observed values. The main components of RMSD were LC (lack of correlation) and SB (square bias). The LC component indicates no systematic error in the simulation, whereas the SB component suggests there may be a systematic error. In this specific case, this is most likely the under-prediction of shoot biomass during summer irrigation when very high production levels were observed.

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

	Harvest Number	R_{fed}		I_{surf}	
		Observed	Simulated	Observed	Simulated
2000	7	8.3	7.1	20.3	16.0
2001	5	3.2	3.4	10.1	8.5

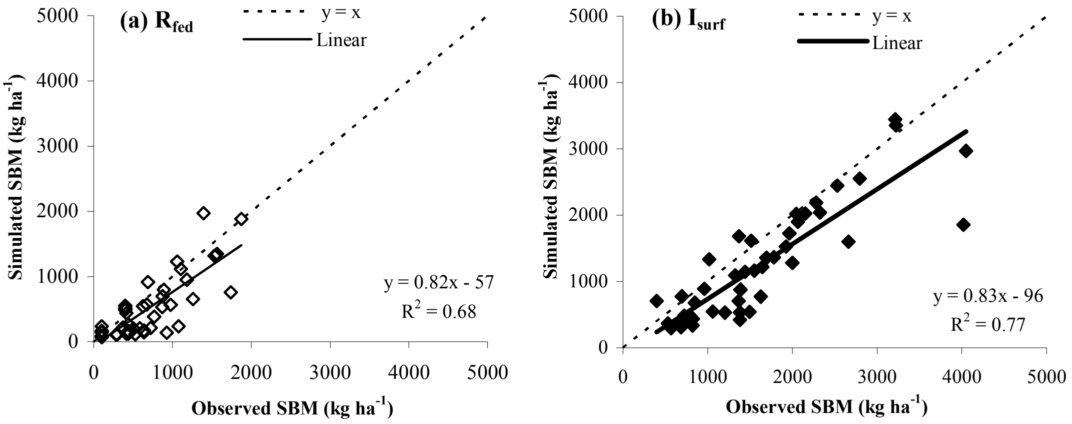


Figure 6.4 Comparison between simulated and observed shoot biomass (kg ha^{-1}) over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) R_{fed} and (b) I_{surf} treatments.

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

	SBM (Kg ha^{-1})		LAI		Leaf (n)	
	R_{fed}	I_{surf}	R_{fed}	I_{surf}	R_{fed}	I_{surf}
N^a	48	48	48	48	44	44
O mean	666	1558	0.8	1.5	7.2	11.4
O range	100-1874	400-4048	0.01-2.6	0.01-4.3	1-28	1-40
RMSD	335	561	0.55	0.64	5.25	9.09
SB	31611	131277	0.05	0.07	1.94	0.74
NU	7589	22316	0.18	0.04	24.72	15.26
LC	73088	160636	0.06	0.30	4.94	66.70
Slope	0.82	0.83	0.46	0.83	0.86	0.56
Intercept	-57	-96	0.12	-0.01	2.4	5.8
R^2	0.68	0.77	0.67	0.77	0.59	0.28

N^a is number of observations, O mean is observed mean, O range is observed range, RMSD is root mean square deviation, SB is squared bias, NU is non unity slope and LC is lack of correlation.

6.3.2.3 Leaf number and LAI

Simulated leaf numbers per stem were not matched with observed values in most of the harvest cycles in both years for both R_{fed} and I_{surf} treatments (Figure 6.5a & c). During summer, simulated values were much higher than observed in the I_{surf} treatment and it was opposite in the R_{fed} treatment. This resulted in high values of RMSD 5 and 9 which were >73% of observed means in both treatments (Table 6.8). This poor agreement was mainly due to LC. Regression analysis also confirmed these results (Figure 6.6c&d) with lower values of (R^2 = 0.59) in R_{fed} and even less in I_{surf} (R^2 = 0.28). LAI simulation in I_{surf} treatment was in general agreement with observed values with RMSD of 6.64, representing 42% of the observed mean. However in early summer in 2000 and for the whole summer in 2001, APSIM under predicted LAI (Figure 6.5d) and that caused deviation in simulated and observed LAI. The main component of LAI RMSD was LC indicating the problem was general lack of correlation rather than any systematic bias. Regression analysis also depicted similar patterns having R^2 = 0.77. APSIM under-predicted LAI in the R_{fed} treatment during autumn-winter periods (Figure 6.5b), resulting in high RMSD (0.4) which was 86% of the observed mean and, unlike the I_{surf} treatment, the main component of RMSD in R_{fed} was NU (non-uniformity of slope) which is clearly evident in the regression analysis with the model under-predicting LAI at observed LAI in the range 2-3.

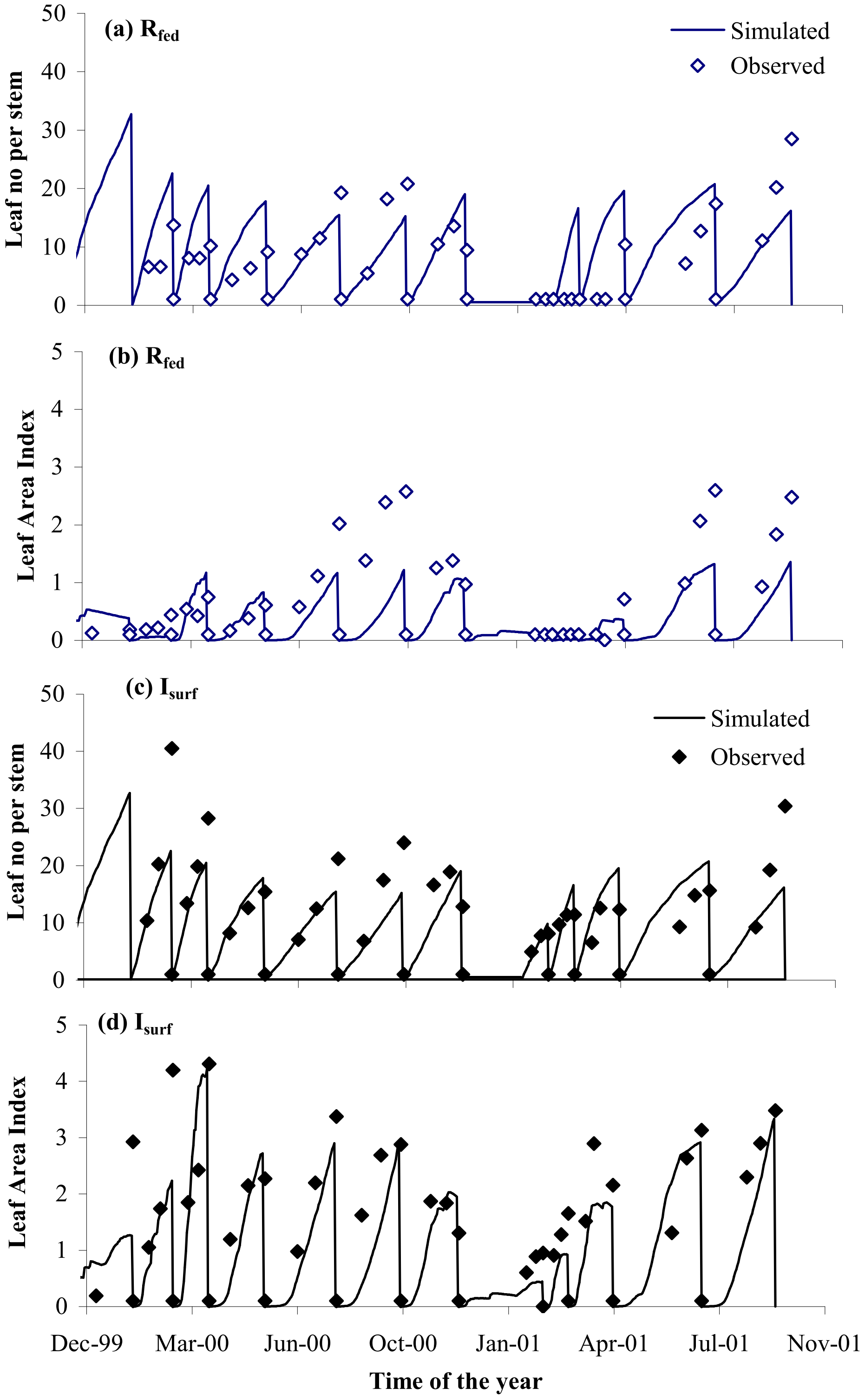


Figure 6.5 Observed (◊) and simulated (–), (a) leaf number, (b) leaf area index in R_{fed} and (c) leaf number and (d) leaf area index in I_{surf} treatment over 12 harvest cycles.

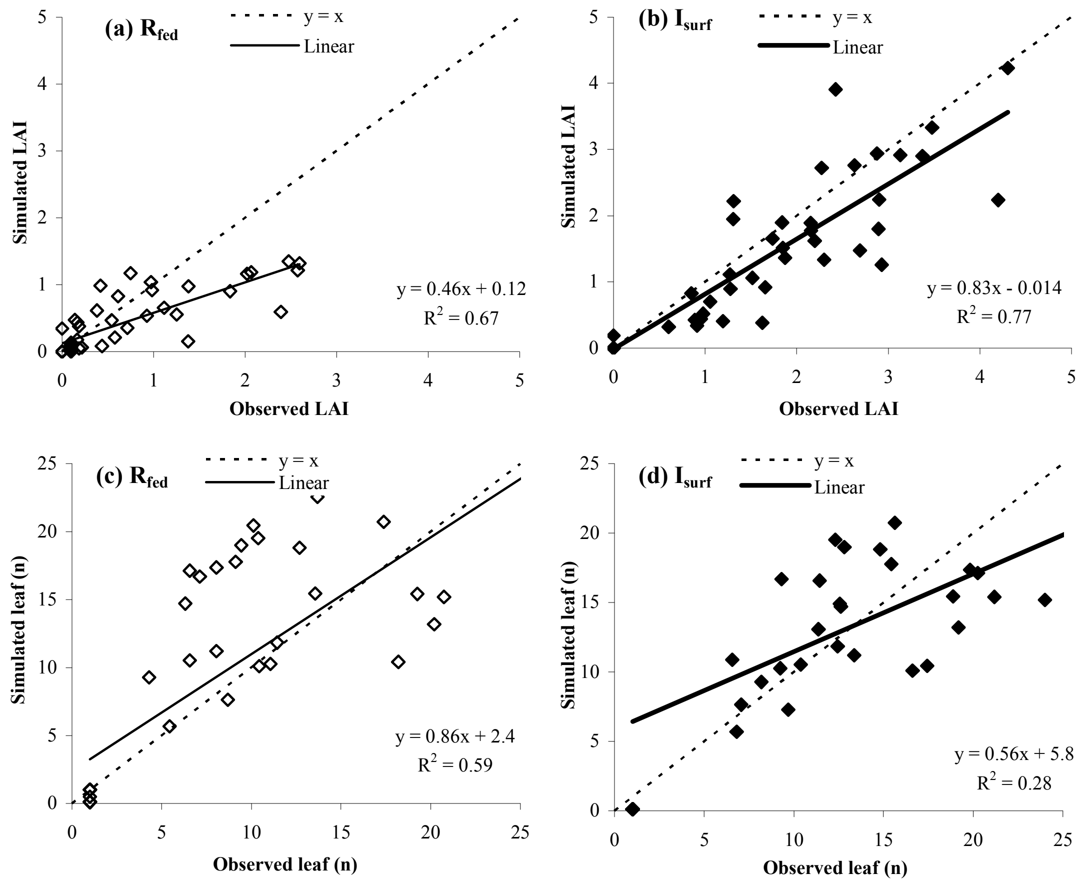


Figure 6.6 Comparisons between simulated and observed LAI and leaf number per main stem over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) LAI R_{fed}, (b) LAI I_{surf}, (c) leaf number R_{fed} and (d) leaf number I_{surf}.

6.3.2.4 Plant height and node number

Height was consistently over estimated in the R_{fed} treatment by APSIM (Figure 6.7a), resulting in a high RMSD (68 which is 69% of observed mean). The main component of RMSD was LC (Table 6.9). Regression analysis (Figure 6.8a) also showed the same level of agreement (R^2 = 0.79). In contrast, plant height in the I_{surf} treatment was predicted well during growing seasons (April-November) of both years of study (Figure 6.7c). However, in summer seasons the model under-predicted plant height in this treatment and resulted in RMSD of 94 (56% of observed mean), SB and NU were the main components of RMSD for plant height (Table 6.9). In contrast to RMSD analysis, regression coefficient obtained as a result of regression analysis showed poor agreement with (R^2 = 0.69) in I_{surf} treatment (Figure 6.8b). APSIM adequately simulated node number in most cases in the I_{surf} treatment (Figure 6.7d) with RMSD of 2.2 (33% of observed mean). In contrast to this, in the R_{fed} treatment some over-estimation in summer and under estimation in autumn-winter resulted in poor agreement between simulated and observed node number (Figure 6.7b) ending-up with a high RMSD of 2.98 (58% of observed mean node number). The LC component was the major contributor to this lack of agreement (Table 6.9). The regression analysis was in general agreement with the RMSD analysis, having R^2 = 0.67 & 0.79 in R_{fed} and I_{surf} treatments respectively (Figure 6.8c&d).

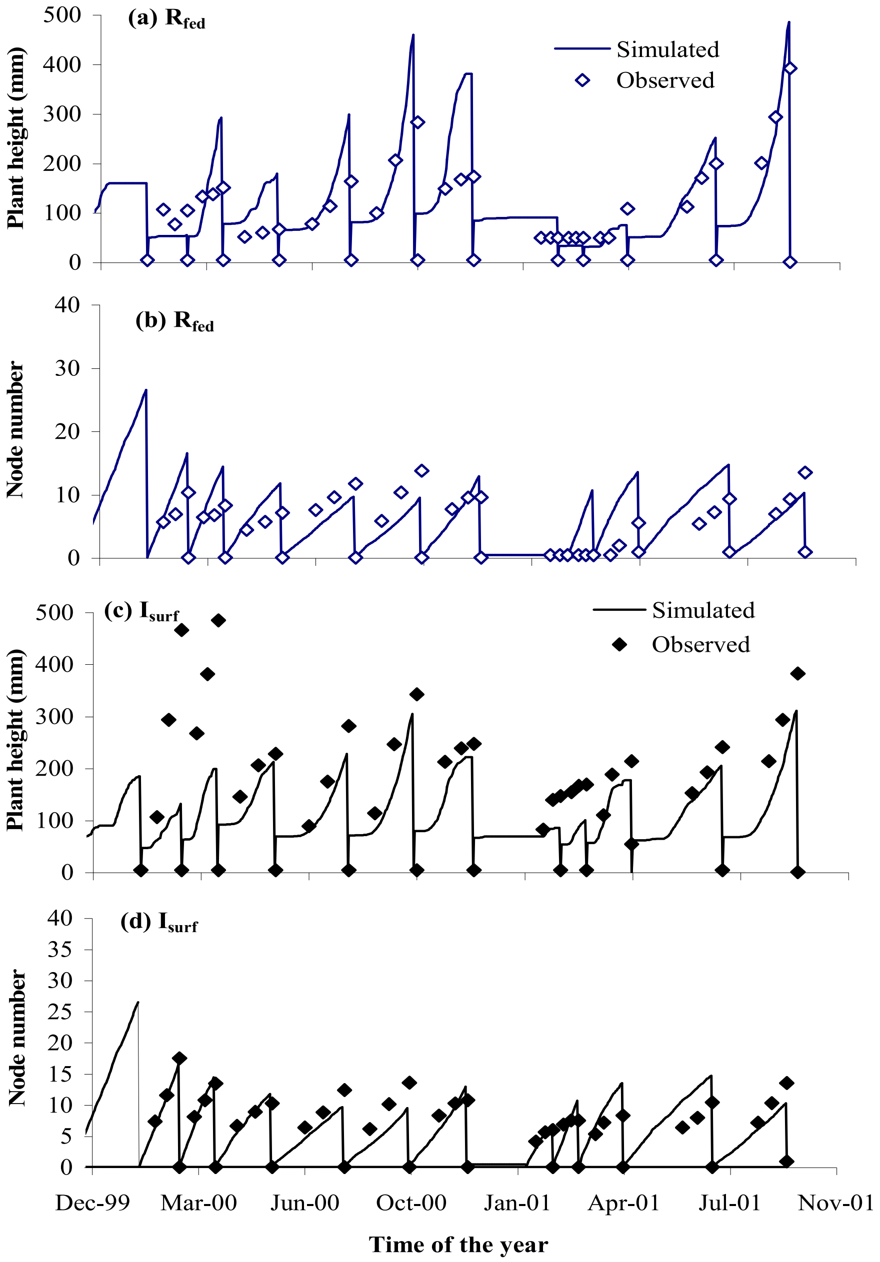


Figure 6.7 Observed (◊) and simulated (–), (a) plant height (b) node number in Rfed, and (c) plant height (d) node number in Isurf treatments over 11 harvest cycles.

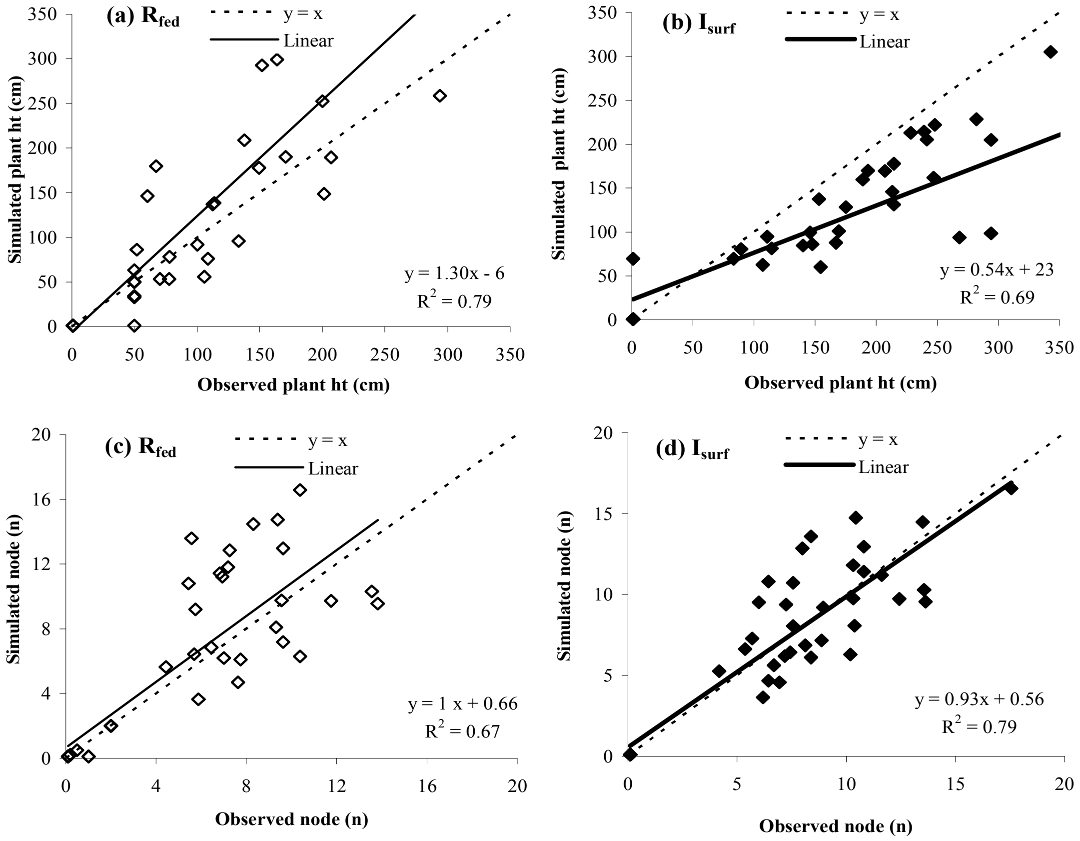


Figure 6.8 Comparisons between simulated and observed plant height and node number over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) plant height R_{fed} (b) plant height I_{surf} (c) node number R_{fed} and (d) node number I_{surf}.

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

	Plant height (cm)		**Node (n)**		**Leaf weight (g m^{-2})**		**Stem weight (g m^{-2})**	
	R_{fed}	**I_{surf}**	**R_{fed}**	**I_{surf}**	**R_{fed}**	**I_{surf}**	**R_{fed}**	**I_{surf}**
N[a]	44	44	44	44	48	48	48	48
O mean	98	168	5.11	6.78	31	85	36	101
O range	50-392	50-486	0.1-14	0.1-18	1-110	2-239	5-134	35-224
RMSD	68	94	2.98	2.20	19.76	47.51	24.05	39.1
SB	541	3032	0.55	0.01	121	1270	46.13	1048
NU	679	3579	0.003	0.10	128	453	262.7	177.7
LC	3411	2185	8.34	4.75	142	533	269.8	335.63
Slope	1.03	0.54	1	0.93	0.66	0.67	0.54	0.69
Intercept	-6	23	0.06	0.56	-0.51	-7.5	9.9	-1
R^2	0.79	0.69	0.67	0.79	0.77	0.78	0.58	0.72

N[a] is number of observations, O mean is observed mean, O range is observed range, RMSD is root mean square deviation, SB is squared bias, NU is non unity slope and LC is lack of correlation

6.3.2.5 Leaf and stem weight

APSIM-Lucerne under-estimated leaf and stem weight simulation during some of the sampling times in R_{fed} treatments (Figure 6.9). However simulation was better in the I_{surf} than in R_{fed} treatment. This occasional disagreement in case of leaf weight in R_{fed} treatment resulted in high RMSD values 19.76 that was 64% of observed leaf weight mean however, in I_{surf} treatment RSMD value was 47.51 and it was 56% of the observed means. All three components of MSD mean square deviation (SB, LC and NU) were equally sources of deviation in simulated and observed leaf weight data (Table 6.9). However, regression analysis showed relatively better agreement between simulated and observed leaf and stem weight having high regression coefficients (R^2 >0.77) in both treatments (Figure 6.10a&b). Prediction level was also poor in stem weight in R_{fed} RMSD (24.5, ie. 66% of observed mean, and LC and NU mainly caused this deviation, Table 6.9). This weak regression (R^2 = 0.58) also verified the RMSD results (Figure 6.10c). In the I_{surf} treatment, simulated stem weight was in better agreement than the R_{fed} treatment (Figure 6.9d) having RSMD 39 and it was 40% of the observed mean. Similar was regression analysis result (R^2 = 0.72).

In terms of below ground growth, root biomass was simulated against the observed values (three sample dates only, data not shown). APSIM under-estimated root biomass against the observed values for all sampling times during Dec 1999 to Sep 2001 in both treatments.

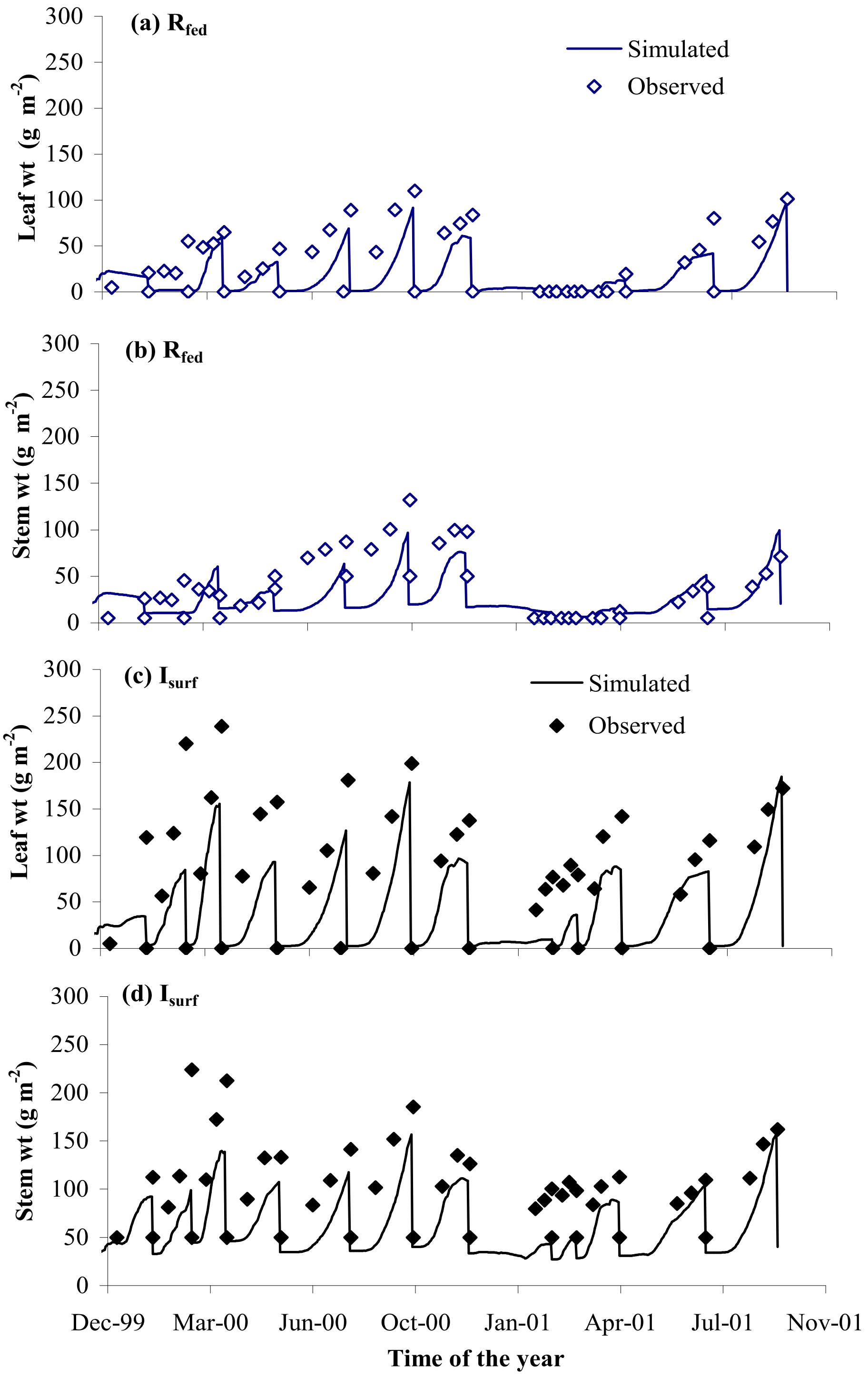


Figure 6.9 Observed (◊) and simulated (–), (a) leaf weight (b) stem weight in R$_{fed}$ and (c) leaf weight (d) stem weight in I$_{surf}$ treatments over 12 harvest cycles.

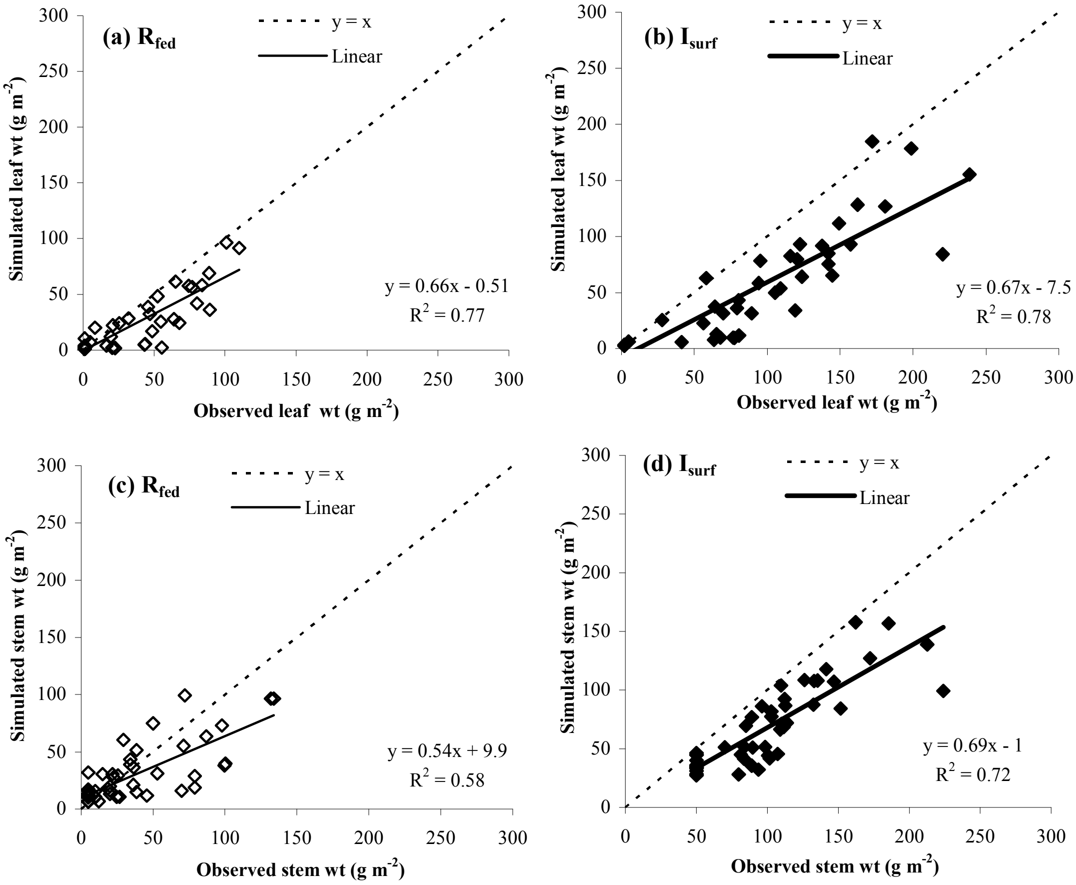


Figure 6.10 Comparisons between simulated and observed leaf and stem weight over 12 harvest cycles from Dec 1999 to Sep 2001 in (a) leaf wt R_{fed}, (b) leaf wt I_{surf}, (c) stem weight R_{fed} and (d) stem weight I_{surf}.

6.3.3 Soil water

Changes in soil water over time reveal the seasonal pattern of rainfall and the influence of summer irrigation (Figure 6.11 & 6.12). APSIM was able to demonstrate (capture) the effects of all the major events of rainfall and irrigation. A rainfall event of 74 mm, over 36 hours in summer 2000, was well captured by the model (Figure 6.11a). In summer 2000 a continuous decrease in soil water in 0-600 mm soil profile under R_{fed} treatment was captured closely (Figure 6.11a). There was some minor over-estimation of soil water in both the 2000 and 2001 growing seasons (Apr-Nov) under rainfed conditions (Figure 6.11a). Similarly, in the I_{surf} treatment some over-prediction in summer in response to irrigation was noticed for total soil water (Figure 6.11b).

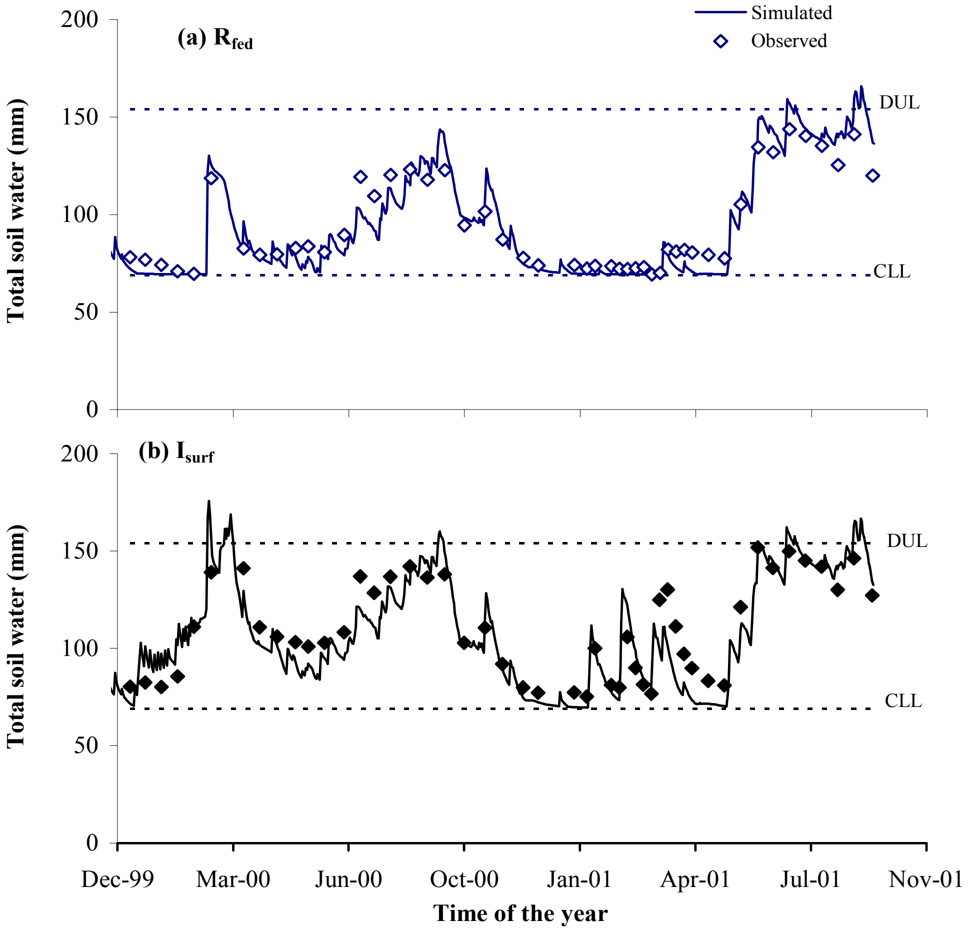


Figure 6.11 Observed (◊) and simulated (–) total soil water in 0-600 mm soil profile for (a) R_{fed} and (b) I_{surf} during Dec 1999 to Sep 2001. Dashed lines (---) represent DUL and CLL.

The model also predicted soil water moving above DUL in this profile in summer 2000 and during growing seasons of 2000 and 2001. Generally, APSIM followed almost every trend in soil water over the study period. This is reflected in the low RMSD of 8 and 10 (9 and 10% of the observed means) in R_{fed} and I_{surf} treatments in the 0-600 mm soil profile (Table 6.10).

However minor discrepancies in over and under prediction also caused some variations in observed and simulated total soil water and the main component of deviation was LC, indicating a general lack of correlation rather than any systematic bias. In general, the simulated soil water was close to the x = y line (Figure 6.13a & b). Similarly, regression analysis confirmed these results with a high level of agreement ($R^2 > 0.94$ & 0.84). A similar, though slightly weaker agreement compared to 0-600 mm profile, was observed for the 0-2000 mm soil profile. The main exceptions to this general conclusion were during summer 2000 when APSIM was not able to match the observed drying profile during March 2000, and some over-prediction in late spring in the R_{fed} treatment (Figure 6.12a).

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

	R_{fed}	I_{surf}	R_{fed}	I_{surf}
	0-600	0-600	0-2000	0-2000
N^a	49	49	49	49
O mean	94	110	431	470
O range	69-144	75-152	400-488	413-533
RMSD	8	11.4	14.8	24.4
SB	0.13	7.4	14.5	217
NU	49.9	127	169	346
LC	16.6	0.51	37	46
Slope	1.15	1.03	1.3	0.80
Intercept	-16	-5.89	-106	80
R^2	0.94	0.84	0.84	0.68

N^a is number of observations, O mean is observed mean, O range is observed range, RMSD is root mean square deviation, SB is squared bias, NU is non unity slope and LC is lack of correlation.

Figure 6.12b illustrates soil water changes in the 0-2000 mm soil depth under the I_{surf} treatment. It shows close agreement between simulated and observed soil water except for early summer over-prediction and some under-estimation of total soil water during early winter under this treatment. The statistics of goodness of fit for 0-2000 mm soil profile (Figure 6.13a&b, Table 6.10) indicates RMSD values of 15 and 24 (3% and 5% of the observed means) in R_{fed} and I_{surf} treatments respectively. However, some over and under prediction in this profile caused variations between simulated and observed total soil water and the major component of variation was also LC. Variation was higher under the I_{surf} treatment and this was also confirmed by regression analysis (Figure 6.13d) showing weaker regression ($R^2 = 0.68$) compared a $R^2 = 0.84$ under R_{fed}.

The simulated time course in soil water in individual soil layers for both of the tested treatments is provided in Appendices G to L. These figures indicate good agreement between observed and simulated soil water data for the 10 individual layers in most circumstances. The model captured the observed lack of change in soil water content in deeper layers, specifically under the R_{fed} treatment (Appendix G-I). However there was a slight over-prediction in depth 700 mm for the whole study period and in the first year for depths 900-1600 mm in the R_{fed} treatment (Appendix I). Conversely, some under prediction was noted in lower depths (1200-2800, mm) of the soil profile in the I_{surf} treatment (Appendix J-L). APSIM-SOILWAT2 and APSIM-Lucerne were able to adequately capture the distribution and soil water extraction patterns observed under lucerne in this duplex soil.

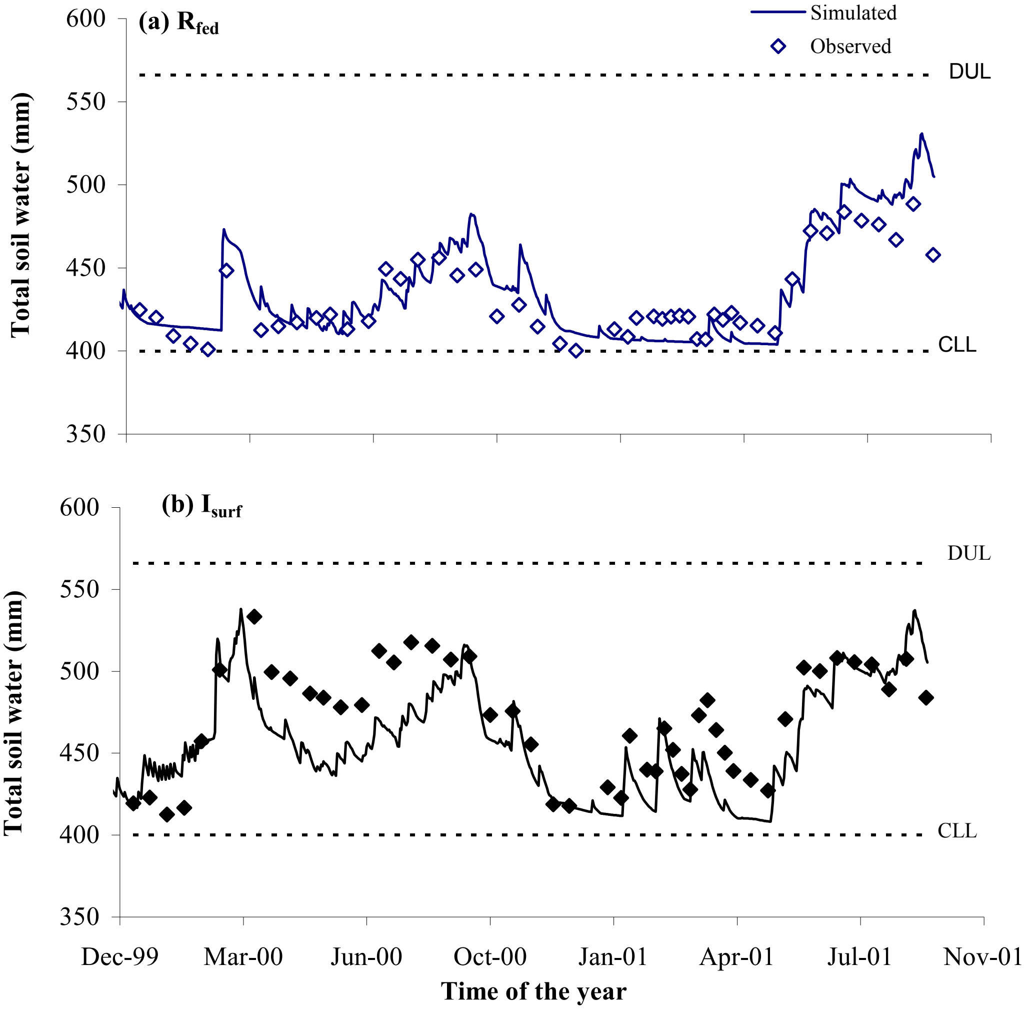


Figure 6.12 Observed (◊) and simulated (–) total soil water in 0-2000 mm soil profile for (a) R_{fed} and (b) I_{surf} during Dec 1999 to Sep 2001. Dashed lines (----) represent DUL and CLL.

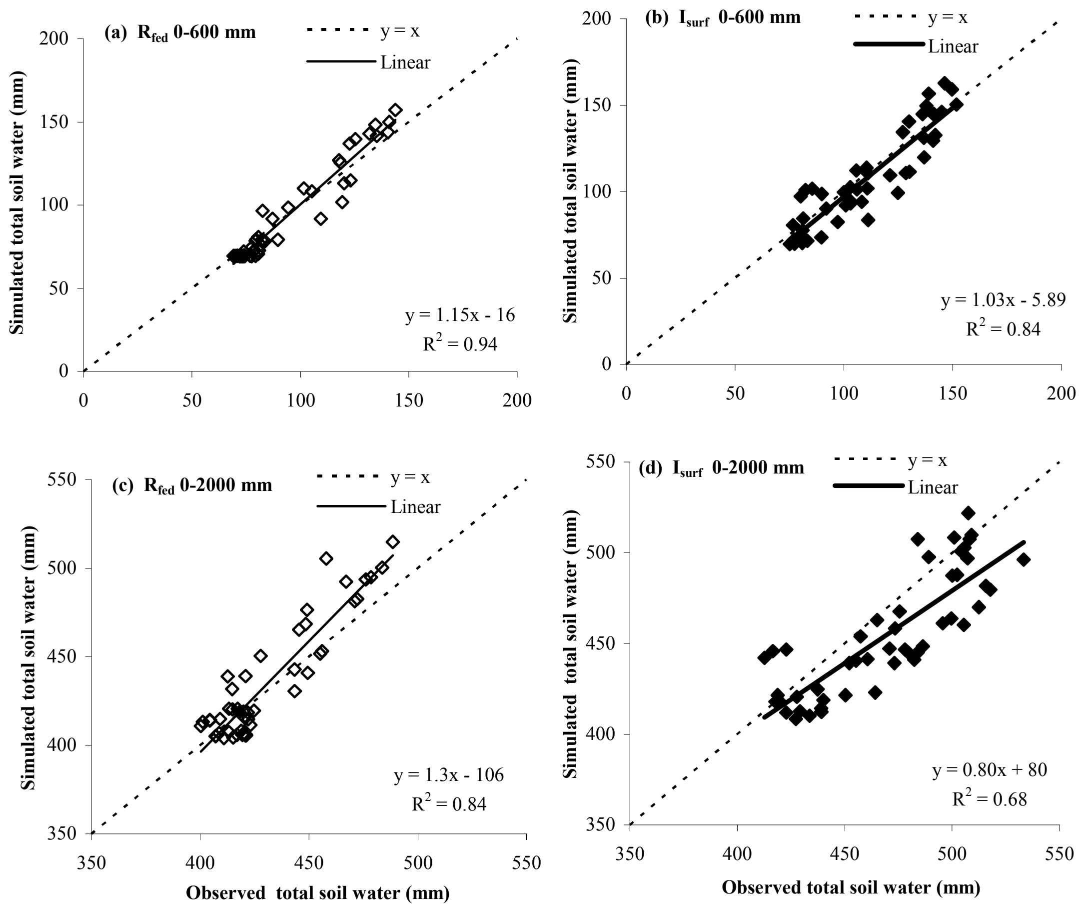


Figure 6.13 Comparison between simulated and observed total soil water (mm) from Dec 1999 to Sep 2001 in (a) R_{fed} 0-600 mm, (b) I_{surf} 0-600 mm, (c) R_{fed} 0-2000 mm and (d) I_{surf} 0-2000 mm soil profiles.

6.3.3.1 Predicted water balance under lucerne in APSIM.

The water balance under lucerne in two treatments (R_{fed} and I_{surf}) is presented in Table 6.11. There were 797 and 1416 mm of water applied as either rainfall (R_{fed}) or rainfall plus irrigation (I_{surf}). APSIM predicted no water losses through drainage under these conditions. There were only 10 and 18 mm of runoff in R_{fed} and I_{surf} treatments respectively in Feb 2000 in response to a large (74 mm) rainfall event. Loss of water through evaporation from the soil was 487 mm (R_{fed}) and 608 mm (I_{surf}), representing by far the greatest unproductive loss of water from the system. Evaporation losses were higher in the I_{surf} treatment during summer 2000 and 2001 when the surface soil was wet for longer periods following frequent surface irrigation allowing a longer period of stage-

1 evaporation. In contrast, under rainfed conditions greater soil evaporation losses occurred during the growing season (Apr-Nov) in both years. The change in stored soil water under R_{fed} and I_{surf} treatments was 43 and 86 mm respectively.

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

		Treatments	
S. No	Components of water balance	R_{fed}	I_{surf}
	(a) Input components	(mm)	(mm)
1	Rainfall	797	797
2	Irrigation	-	619
	Total Iput	**797**	**1416**
	(b) Output components	(mm)	(mm)
1	Soil evaporation	487	608
2	Transpiration	257	704
3	Drainage	0	0
4	Runoff	10	18
5	Change in soil water	43	86
	Total output	**797**	**1416**
	Balance: (Input – output)	**0**	**0**

6.3.4 Nitrogen

6.3.4.1 Soil Nitrogen

Total soil nitrate (kg ha^{-1}) in the 0-1500 mm soil profile for the R_{fed} treatment was simulated reasonably closely in 4 out of 5 sampling times (Table 6.13). This reasonable agreement resulted in a low RMSD of 15, which was 26% of the observed mean. In contrast, under the I_{surf} treatment, simulation of soil nitrate was unsatisfactory. Total soil nitrate was over-estimated in 4 out of 5 sampling times under this treatment. N mineralisation rates in response to summer irrigation appear to have been over-estimated resulting in a RMSD of 26, which is 86% of the observed mean. The regression analysis also reveals a weak relationship between simulated and observed soil nitrate ($R^2 = 0.06$).

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

Treatment	28 Feb* 2000		9 June 2000		1 Oct 2000		20 May 2001		8 Oct 2001	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
R_{fed}	45	62	54	77	50	62	75	77	65	78
I_{surf}	28	81	51	69	43	41	72	98	35	91

*Data on 28th Feb 2000 is for 0-1000 mm soil depth.

6.3.4.2 Shoot Nitrogen

Total shoot nitrogen (total N-uptake) was under-predicted for both rainfed and irrigated treatments for most of the sampling times (Figure 6.14). In summer 2000 the model predicted 161 (kg ha^{-1}) of shoot N against the observed value of 391 (kg ha^{-1}) in three harvests taken during that period (Figure 6.14b). Similarly in summer 2001, predicted shoot nitrogen was also lower than observed.

6.3.4.3 N_2 fixed

The N_2 fixed prediction was extremely impacted in summer periods than Apr-Nov growing seasons and this is partly explained by the poor prediction of shoot biomass for this same period. However, N_2 fixed simulation in R_{fed} was relatively better than I_{surf} treatment (Figure 6.15).

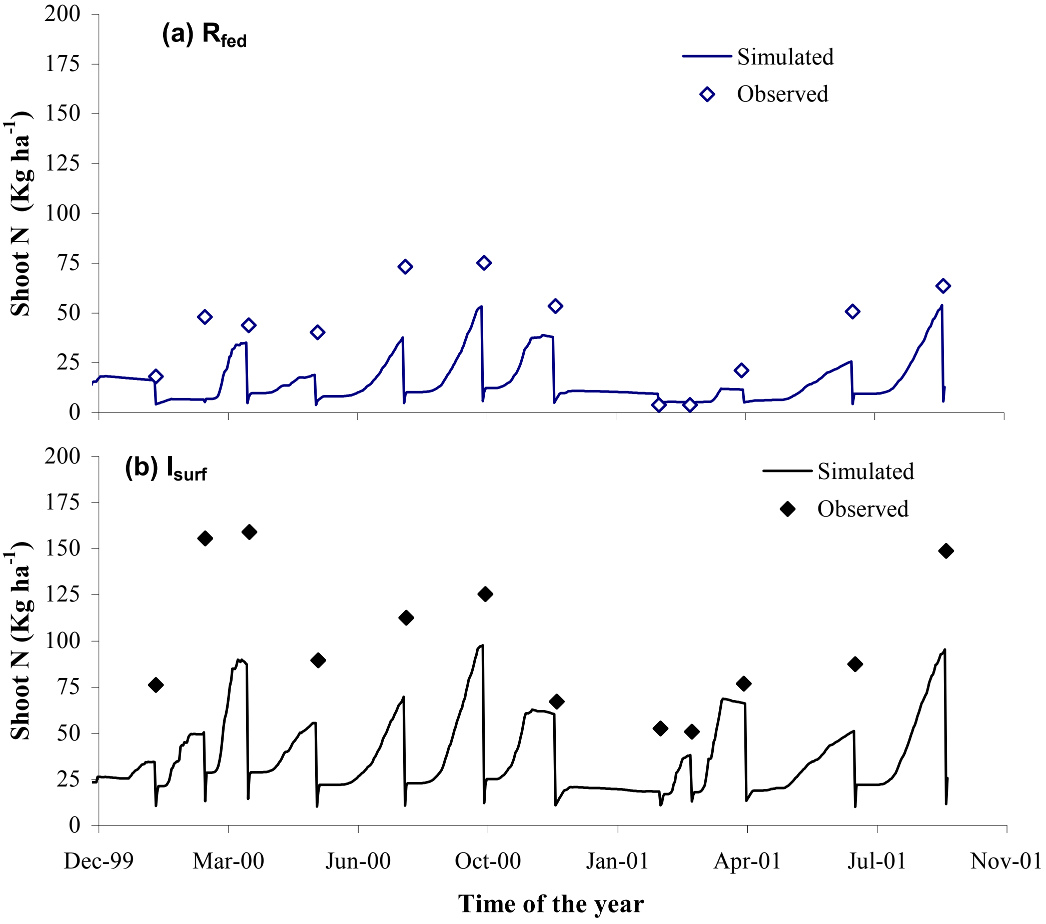


Figure 6.14 Observed and simulated total nitrogen in green biomass of lucerne (a) R_{fed} and (b) I_{surf} over twelve harvest cycles during Dec 1999 to Sep 2001.

6.3.4.4 Cumulative N_2 fixed under lucerne

Predicted cumulative N_2 fixed was far less than the observed values (Figure 6.16). In the R_{fed} treatment it was comparatively better than I_{surf} treatment throughout the study period (Dec199-Sep 2001).

In Figure 6.16 the simulated starting value for N_2 fixation is higher than observed. This is an artificial result reflecting the different nature of the simulated output and observed data. The simulated output is the result of a simulation of lucerne that was sown in June 1998 and the time axis in Figure 6.16 starts in December 1999. The simulated values reflect the accumulated N_2 fixation at that date whereas the observed data commenced in January 2000, so the results are not strictly comparable.

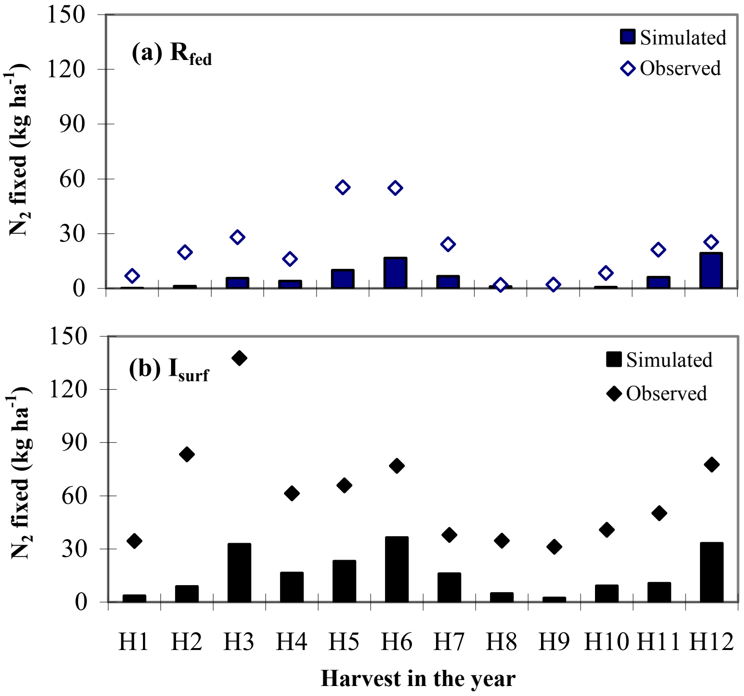


Figure 6.15 Observed and simulated N_2 fixed in 12 harvest cycles in (a) R_{fed} and (b) I_{surf} from Dec 1999 to Sep 2001.

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

	Harvest Number	R_{fed}		I_{surf}	
		Observed	Simulated	Observed	Simulated
2000	7	205	44	498	127
2001	5	59	27	234	60

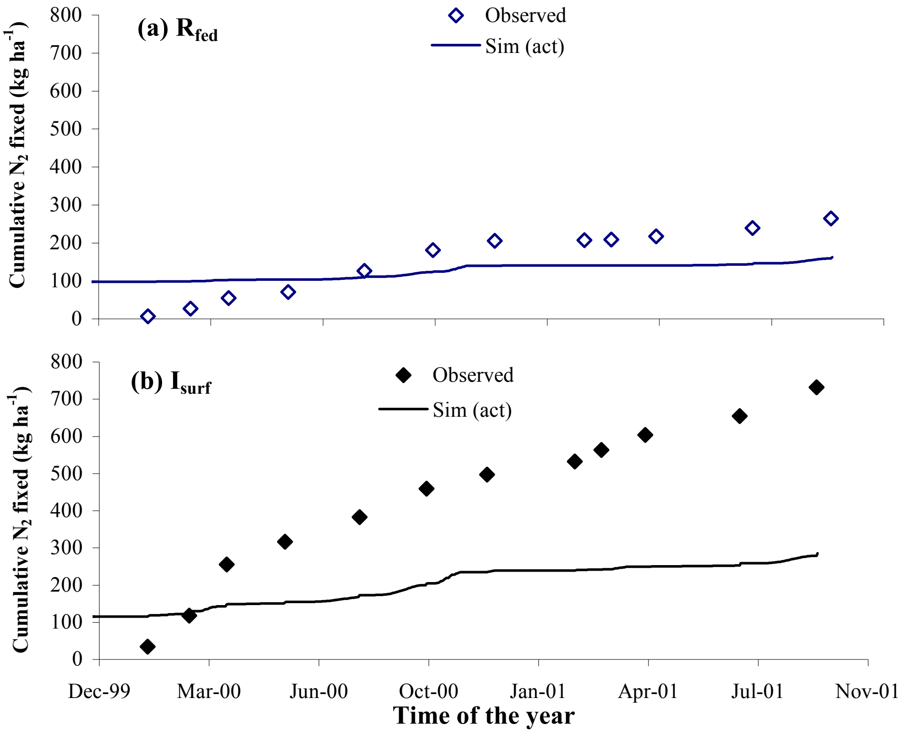


Figure 6.16 Cumulative observed and simulated N_2 fixed opting active mode in APSIM-Lucerne ini_file in 12 harvest cycles in (a) R_{fed} and (b) I_{surf} from Dec 1999 to Sep 2001.

6.4 Discussion

The performance of APSIM-lucerne was evaluated using detailed measurements on growth, soil water and nitrogen dynamics over a period of 22 months. The study was undertaken on an 18 months old (at commencement of data collection) lucerne stand growing on a duplex soil with the highly winter active cultivar ‘Sceptre’. Two treatments were simulated, one solely relying on rainfall (R_{fed}) and the second having supplemental irrigation only in summer (I_{surf}). Further, the amount of irrigation applied varied between years. Accepted statistical procedures (RMSD, MSD, linear regression) were applied to estimate the level of agreement between simulated and observed data and also reasons for model departure from observations. In general, model performance was in moderate agreement with the observed data for growth and its components. Soil water dynamics were generally well predicted, but this is to be expected given that the data set used to test the model was also used to parameterise the soil water module. Lucerne shoot biomass was well predicted for the period of the normal growing season (April-

November in southern Australia), but was greatly under-predicted following summer irrigation. Shoot N uptake and N_2 fixation were generally poorly simulated. Soil nitrate was simulated reasonably well under rainfed conditions, but very poorly under summer irrigation conditions. Model performance is discussed in more detail below.

6.4.1 Model performance

6.4.1.1 Phenology

Lucerne flowering time was well predicted for most observations (Figure 6.4), as also reported by Chen *et al*. (2003). Non-prediction of flowering at the 9th harvest cycle was most likely the result of soil water deficit coupled with longer degree-days and higher temperature. Floral initiation is determined by thermal time and photoperiod in the model. The period from the end of juvenile stage to floral initiation is the only phenological stage that is sensitive to both factors. However, severe moisture stress can also influence flowering time. APSIM does have the capability for inclusion of the effects of moisture stress on phenology (Robertson *et al*. 2002) but there is a lack of published information regarding developmental processes in lucerne, especially under Mediterranean climate conditions and for the range of lucerne cultivars used in Australia (Dolling *et*. *al*. 2005). Further research is needed to understand the mechanisms involved in water stress, phenology and flower initiation in lucerne. New understanding can be incorporated into APSIM-lucerne to enable this phenomenon to be simulated.

6.4.1.2 Morphology (LAI, height, node & leaf number)

Model performance in predicting morphological parameters such as LAI, leaf number, node per stem, stem height and leaf-stem weight varied with both time of year and treatment. Predictions were rarely in agreement with observed data in the R_{fed} treatment having a RMSD (average for all these traits) ~66% of observed means for all these components during most of the sample times. However, in the I_{surf} treatment agreement level between the simulated and observed data was relatively better than R_{fed} for most of the time with a RMSD ~53% of the observed means for all the morphological parameters. A possible explanation for the treatment difference is that the model was not able to capture the effects of the extreme soil water stress experienced in the rainfed treatment (Figure 6.18). However the level of agreement regarding most of the studied parameters is comparable with other studies (Probert *et al*. 1998, Moot *et al*. 2001, Robertson *et al*. 2002, Chen *et al*. 2003).

APSIM generally under-predicted LAI and leaf number and this may be expected since there is no concept of stem branching in the model; every node bears one leaf (Robertson *et al*. 2002). In reality, under these field conditions, lucerne does produce branches and it was often observed in this study. Greater leaf number than node number confirmed that branches were produced in lucerne stems (Figure 6.5 &7). Similarly, Brown *et al*. (2005) reported that branches start appearing after the 5th main stem node appearance. Evans and Peaden (1984) demonstrated that 17-27% of the yield of field grown lucerne was derived from branches for 68 different cultivars. Prediction of leaf and node number per stem was the same in both treatments and this was also expected, as there is no inclusion of the effect of water deficit on node appearance rate in the model. Under these field conditions, greater numbers of nodes per main stem were recorded in the I_{surf} treatment compared to the R_{fed} treatment (Figure 6.7). Scientific understanding of the influence of water stress on node number is incomplete, with some researchers claiming that water stress (49% of field capacity) reduces node number (Perry and Larson 1974), whereas others have the opposite point of view (Bolger and Matches 1990, Brown and Tanner 1983). Furthermore, Medler *et al*. (1955) concluded that the number of nodes in each cultivar is associated with day length. Moot *et al*. (2001) also found that node appearance in lucerne is sensitive to photoperiod. The effect of moisture stress on leaf number in lucerne is also debated among researchers; some workers believe that moisture stress in lucerne forces it to produce a greater number of smaller leaves (Vough and Marten 1971) while others found higher number of leaves under irrigated conditions (Brown and Tanner 1983, Saeed and El-Nadi 1997). This apparent confusion may be explained by taking account of the different levels of moisture stress experienced in each study. However, it has been unanimously confirmed that water stress dramatically decreases stem numbers and height in lucerne (Cowet and Sprague 1962, Cohen *et al*. 1972, Perry and Larson 1972, Brown and Tanner 1983, Carter and Sheaffer 1983, Bolger and Matches 1990, Saeed and El-Nadi 1997). Given these findings it was surprising that APSIM estimated higher stem height in the R_{fed} treatment than in the I_{surf} treatment during most of the sampling time, which was opposite to the actual height observations (Figure 6.7).

It is concluded that APSIM was unsatisfactory in predicting morphology of lucerne under these conditions. Model performance was slightly better under the rainfed treatment compared to the summer irrigation treatment. Further improvements in model performance are needed in the following areas, with particular reference to Mediterranean environments.

Plant height in relation to water supply

LAI in response to moisture deficit

Node and leaf number in relation to water deficit and cardinal temperatures

Branching pattern in different cultivars in a range of environments

Flowering in relation to water deficit and cardinal temperatures

6.4.1.3 Green shoot biomass

Shoot biomass was predicted closely under most circumstances when '*rue*' parameters were based on RUE derived from observed shoot biomass and intercepted radiation. The RMSD in the R_{fed} treatment was around 50% of the observed mean (linear regression $R^2 = 0.68$), and for the I_{surf} treatment model performance was slightly better (RMSD around 36% of the observed mean, $R^2 = 0.77$ (Figure 6.20). The main component of RMSD was LC, lack of correlation, indicating that the deviations were mainly due to random scatter rather than any systematic deviation. This level of model performance is comparable or better than that reported in similar studies elsewhere (Probert *et al.* 1998a, Robertson *et al.* 2002, Chen *et al.* 2003, Dolling *et al.* 2005), who performed their studies across a range of different climatic regions. Some over-prediction of shoot biomass during spring in the R_{fed} treatment can be associated to the stress level experienced at the site for this treatment that also affected LAI, RUE and consequently growth (Figure 3.12 & 3.16). Further, under water stress lucerne may have been partitioning more assimilates toward roots resulting in slow-growing shoots (Cohen 1972, Hall 1998). Currently APSIM-Lucerne presently has no capacity for dynamically simulating seasonal changes in below ground partitioning of assimilate. Dolling *et al.* (2005) reported a similar type of over-prediction of APSIM-lucerne shoot biomass during spring in a Mediterranean environment of Western Australia. The inability of the model to capture the observed biomass in the irrigated treatment during summer (Dec-Mar) of 2000-2001 despite using higher observed summer RUE (1.7 g DM MJ^{-1}) is intriguing. Daily biomass production in APSIM is a function intercepted radiation in relation to LAI, daily temperature and soil water supply, which can be influenced by soil water deficit, N deficit or ultra-super temperature >32°C (Probert *et al.* 1998a, Robertson *et al.* 2002). Higher mean (maximum) air temperatures in the summer months of January and February, 30-34°C in 2000 and 33-36°C in 2001, respectively (Table 3.5) could contribute to the under-estimation of shoot biomass following summer irrigation. Currently, high temperatures up to 32°C do not limit RUE in the model (Robertson *et al.* 2002). It is unlikely that N deficit is the reason for underestimation of shoot biomass following summer irrigation since the model over-predicted soil nitrate in the upper soil depths during this period of time (Table 6.12). Despite 642 mm of irrigation in summer and consequently an ample amount of extractable soil water (94-110 mm) at the time of the 2nd and 3rd harvests (seen in summary file), the model predicted severe soil water stress during this period (Figure 6.17). Closer examination of model output revealed that lucerne water demand (*sw-demand*) greatly exceeded soil water supply (*sw_supply*) on many occasions during that summer (Figure 6.18). Lucerne water demand is a function of current shoot biomass and atmospheric conditions (VPD and temperature). These insights suggest that improved understanding and model development is required to better predict lucerne biomass following summer irrigation. Two likely areas of focus are the response of lucerne growth to irrigation under high temperatures, and the sensitivity of lucerne growth processes to water stress. Dolling *et al.* (2005) also reported an under-prediction of shoot biomass during periods of summer temperatures above 25°C.

These observations suggest that the model is too sensitive to soil water stress. Further research is needed to better define the relationship between soil water deficit and growth. The existing model structure is adequate to accommodate the effects of soil water stress, but the results of this study indicate that the current relationships may not be applicable under all conditions. The existing relationship between soil water and the soil water stress factor for photosynthesis (‘*swdef_photo*’) is presented in Figure 6.19, along with an example of a proposed less-sensitive relationship. Further research is needed to define this relationship. Further improvements are also needed to better define relationships between water stress and LAI, RUE and TE, although it is not apparent how the model can be modified to improve performance in these areas. A few options, such as resetting '*sla*' and leaf:stem fraction parameters, were evaluated but provided little improvement in predicted shoot biomass. Clearly, further research is needed to improve model performance under these conditions.

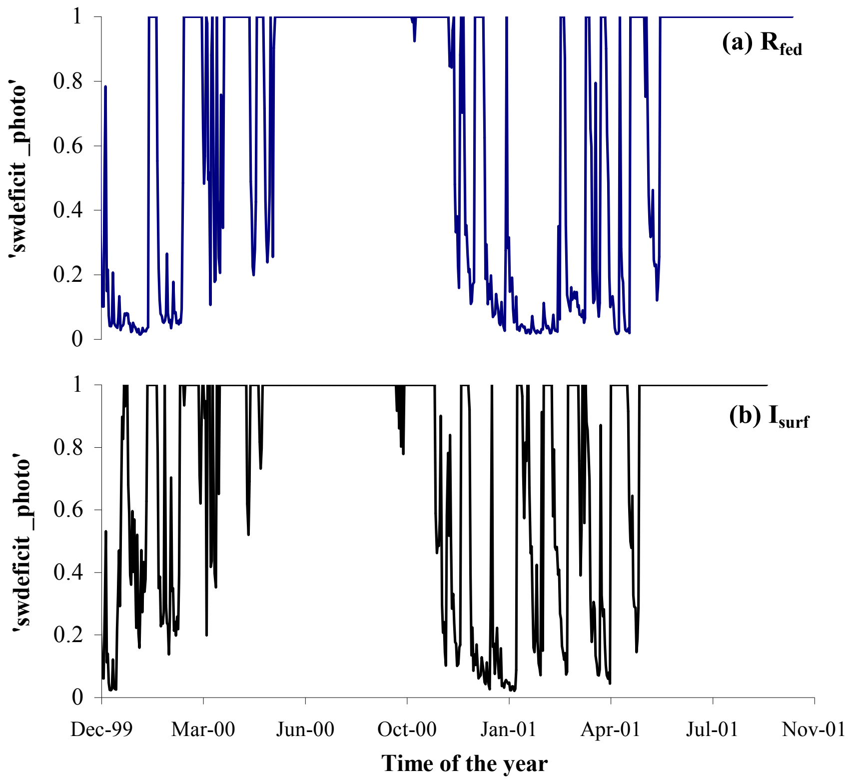


Figure 6.17 Average of *'swdef_photo'* simulated by APSIM in (a) R$_{fed}$ lucerne and (b) I$_{surf}$ treatments during the study period (Dec 1999 to Sep 2001).

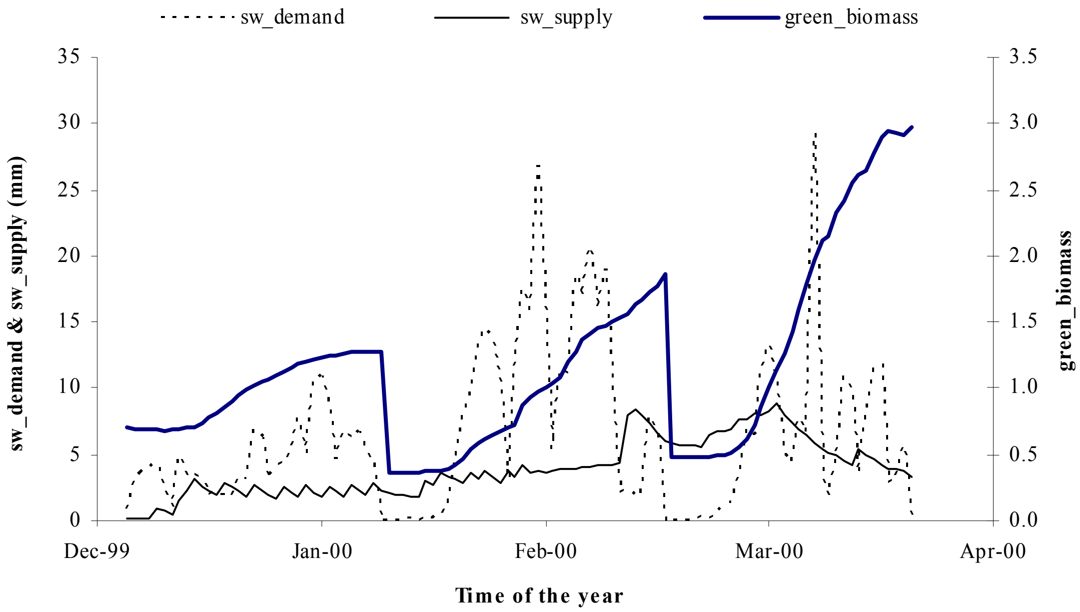


Figure 6.18 APSIM-Lucerne simulated green _biomass (t ha^{-1}), sw_demand (mm) and sw_supply for irrigated lucerne (I$_{surf}$) during Dec-99 to Mar-2000.

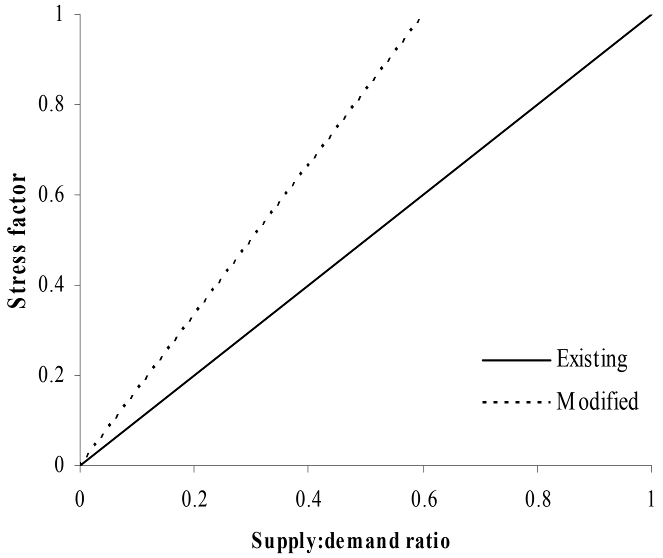


Figure 6.19 Existing and proposed modification in water deficit factor for photosynthesis in lucerne.

6.4.1.4 Model performance against observed data

There are variety of methods and statistical techniques being used to assess the model performance compared to observed measurements. Amongst these regression analyses and Root Means Squared Deviation (RMSD) are common. RMSD is considered a more accurate and robust statistic to compare the actual difference between the observed values and associated model prediction (Mayer and Butler 1993). It not only quantifies the relative degree of model deviation from field observation but also identifies the sources causing that deviation. Generally the higher the value for RMSD the greater the overall difference between model prediction and field observation. RMSD is the square root of MSD. MSD can be further partitioned in to its three components SB, NU and NU. Figures 6.20 & 6.21 illustrate these four statistics for shoot biomass, LAI and soil water.

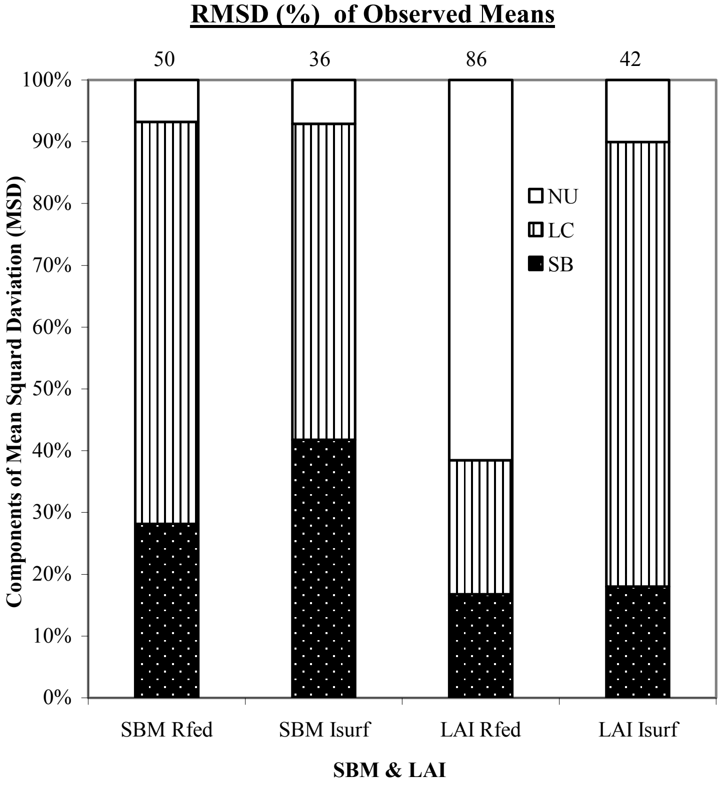


Figure 6.20 Components of mean squared deviation (MSD) for shoot biomass (SBM) and LAI in R_{fed} and I_{surf} treatments. The three components are non-unity slope (NU), lack of correlation (LC), and squared bias (SB). Root mean squared deviation is % of observed mean in each treatment for SBM and LAI.

Perfect model performance would result in the y = x line and under these circumstances MSD would be 0, this relation can deviate in three ways;

1. Squared bias SB (translation) $y \neq x$ a systematic error in simulated data compared to observed data;
2. Non unity slope (NU) represents the slope of the linear regression departs from unity and;
3. Lack of correlation LC due to random scatter of observations and simulated output $R^2 \neq 1$.

However, MSD and its components do not indicate the level of significance of any observation and for this reason regression analysis was also considered.

6.4.2 Soil water

APSIM predicted soil water dynamics over time and depth accurately under a Mediterranean-type climate, on a duplex soil with known subsoil constraints to root function for both rainfed (R_{fed}) and irrigated (I_{surf}) treatments. The statistics of goodness of fit were impressive (well within the range of experimental error) having a RMSD of 8-10% of the observed mean under 0-600 mm and 3-5% in 0-2000 mm soil profiles in R_{fed} and I_{surf} treatments respectively (Figure 6.21). This figure further confirmed that the low level of deviation was mainly due to lack of correlation (LC) between the simulated soil water and experimental observation. This level of performance should provide potential users with confidence in relation to predictive modelling for soil water dynamics and water balance in similar environments.

However, this level performance comes at a cost of detailed soil and plant x soil parameterisation. Extensive field measurement is required to determine key parameters such as drained upper limit (DUL) and crop lower limit (LL). Since initial parameterisation provides a starting point from which additional parameters are specified to match the observed soil water patterns. This process of fitting the model to match observed soil water extraction patterns and redistribution dynamics involves sensitivity analysis of parameters such as '*kl*' (fraction of PAWC potentially available for uptake per day) and '*xf*' (root extension rate), as well as parameters such as '*diffus_const'* and '*diffus_slope',* that determine movement of water when soil water content is below the drained upper limit.

Model fitting can be time consuming but the end result is a high level of accuracy in predicting soil water for that specific site (Figure 6.9 & 6.10). Further research is needed to determine how transferable these parameters are to other sites. Also, rapid procedures for generating these parameters are needed if the models are going to be used more widely (Hochman *et al*. 2001).

Other researchers have also reported that APSIM can capture observed soil water dynamics over a range of climate, soil, and plant systems. For example, under lucerne in eastern Australia (Probert *et al*. (1998), under wheat and lupin in Western Australia (Asseng *et al*. 1998, Farre *et al*. 2002), under a 12 year crop sequence in temperate eastern Australia (Lilley *et al*. 2003), under wheat in winter dominant and uniform rainfall regions of eastern Australia (Meinke *et al*. 1998), under different cropping systems in the Murray-Darling Basin (Keating *et al*. 2002), under wheat in temperate climatic condition of Netherlands (Asseng *et al*. 2000), under lucerne at 9 different sites in western Australia (Dolling *et al*. 2005), under lucerne in southern Australia (Verburg *et al*. 2007). Despite this generally good performance, further improvement is required, particularly if drainage or evaporation losses are of interest. There are several possible explanations for the relatively minor discrepancies observed in this study. Firstly, small under- and over-predictions, and time lag effects may be due to the difference in time scale, where simulation is daily and observations were taken on a 14 day interval. Another likely source of error is the inability of the relatively simple 'tipping bucket' approach to soil water modelling for handling complex water dynamics associated with the shrink-swell subsoils found in this experiment. Further research is needed to be confident that APSIM-lucerne can accurately predict drainage, runoff and evaporation under lucerne in a range of environments.

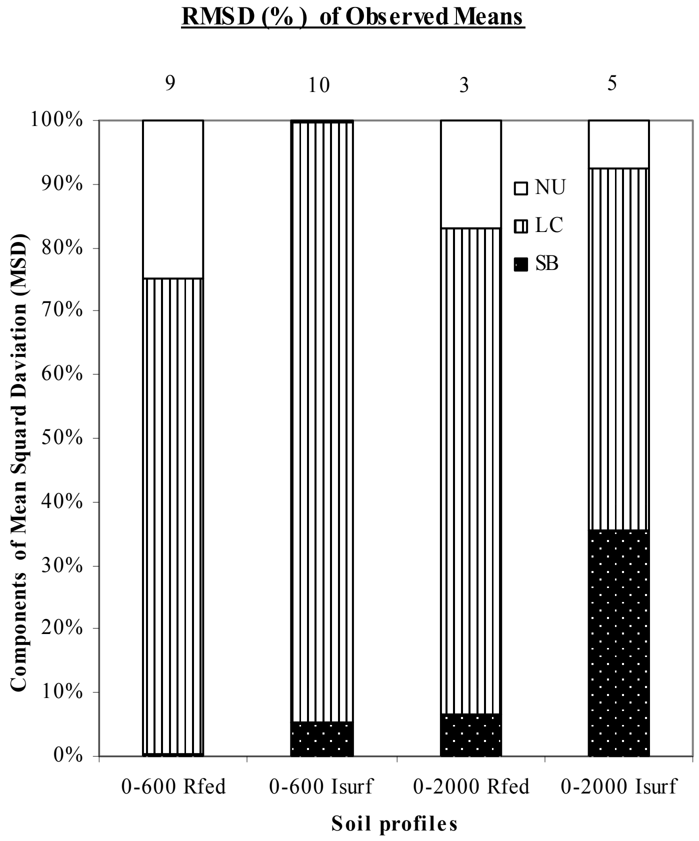


Figure 6.21 Components of mean squared deviation (MSD) for 0-600 and 0-2000 mm soil profiles under lucerne in R_{fed} and I_{surf} treatments. The three components are non-unity slope (NU), lack of correlation (LC), and squared bias (SB). Root mean squared deviation is percent (%) of observed means in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

6.4.2.1 Water balance

Evaporation and transpiration dominate the water balance under lucerne pastures in this environment. Runoff and drainage were predicted to be low or negligible. Runoff was quite possible following a large rainfall event where 74 mm rainfall occurred during 36 hours in Feb 2000. Comparatively higher runoff in the I_{surf} treatment, compared to the R_{fed} treatment, was logical as surface soil water was already higher after irrigation in this treatment.

Predicted evaporation losses appeared sensible. Firstly, soil evaporation was higher during the periods of summer irrigation and this is consistent with longer periods of stage-1 evaporation following frequent surface irrigation. Secondly, higher evaporation was predicted in the R_{fed} treatment (56-61% compared to 43% in I_{surf}) during the traditional growing season (April-November) and this is consistent with the lower LAI (Figure 6.5) in this treatment allowing more radiant energy to reach the soil surface, thus driving higher rates of stage-1 and stage-2 evaporation.

6.4.3 Nitrogen

Simulation of soil nitrate was inconsistent in both treatments (Table 6.12). Soil nitrate was consistently over-predicted in summer in the I_{surf} treatment suggesting the need for further research to define rates of organic matter decomposition and mineralisation in these soils in response to wetting events over summer. These results are close to those of Lilley *et al.* (2003), who also found inconsistent behaviour of APSIM in simulating N mineralisation for a 12 years cropping system study. They further reported that soil mineral N needed to be reset to observed values every year to achieve reasonable simulation. However, soil nitrate simulation results under the R_{fed} treatment concur with other researchers who have found good agreement between simulated and observed data for nitrate distribution under wheat based cropping systems (Probert *et al.* 1995, Asseng *et al.* 2000), although no one has previously reported soil nitrate simulation results under lucerne. The simulated data in the I_{surf} treatment (Table 6.7) also contradicted actual data showing that lucerne maintained constantly low levels (<50 kg ha^{-1}) of soil nitrate down to 2 m of soil profile under growing lucerne (Peoples *et al.* 1998). Distribution of soil mineral nitrogen is affected by many complex factors including organic matter C:N ratio, cropping history, soil type, amount and distribution of rainfall, amount of soil water, and soil temperature. Further research is needed to better understand nitrogen dynamics under lucerne and this knowledge needs to be incorporated into the model.

Total shoot N was poorly predicted most of the time in both treatments (Fig 6.14). These results differ from those of Probert *et al.* (1998) who found better performance of APSIM simulation of lucerne shoot N under irrigated conditions compared to rainfed conditions (water limiting condition). Robertson *et al.* (2002) also reported good agreement between observed and simulated total shoot N over eleven harvest cycles of lucerne conducted under irrigated conditions at Lawes, QLD, Australia.

Model performance in simulating N_2 fixed was poor under both treatments, but slightly better under the R_{fed} treatment (Figure 6.15 & 6.16). The process of N_2 fixation is complex and depends on plant, soil and rhizhobia interactions. There are several possible explanations for the poor ability to predict N_2 fixed. Firstly, APSIM assimilates N on any day on the basis of demand or supply, the demand is to fulfil prior needs of N content and current day weight gain (Herridge *et al*. 2001, Robertson *et al*. 2002). In APSIM legumes can satisfy N demand from three mechanisms; uptake in the transpiration stream (mass flow), uptake through diffusion (active uptake), and N_2 fixation. The first preference is to supply N from soil, it assumes N_2 fixation is more costly in terms of energy therefore, N_2 fixation is supposed to contribute to the demand only when supply from the soil is inadequate (Herridge *et al*. 2001). These assumptions are obviously a simplification of the complex reality involved in this phenomenon. In reality, fixation and assimilation run in a complementary manner during the period of rapid growth in lucerne, some initial soil nitrate is necessary to initiate lucerne growth after cutting, and also after initiation of flowering (Wery *et al*. 1986). In addition, presence of nitrates under most legume crops induces suppression of legume nodulation and N_2 fixation (Doughton *et al*. 1993, Peoples *et al*. 2001) but lucerne appears capable of fixing nitrogen in the presence of high soil mineral N (Blumenthal and Russelle 1996). At this stage the model does not account for any direct effect of soil mineral N on the rate of N_2 fixation through the mechanism of impaired nodulation (Robertson *et al*. 2002).

The present APSIM N_2 fixation approach is based on a limited amount of available published information and is based mostly on annual legume species. Additional complications associated with perennial legumes are poorly understood and further research is needed to improve understanding and capacity for predicting N_2 fixation under lucerne and other perennial legumes.

The current APSIM-lucerne module provides the user with the option of specifying if active uptake by diffusion or N_2 fixation should have priority for meeting legume N demand (Robertson *et al*. 2002). In the final version of the model reported in this chapter, this user-specified option was set to *'fixation'*. The impact of setting this option to '*N_2 fixation*' was explored and the result is presented in Figure 6.21. This change does improve N_2 fixation, particularly in the R_{fed} treatment (Figure 6.21), but also results in slightly higher amounts of nitrate nitrogen in the soil. Further research is needed to better understand and simulate N_2 fixation under lucerne.

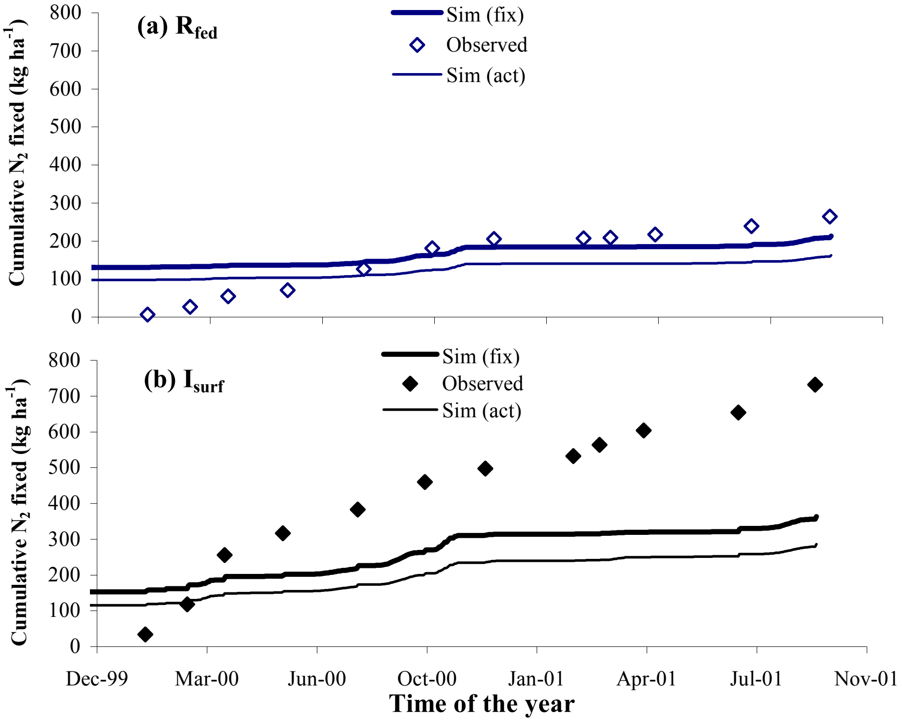


Figure 6.22 Cumulative observed and simulated N_2 fixed illustrating the impact of the user specified uptake preference *'active'* or *'fixation'* mode in APSIM-Lucerne for 12 harvest cycles in (a) R_{fed} and (b) I_{surf} from Dec 1999 to Sep 2001.

6.5 Conclusion

The simulation model APSIM-lucerne was able to adequately simulate soil water dynamics ie. water use, water losses and, most importantly, trends in water movement in the soil, during a two year period for an established lucerne stand with a winter active variety growing on a duplex soil; testing included two water supply treatments, rainfed and supplemental summer irrigation with a variable amount of irrigation in each year. APSIM Lucerne shoot biomass was well predicted for the period of the normal growing season (April-November), but was greatly under-predicted following summer irrigation. Model performance in simulating morphological traits was also relatively less accurate compared to soil water. Shoot N uptake and N_2 fixation were generally poorly simulated. Soil nitrates were simulated reasonably well under rainfed conditions, but very poorly under summer irrigation conditions.

Notwithstanding the above summary, the performance of APSIM-Lucerne in this study compares favourably with other evaluation studies conducted in different environments. For example, Robertson *et al.* (2002) reported model performance for simulating shoot biomass with a $R^2 = 0.55$ and RMSD (33% of observed mean). Secondly, Dolling *et al.* (2005) compared shoot biomass and soil water with observed data on an individual and seasonal basis and reported RMSD ~71 and 58% of the observed means respectively in shoot biomass and 32% of the observed mean in plant available water.

The performance of APSIM was excellent for those parameters where maximum site-specific inputs were provided to the model rather than assumptions based on values from the literature. These results also confirmed that APSIM's performance is gradually improving with rigorous testing and validation against observed data and is potentially capable of performing better with addition of new inputs in terms of parameters and physiological functions which are presently lacking for growth and phenology. Improvements to the simulation of phenology, autumn-winter decline in radiation-use efficiency and also in response to water stress, inclusion of carbohydrate storage and depletion in root reserves, and nitrate used and N accumulation would be valuable to incorporate in the APSIM-Lucerne framework. Further research is needed to determine why APSIM-lucerne was not able to predict the very high shoot biomass observed in this study in response to high amounts of irrigation in summer.

Chapter 7

7 General Discussion

7.1 Introduction

The introduction to this thesis highlighted the many characteristics of lucerne that make it a potentially good candidate for addressing sustainability issues in Australian farming systems currently based largely around annual crops and pastures. Considered among the most important traits were; the adaptation to a wide range of climates, the perennial nature that enables maximum resource use and productivity all year round, the deep rooting habit that allows exploitation of soil water and nutrients such as nitrates beyond the range of annual plants, and the ability to fix N_2 symbiotically and thus increase soil N fertility (Vance *et al.* 1988, Crawford and Macfarlane 1995, Williams 1998).

The major focus of this work was to quantify agronomic performance (productivity) in the Mediterranean climatic region of South Australia (Chapter 3) and to describe associated plant-soil processes with respect to water (Chapter 4) and nitrogen (Chapter 5) for lucerne, on a duplex (texture contrast) soil under varying water supply during summer. The secondary focus was to use the experimental output regarding productivity and related physiological processes, soil water and nitrogen to parameterise and evaluate the performance of the APSIM-Lucerne model for better prediction of lucerne productivity over a wider range of potential environments (Chapter-6).

7.2 Productivity of rainfed lucerne in a semi-arid Mediterranean climate on a duplex soil

It is clear from this research that lucerne growth and development and related physiological processes were severely affected by the harsh edaphic and climatic conditions present at this South Australian location. Since there was no limitation caused by other climatic contributors to growth and yield (radiation and lower temperature) at this latitude it is hypothesized that the main limiting factor is supply of water. Indeed, measurement showed that after exploiting any stored moisture in the subsoil during the early part of the study, rainfed lucerne was reliant on incident rainfall with about 70% of annual productivity occurring during the wetter and cooler growing seasons (August to November). The measured decrease in seasonal yields over the two years, plus higher leaf:stem and root:shoot ratios, as well as a 64% reduction in radiation use efficiency (RUE) over summer, were all a reflection of the constant water stress that was affecting plant growth and development in the rainfed treatment (Dunin 2001, McCallum 1998, Collino *et al.* 2005). The value of the soil water stress index '*soil water deficit_photo'* predicted by APSIM was in the range of 0.03-0.68 for summer 2000-2001, indicative of the level of stress being experienced by lucerne under these conditions. The stress was mainly a function of the inherently low and variable rainfall that was insufficient to wet the soil to maximum capacity during the entire study, so that field capacity (DUL) was never achieved. Also, there was very little movement of water into the 600-1800 mm soil depth and plant-available water largely accumulated in the top 0-600 mm soil depth where it was subject to either plant uptake or evaporative losses. Thus, not only was growth limited by soil moisture deficits during the main winter growing season but also there was very little deep storage of water during the winters for the lucerne to draw upon over the hot dry summers. The effects of the water stress were clearly observed as reduced shoot growth, but were also manifest as a reduction in water use efficiency (>50%), transpiration efficiency (>50%), RUE (>40%) and ultimately, in conjunction presumably with the high temperatures over summer, in death of plants and a decreased plant population (>70%).

However, there was some evidence of lucerne's ability to adapt and survive in these harsh conditions because many plants in the second summer survived and during the subsequent growing season were able to partially compensate for the loss in plant numbers by increasing the numbers of stems per plant, so that the growth rate (kg ha^{-1}) in the second winter was not markedly different to the first. Perhaps the very low TE (6 kg ha^{-1} mm^{-1}) observed for lucerne over this second summer was due to the allocation of carbon to the crown and taproot (Cohen 1972, Hall 1998) to setup a potential for greater stem production under more favourable conditions (a form of survival mechanism); although, due to resource constraints, insufficient measurements of TNC in this study were carried out to fully determine the validity of this hypothesis. The other reason for a lower TE, as observed in rainfed lucerne during the first summer compared to lucerne under irrigation, may be greater carbon investment in deeper roots searching for water (Dunin *et al*. 2001) at the expense of shoot growth, and indeed the root:shoot ratio for the rainfed treatment was higher than the irrigated treatments, particularly in the summer.

Although lucerne roots in this study were observed to a depth of 1800 mm, and appeared to function at this depth in terms of water and nitrate extraction, the proportion of roots at depth was extremely low; in fact three-quarters of the RLD and root biomass were in the top 400 mm of the soil. A number of subsoil conditions were highly likely to be restricting root proliferation at depths below 700 mm, since not only would the increasing bulk density (>1.56 Mg m^{-3}) present a physical barrier to root penetration (Bengough and Mullins, 1990) but the soil was also chemically hostile being alkaline (pHw >9.0) and calcareous (>50% calcium carbonate) with concentrations of salt and boron reported to severely impair root growth and function in many plants (Moody 2003, Maschmedt 2004, Adcock *et al*. 2007). Nevertheless, lucerne demonstrated that continuous and extended soil water extraction round the year kept the soil profile dry to a depth of 1.8 metres, and prevented deep drainage even where large amounts of irrigation water were applied, confirming the reported potential to reduce the risk of salinity and acidification associated with deep drainage in Australia (Ward and Dunin 2001, Lolicato 2000, McCallum *et al*. 2000). The area of duplex soils in South Australia with characteristics similar to the Roseworthy site is fairly extensive (Chittleborough 1992), and particularly in regions where there is widespread irrigated production of lucerne (Stanley and Christinat, 1994), so that the data generated by this study should be applicable over a wide area.

N_2 fixation by lucerne appeared reasonably adapted to the variable rainfall associated with the Mediterranean type climate. Amounts of N_2 fixed were correlated with shoot biomass, and proportional dependence on N_2 fixation was the same (about 45%) at the beginning of the study as at the end in the rainfed treatment. Nevertheless, Ndfa did respond to changes in rainfall between harvests, probably as a consequence of direct effects of water stress on nodule/nitrogenase activity (Carter and Sheaffer 1983, Wery *et al*. 1986, Mohammed *et al*. 1996, Carranca *et al*. 1999). There was no inverse relationship between amount of mineral N in the soil and Ndfa, rather, uptake of mineral N appeared to occur along with N_2 fixation. Relatively little work has been reported on the seasonal dynamics of lucerne Ndfa and mineral N supply under Mediterranean type climates and further studies would be useful in assessing the contribution that lucerne can make to improving soil fertility in these environments. Indeed, the contribution of lucerne to total soil N was not directly assessed by this study as it is unlikely differences in such a large pool would have been detectable over two years, but if one accepts the estimation (McNeill *et al.* 1997, Peoples and Baldock 2001) that below-ground N accumulation from pasture legumes may represent 50% of the total plant N, then clearly the fixed N inputs to soil under the rainfed lucerne would have been substantial (205 kg N ha^{-1}) in the first year, although much less (59 kg ha^{-1}) in the second.

The overall dry matter performance and decrease in plant population (69-20 plants m^{-2}) for rainfed lucerne in this environment indicates that productive stand life (from an agronomic point of view) might only be 3-4 years, not necessarily an attractive option for replacing annuals considering the expense and work involved. However tactical management for lucerne in these drier environments, including changes to the frequency of defoliation/grazing and keeping the sward free from weeds, can extend the availability of fodder in summer (Dunin 2001, Angus 2001, McCallum 1998). Furthermore, provision of high quality fodder at critical times, weed and erosion control in summer, nitrogen and carbon organic matter inputs and the benefits of deep drainage control may well be enough to present lucerne as a sustainable option in the farming system and offset the possible disadvantage of lower yields (compared to annuals) in dryland lucerne (Dunin *et al.* 2001, Peoples *et al.* 2001, Chan *et al.* 2001).

7.3 Productivity of irrigated lucerne in a semi-arid Mediterranean climate on a duplex soil

The limitations imposed by water in this environment were, of course, to a large extent overcome by providing irrigation, even in relatively small quantities. Productivity of well-irrigated lucerne over summer was similar to many other irrigated lucerne stands around the world (Carter and Sheaffer, 1983) Furthermore, the capacity of lucerne to recover excess irrigation water that had moved deeper in the soil profile (600-1800 mm) was demonstrated, and shoot productivity in the growing seasons was also greater than under rainfed conditions. Combined with sufficient water (~200 mm per growth cycle) from irrigation the high air temperatures (~25^{o}C) over summer had a positive effect on all yield determining components as well as water use, transpiration efficiencies (>21 kg ha^{-1} mm^{-1}) and RUE (1.7 g DM MJ^{-1}), with the increase in growth rate ultimately resulting in higher production. The application of sufficient water (~80% of the field capacity) also resulted in a high proportional dependence on N_2 fixation for both irrigated treatments in the first summer, although this was not achieved during the second summer when smaller amounts of irrigation water were applied, highlighting the direct sensitivity of the symbiotic machinery (nodules) to soil moisture deficit. The demonstration of the potential productivity and performance of lucerne under this environment when water stress is reduced has provided essential and previously unavailable information to the farming community in regard to assessing the financial viability of scheduling supplemental irrigation.

Comparison of both the irrigated treatments established that on this duplex soil type supplying irrigation water at the 350-400 mm depth was sufficient to reduce evaporative losses, yet still shallow enough to avoid most of the subsoil constraints to root growth. The increased efficiency of supplying irrigation sub-surface as opposed to overhead might well be considered a worthwhile adoption for high value commodity enterprises, such as vegetable and orchard farming, on similar soil types in South Australia in the wake of insufficient water supplies due to climate change in future.

7.4 APSIM evaluation

The detailed soil and plant data collected in this research provided an ideal opportunity to test the performance of APSIM-Lucerne in southern Australia. It is rare to have such a comprehensive set of related soil water, soil nitrogen, plant growth and development data. Overall, against this data set the accuracy of model predictions were moderate for growth, precise for soil water and poor for nitrogen. The irrigation treatment provided a further extreme in terms of water availability, and the model captured the observed soil water responses accurately.

Even with the benefit of the detailed dataset available in this research, performance of APSIM in simulating the observed data was variable. Soil water dynamics were well simulated, with RMSD ranging from just 3-10% of the observed mean. Shoot biomass production and related morphological traits were less well simulated. The RMSD for shoot biomass ranged from 36-50% of the observed mean. Soil nitrogen dynamics and nitrogen fixation were poorly simulated by APSIM, and this reflects the greater complexity of these processes. Nevertheless, the performance of APSIM-Lucerne in this study compares favourably with similar evaluation studies conducted in other parts of Australia.

The degree of accuracy achieved in model performance in soil water reported in this study was dependent on detailed definition of soil and plant parameters. Meticulous attention needs to be given to estimating parameters if accurate model performance is required. A good example is the effort required to define parameters associated with root growth and root activity. This experiment was conducted on a duplex soil with known subsoil constraints. The APSIM-Lucerne model is not 'aware' of these constraints and parameters such as the lower limit of water extraction '*ll*', the rate of root extension through a layer '*xf*', and the proportion of water in a layer that can be taken up in one day '*kl*', all need to be defined to reflect root distribution and root activity. This research has shown that it is possible to parameterise the model to mimic observed patterns of root distribution and water uptake activity. In this case, key parameters were defined, and accurate model performance was achieved, with the aid of detailed soil water extraction data (two weekly intervals), but this detailed data is not always available. When users have to rely on uninformed assumptions for parameter values model performance could be expected to deteriorate.

The APSIM-Lucerne model will have many diverse applications in agriculture and natural resource management. Ideally, future research using the model will involve close partnership with end users such as the lucerne forage industry, potentially the lucerne seed industry, the grains industry where growers are interested in integrating lucerne into cropping systems, and with natural resource management groups where interest in lucerne for reducing recharge is attracting increasing interest. The rigorous testing of model performance presented in this thesis will provide future users of the model with increased confidence, and awareness of limitations, in some aspects of the model predictions.

7.5 Future recommendations

This study has been unique in its kind in this semi-arid region of South Australia in which detailed information in terms of growth and development dynamics (shoot and root) soil water dynamics and nitrogen dynamics under varying water supply was explored under lucerne. This detailed and comprehensive dataset was then used to test the performance of the APSIM-Lucerne simulation model. The integration of field experimentation with simulation modelling has greatly benefited interpretation of the data.

While this research has generated a detailed data set for a limited range of treatments, it has not been possible to study several topics that are both relevant to practical management of lucerne in this environment and also significant in terms of the processes currently included in the model. Some of these are listed below:

- Partitioning between root and shoot is currently based on a fixed proportion of the daily growth increment that varies with growth stage. In practical terms this does not realistically simulate the seasonal dynamics of root/shoot partitioning.

- The model currently does not simulate crown and root carbohydrate reserves that are known to be highly dynamic and closely involved in shoot regrowth after defoliation.

- Lucerne plant population typically declines with time in this environment but the model currently does not attempt to simulate this process. In reality population decline often is a key factor limiting productive life of a lucerne stand and currently plant (stem) density must be provided as an input to the model.

- In this study root distribution and activity was mimicked through sensitivity analysis of available root parameters (*ll, xf, kl*) to match observed soil water patterns. An alternative approach would involve prediction of root distribution and activity from soil physical and chemical properties.

Future research is required to develop our understanding of these processes to a point where it is possible to include predictive relationships in future versions of the model.

This study has applied field experimentation and simulation modelling to some agronomic and physiological aspects of lucerne production and water use under two different soil water regimes. However water resources for irrigation are becoming more scarce and expensive. This study provides the production inputs that are essential for a comprehensive economic analysis of irrigated lucerne production at this location and potentially almost any other location. Therefore further study is suggested to determine the value of lucerne biomass and the cost of irrigation water to assess the financial viability of irrigated lucerne for industry. Other issues that could be addressed in the future include:

- What is the potential productivity of lucerne on different soils and climates?
- Where on a farm is the best place to grow lucerne for both productivity and recharge reduction?
- What sort of crop rotations can we use lucerne in? eg. a phase of lucerne followed by a phase of crops, eg. companion cropping where wheat or another crop is sown over living lucerne.
- Water and N management in lucerne – wheat rotations
- Integrated weed management, particularly for herbicide resistant weeds.
- To identify optimum irrigation strategies for this local region, but more likely for areas such as the Upper South East where irrigated lucerne is already an established enterprise.
- Future simulation studies would be best conducted in close collaboration with industry groups so that research priorities reflect the needs of industry users.

Appendices

8.1 Appendix A

History of simulation computer modelling in lucerne

Model name	Authors/ year	Primary objectives
The field model	(Field 1974)	Explanation
ALSIM1 (LEVEL1)	(Fick 1975)	Prediction
SIMED	(Holt *et al.* 1975)	Explanation
The California model I	(Gutierrez *et al.* 1976)	Prediction
The California model II	(Regev, *et al.* 1976)	Prediction
SIMED II	(Dougerty 1977)	Explanation
REGROW	(Fick 1977)	Hypothesis comparison
SIMFOY	(Selirio and Brown 1979)	Prediction
The Canberra model	(Christian and Milthorpe 1981)	Explanation
ALSIM1 (LEVEL2)	(Flick, 1981)	Prediction
YIELD	(Hayes *et al.* 1982)	Prediction
ALSIM1 (LEVEL0)	(Fick and Onstad 1983)	Prediction
GROWIT	(Smith and Loewer 1983)	Prediction
ALFALFA	(Denison *et al.* 1984)	Explanation
ALSIM (LEVEL ZERO)	(Fick 1984)	Hypothesis-comparison
The Gosse model	(Gosse *et al.* 1984)	Prediction
ALFMAN	(Onstad and Shoemaker 1984)	Prediction
SPUR	(Hanson *et al.* 1988)	Prediction
WAVES	(Dawes and Short 1993)	Prediction
Modified SPUR	(Moore *et al.* 1997)	Prediction
APSIM	(Probert *et al.* 1998)	Prediction, Explanation Hypothesis-comparison

After Fick *et al.* 1984 and with four other added references.

8.2 Appendix B

Protocol of Total Nonstructural Carbohydrates (TNC) estimation given by Wolf (1978).

It is an alternative gravimetric method involves less expence and labours than chemical methods. It included following steps to follow.

- Removal of lucerne plants from soil to a depth of about 15 cm.
- Excavation of 20 representative roots per treatment with about 20-60 g fresh weight.
- Crown was removed and lateral branch roots were also trimmed, taproot was cut to a 10 cm length.
- Cleaned free of soil taproot were submerged into water for 2 hours.
- Removed from the water and raped in absorbent paper towels.
- Additional towel were used until firm pressure from hand compression left very little detectable moisture on the towel.
- Roots were weight immediately to a nearest mg to obtain saturated weight.
- Root samples were oven-dried in well ventilated container to a constant dry weight at 70^{o}C.
- Divided the dry weight by saturated weight and multiplying by 100 gave percentage dry matter.

8.3 Appendix C

Watering date, Julian day and quantity of water applied in I_{surf}

Date	I_{sub}	I_{surf}
	Water applied (mm)	
19/12/1900	5	20.5
23/12/1999	5	20.75
24/12/1999	-	20.5
25/12/1999	5	20.75
28/12/1999	5	-
29/12/1999	5	20.75
30/12/1999	5	-
2/01/1999	5	20.75
6/01/2000	5	20.5
9/01/2000	-	20.5
10/01/2000	5	-
12/01/2000	-	20.75
14/01/2000	5	-
15/01/2000	-	20.5
16/01/2000	5	20.5
23/01/2000	7.5	-
24/01/2000	7.5	-
25/01/2000	10	23.5
26/01/2000	10	-
27/01/2000	10	23.5
28/01/2000	10	-
29/01/2000	10	-
30/01/2000	10	-
31/01/2000	10	23.5
1/02/2000	10	-
2/02/2000	10	23.5
3/02/2000	10	-
4/02/2000	10	23.5
5/02/2000	10	-
6/02/2000	10	23.5
7/02/2000	10	-
8/02/2000	10	11.5
9/02/2000	10	9
10/02/2000	10	8.5
11/02/2000	10	9.25
12/02/2000	10	9
13/02/2000	10	9.5
14/02/2000	10	11.5
15/02/2000	10	9
16/02/2000	10	9.25
17/02/2000	10	9.75
18/02/2000	10	9
19/02/2000	10	9.75
20/02/2000	10	9.75
3/03/2000	5	-
4/03/2000	10	23.5
5/03/2000	10	11.5
6/03/2000	12	9
7/03/2000	10	9
8/03/2000	7.5	23.5
9/03/2000	7.5	9
10/03/2000	7.5	23.5
11/03/2000	7.5	11.5
12/03/2000	7.5	5
13/03/2000	7.5	-
14/03/2000	7.5	-
15/03/2000	7.5	-
16/03/2000	7.5	-
17/03/2000	7.5	-
18/03/2000	6.5	-
16/01/2001	20	25
17/01/2001	20	20
18/01/2001	20	20
12/02/2001	20	25
13/02/2001	20	20
14/02/2001	20	20
12/03/2001	20	25
13/03/2001	20	20
14/03/2001	20	20

8.4 Appendix D

Mean δ^{15}N values (four replicates) for reference plants during different sampling times for the study period (Dec 1999-Sep 2001) under rainfed lucerne (R_{fed}) and lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Sampling date	Species	R_{fed}	I_{sub}	I_{surf}
Jan-00	Potato weed	1.54	-0.79	1.49
Feb-00	Potato weed	2.73	2.91	4.20
Mar-00	Potato weed	1.90	1.61	1.58
May-00	Wild mustard	2.50	4.08	3.88
Jul-00	Cape weed	8.50	7.77	7.15
Sep-00	Milk thistle	3.04	1.72	2.35
Nov-00	Ryegrass	1.63	1.17	0.91
Feb-01	No Weed	2.50	2.26	2.86
Mar-01	No Weed	2.50	2.26	2.86
Apr-01	Wire weed	2.32	2.26	2.86
Jul-01	Milk Thistle	2.67	2.67	3.05
Sep-01	Milk Thistle	1.68	3.22	3.19
LSD (α=0.05)		0.50*	0.50**	

* For comparison between treatments.

** For comparison with same level of treatment at different time

8.5 Appendix E

Amounts of mineral soil N (kg ha^{-1}) (nitrates and ammonium) at various soil-depths during different sampling times for the study period under rainfed lucerne (R_{fed}) or lucerne supplied with supplemental water over summer via surface (I_{surf}) or sub-surface (I_{sub}) irrigation.

Sampling date	Soil mineral N (kg ha^{-1})				LSD (α=0.05)
	Depth (mm)	Rfed	I_{sub}	I_{surf}	
Jan 2000	0-200	19	45	25	6.0*
Feb 2000	0-200	21	24	8	6.4**
June 2000	0-200	10	4	5	
Oct 2000	0-200	4	4	4	
May 2001	0-200	34	35	18	
Oct 2001	0-200	10	7	6	
Jan 2000	200-400	15	23	12	5.4
Feb 2000	200-400	16	21	3	5.3
June 2000	200-400	2	2	4	
Oct 2000	200-400	4	3	2	
May 2001	200-400	21	8	36	
Oct 2001	200-400	2	2	2	
Feb 2000	400-600	6	5	4	2.6 (NS)
June 2000	400-600	5	2	2	2.8 (NS)
Oct 2000	400-600	4	3	3	
May 2001	400-600	3	1	6	
Oct 2001	400-600	5	1	2	
Feb 2000	600-800	3	6	12	2.9
June 2000	600-800	5	3	3	3.0
Oct 2000	600-800	7	5	3	
May 2001	600-800	4	1	5	
Oct 2001	600-800	15	1	6	
Feb 2000	800-1000	3	8	3	2.2
June 2000	800-1000	4	5	2	2.0
Oct 2000	800-1000	5	5	6	
May 2001	800-1000	4	0	2	
Oct 2001	800-1000	13	2	4	
June 2000	1000-1300	10	16	16	3.1
Oct 2000	1000-1300	10	15	12	3.3
May 2001	1000-1300	8	4	2	
Oct 2001	1000-1300	11	5	7	
June 2000	1300-1500	18	20	19	3.3
Oct 2000	1300-1500	16	10	12	3.0
May 2001	1300-1500	5	7	4	
Oct 2001	1300-1500	10	7	7	

* For comparison between treatments

** For comparison with in same level of treatment

NS Non-significant

8.6 Appendix F

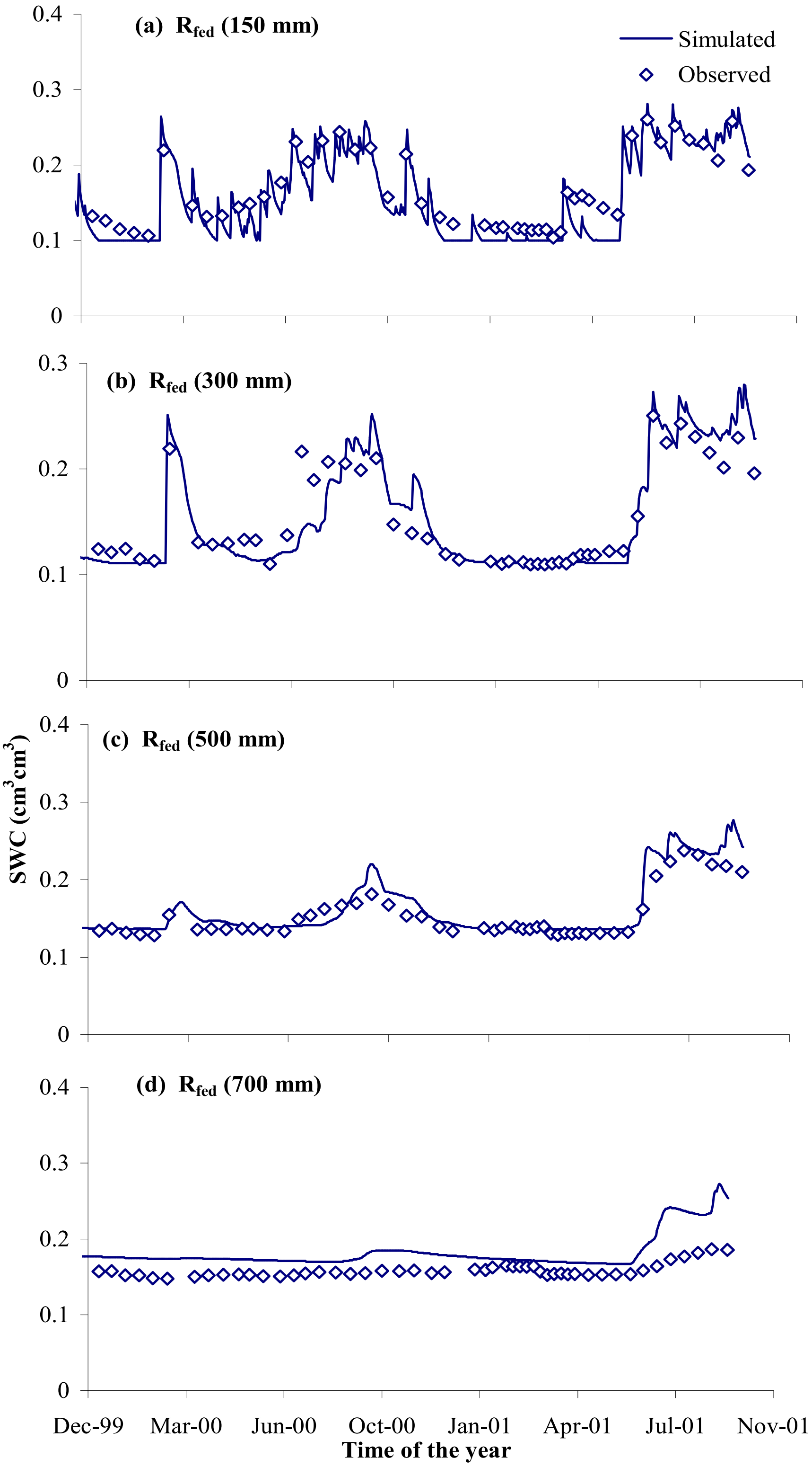
Seasonal dry matter yield, shoot nitrogen content, Ndfa (%) N_2 fixed, N uptake from soil, shoot N_2 fixed per tonne of dry matter and per mm of total water use (ET), during four growing seasons in the study period (Dec 1999-Sep 2001) for rainfed lucerne (R_{fed}) or lucerne supplied with supplemental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

Dry matter yield (tonne ha^{-1})							
Treatment	2000			2001			LSD (α=0.05)
	Summer	Win-Spr	Yr. Total	Summer	Win-Spr	Yr. Total	
R_{fed}	1.15	3.71	4.86	0.24	1.62	1.86	0.57*
I_{sub}	6.90	7.72	14.62	3.13	4.41	7.54	0.45**
I_{surf}	8.00	7.20	15.20	2.77	3.85	6.62	
Total N Produced in DMY (kg ha^{-1})							
R_{fed}	52	152	204	11	72	83	23.51
I_{sub}	242	322	563	110	198	308	22.13
I_{surf}	312	279	591	103	172	275	
N Fixed (kg ha^{-1})							
R_{fed}	27	95	123	5	29	34	21.27
I_{sub}	186	179	365	55	94	149	21.29
I_{surf}	205	171	375	61	93	154	
N uptake (kg ha^{-1})							
R_{fed}	25	57	81	6	43	49	21.41
I_{sub}	55	143	198	55	105	159	21.08
I_{surf}	108	108	216	42	79	121	
Pfix (%)							
			Yr. Mean			Yr. Mean	
R_{fed}	49	58	54	48	41	45	10.52
I_{sub}	78	55	67	52	46	49	10.16
I_{surf}	62	61	62	60	55	57	
Shoot N_2 fixed per tonne dry matter (kg N/t)							
R_{fed}	22	25	23	20	18	19	4.43
I_{sub}	27	23	25	18	21	19	4.27
I_{surf}	24	24	24	22	24	23	
Shoot N_2 fixed per mm total water use (kg mm^{-1})							
R_{fed}	0.232	0.243	0.237	0.124	0.146	0.135	0.073
I_{sub}	0.485	0.397	0.441	0.242	0.431	0.337	0.080
I_{surf}	0.367	0.382	0.375	0.252	0.450	0.351	

* For comparison between seasonal treatments means.

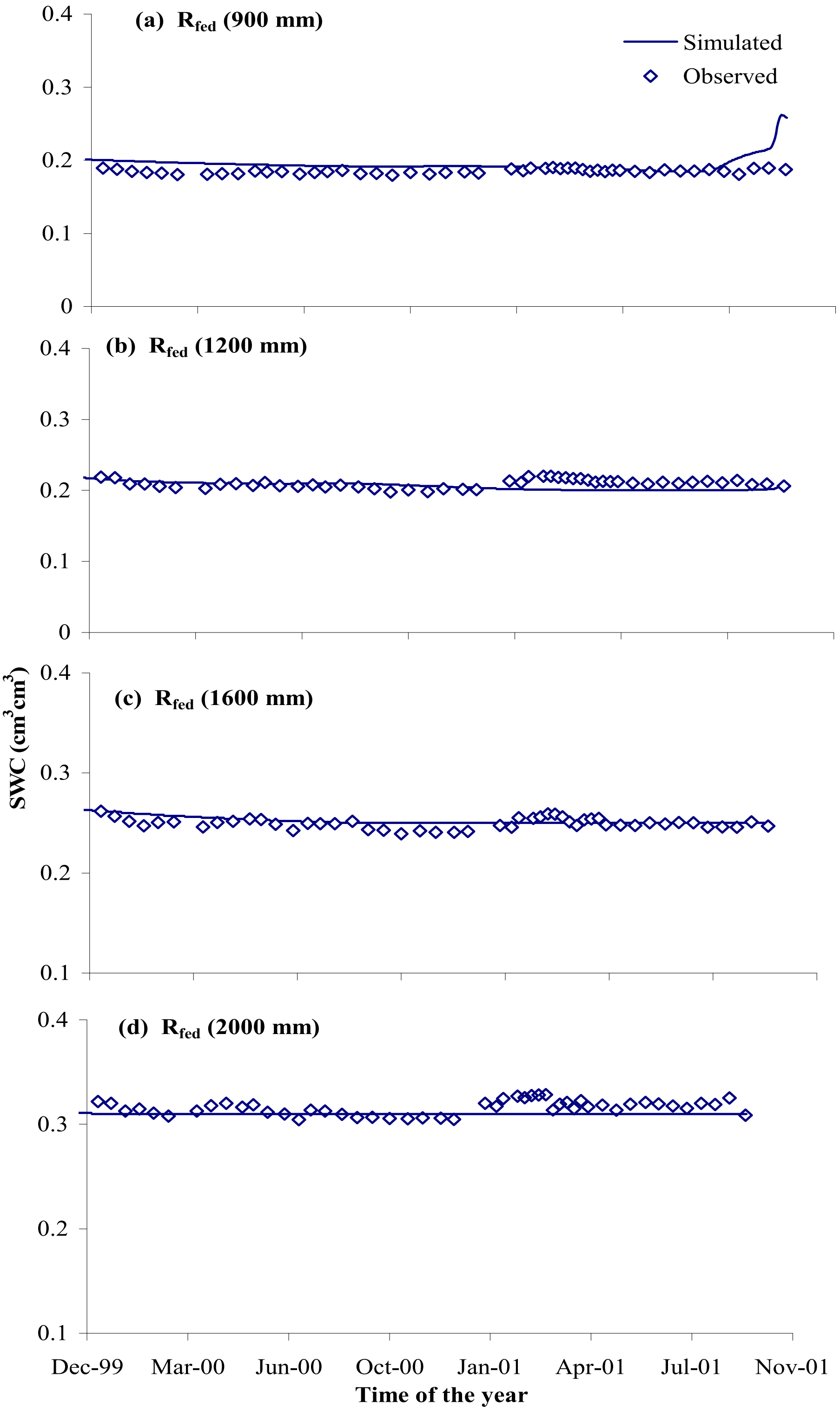
** For comparison with same level of seasonal treatment at different time.

8.7 Appendix G



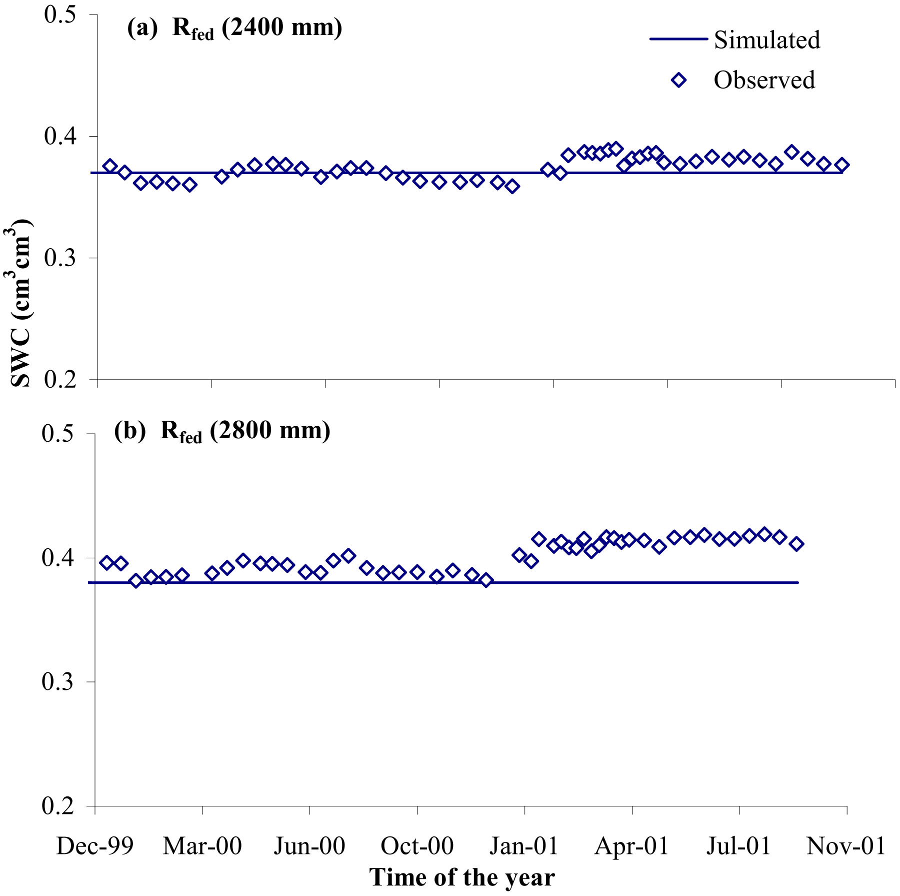
Comparison of simulated and observed soil water content in R_{fed} treatment at various soil depths (a) 150 mm, (b) 300 mm, (c) 500 mm and (d) 700 mm from Dec 1999 to Sep 2001.

8.8 Appendix H



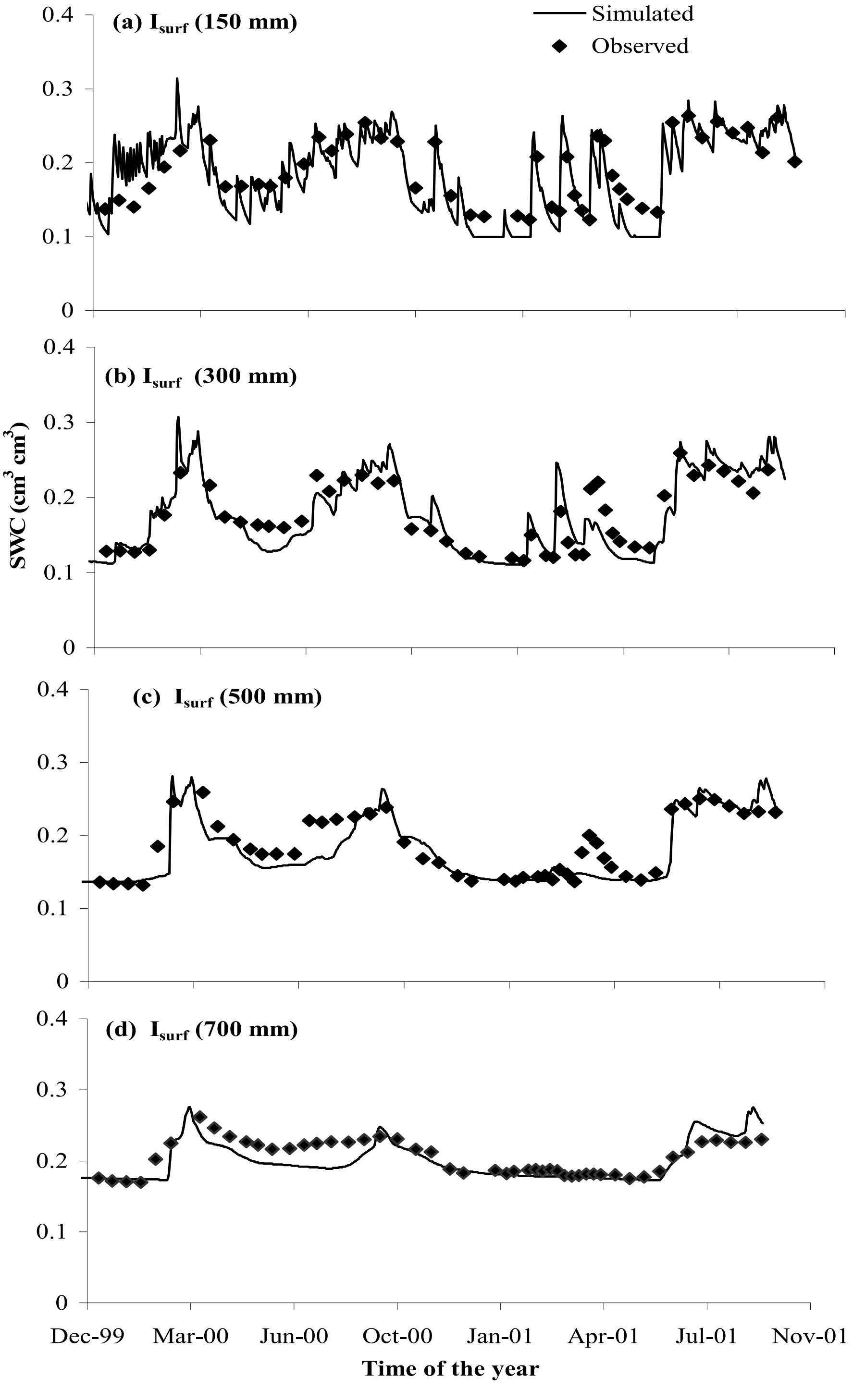
Comparison of simulated and observed soil water content in R_{fed} treatment at various soil depths (a) 900 mm, (b) 1200 mm, (c) 1600 mm and (d) 2000 mm from Dec 1999 to Sep 2001.

8.9 Appendix I



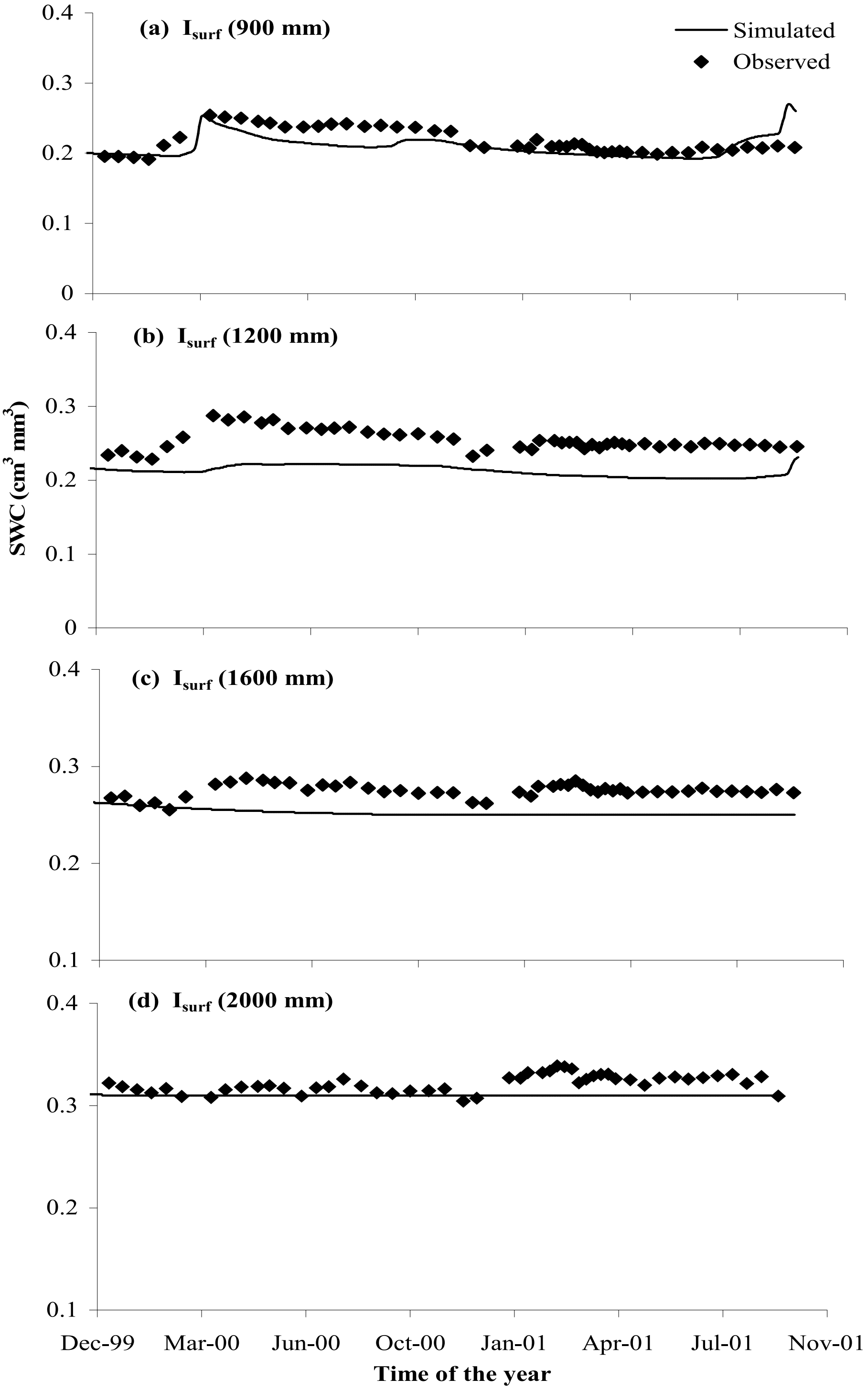
Comparison of simulated and observed soil water content in R$_{fed}$ treatment at various soil depths (a) 2400 mm, (b) 2800 mm from Dec 1999 to Sep 2001.

8.10 Appendix J



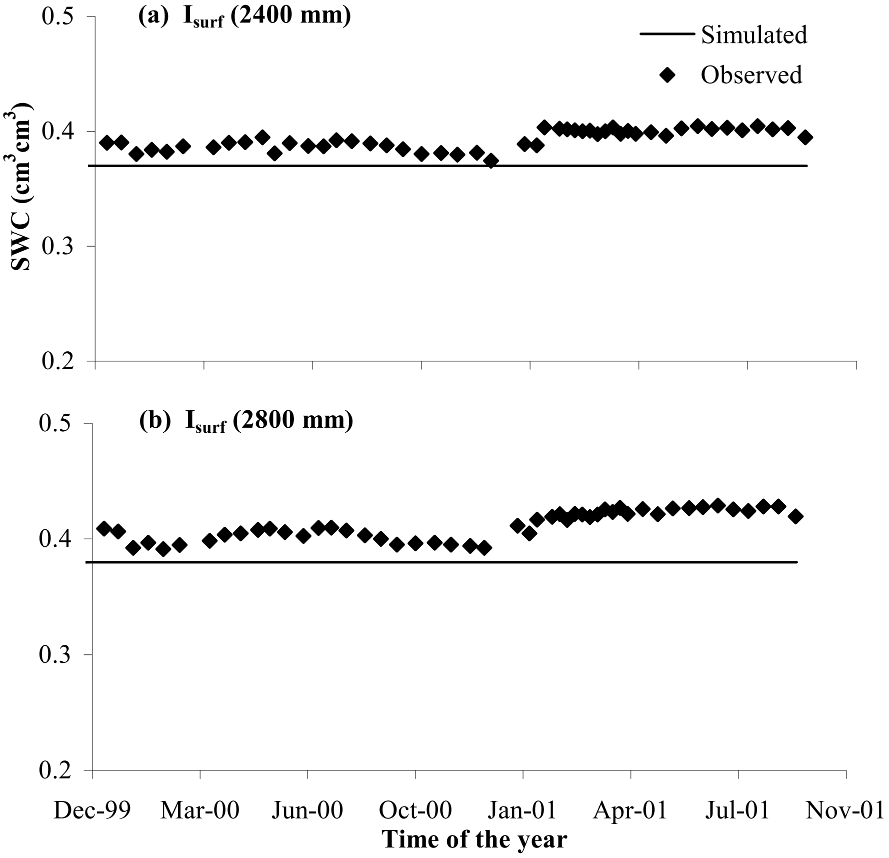
Comparison of simulated and observed soil water content in I_{surf} treatment at various soil depths (a) 150 mm, (b) 300 mm, (c) 500 mm and (d) 700 mm from Dec 1999 to Sep 2001.

8.11 Appendix K



Comparison of simulated and observed soil water content in I_{surf} treatment at various soil depths (a) 900 mm, (b) 1200 mm, (c) 1600 mm and (d) 2000 mm from Dec 1999 to Sep 2001.

8.12 Appendix L



Comparison of simulated and observed soil water content in I_{surf} treatment at various soil depths (a) 2400 mm, (b) 2800 mm from Dec 1999 to Sep 2001.

8.13 Appendix M

Manager file for APSIM simulation Chapter-6

```
[all.manager.init]
cycle = 0

[all.manager.start_of_day]

report do_output

if day =  90 then ! 120 1st April
 lucerne reduce
endif
if day = 334 then  ! 150 (1 Dec Spring)
 lucerne spring          !  regrowth
endif

[rainfed.report.parameters]
title = Rainfed Simulation
screen_output = on
outputfile = U:\Apswork\Apsmsz\rainfed04.out /overwrite
summaryfile = U:\Apswork\Apsmsz\rainfed04.sum /overwrite

[surface.report.parameters]
title = Surface Irrigation Simulation
screen_output = on
outputfile  = U:\Apswork\Apsmsz\surface04.out /overwrite
summaryfile = U:\Apswork\Apsmsz\surface04.sum /overwrite

[rainfed_phenology.report.parameters]
title = Rainfed Simulation
screen_output = on
outputfile  = rainfed_phenology.out /overwrite
summaryfile = rainfed_phenology.sum /overwrite

[surface_phenology.report.parameters]
title = Surface Irrigation Simulation
screen_output = on
outputfile  = surface_phenology.out /overwrite
summaryfile = surface_phenology.sum /overwrite

[all.report.parameters]

module_names=    clock clock  lucerne  lucerne    lucerne    lucerne     lucerne
manager  met
variable_names=  day   year    dlt_tt  tt_tot()   stage_code stage_name  crop_class  cycle
day_length
```

```
variable_alias=    -      -        -    -          -         -          -       -

module_names=   lucerne  lucerne   lucerne    lucerne  lucerne   lucerne    lucerne
lucerne
variable_names=  lai     biomass    green_biomass sum@ep() cep      swdef_photo
sw_demand sw_supply
variable_alias= -       -      -         -    -       -       -      -
units=          -      -      -         -    -       -       -      -

module_names=   soilwat2  soilwat2 soilwat2  soilwat2     soilwat2  soilwat2  soilwat2
soilwat2 soilwat2 soilwat2
variable_names=  esw      sum@es   sum@drain sum@runoff    sw       sw()     eo      es
sw_dep   sw_dep()
variable_alias= -      -     -      -         -      -      -      -      -     -
units=          -      -     -      -         -      -      -      -      -     -

module_names=   lucerne    lucerne  lucerne   lucerne  lucerne   lucerne  lucerne
Lucerne  met   met   met  lucerne
variable_names=  root_depth  root_Wt  height   node_no  plants    leaf_no  leaf_wt
stem_wt  maxt  mint  radn nfact_photo
variable_alias= -        -      -      -     -      -      -      -     -   -   -   -
units=          -        -      -      -     -      -      -      -     -   -   -   -

module_names=   lucerne       lucerne       lucerne      lucerne       lucerne     lucerne
lucerne
variable_names=  swdef_fixation  green_biomass_n  n_conc_stover n_uptake_stover
no3_demand  no3_tot  n_supply_soil
variable_alias= -   -      -      -   -        -          -       -      -
units=          -   -      -      -   -        -          -

module_names=   lucerne    lucerne     lucerne     lucerne     lucerne     lucerne
lucerne
variable_names=  biomass_n  dlt_n_fixed  n_fixed_tops  n_conc_leaf n_conc_stem
n_conc_crit  n_conc_min
variable_alias= -       -        -         -        -        -        -
units=          -       -        -         -        -        -        -
module_names=   soiln2 soiln2 soiln2 soiln2 soiln2 soiln2
variable_names=  no3    no3()  no3ppm nh4    nh4()  nh4ppm
variable_alias= -    -    -     -    -    -
units=          -    -    -     -    -    -

[phenology.report.parameters]

module_names=   clock clock  lucerne  lucerne    lucerne    lucerne     lucerne
manager  met
variable_names=  day   year    dlt_tt  tt_tot()   stage_code stage_name  crop_class  cycle
day_length
variable_alias= -   -    -     -       -       -        -         -     -
module_names=   lucerne
```

```
variable_names=  swdef_photo
variable_alias=  -
units=           -

[sample.clock.parameters]
! Start and end date of run (day number of year and year)
simulation_start_day =  155
simulation_start_year = 1998
simulation_end_day =  263
simulation_end_year = 2001

[rainfed.manager.start_of_day]

if day = 229 and year = 1998 then
  lucerne sow plants = 600 (/m2), cultivar = roseworthy, sowing_depth = 40 (mm)
!30/7/01 set to 70 to match data
   cycle = cycle + 1
elseif day = 349 and year = 1998 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)!stem density from Shafiq's data
   cycle = cycle + 1
elseif day = 100 and year = 1999 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)!stem density data from Shafiq's
data
   cycle = cycle + 1
elseif day = 165 and year = 1999 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)!stem density from Shafiq's data
   cycle = cycle + 1
elseif day = 257 and year = 1999 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)!stem density data from Shafiq's
data
   cycle = cycle + 1
elseif day = 310 and year = 1999 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)!stem density data from Shafiq's
data
   cycle = cycle + 1
elseif day = 19 and year = 2000 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)!stem density from Shafiq's data
   cycle = cycle + 1
elseif day = 57 and year = 2000 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)
   cycle = cycle + 1
elseif day = 90 and year = 2000 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)
   cycle = cycle + 1
elseif day = 143 and year = 2000 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)
   cycle = cycle + 1
elseif day = 211 and year = 2000 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)
```

```
    cycle = cycle + 1
elseif day = 272 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 327 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 42 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 66 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 108 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 192 and year = 2001 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 262 and year = 2001 then
  lucerne harvest height = 50 (mm), plants = 200 (/m2)
    cycle = cycle + 1
elseif day = 262 and year = 2001 then
   lucerne harvest height = 50 (mm)
   lucerne end_crop
endif

[surface.manager.start_of_day]
if day = 229 and year = 1998 then
   lucerne sow plants = 500 (/m2), cultivar = roseworthy, sowing_depth = 40 (mm)
!30/7/01 set to 70 to match data
    cycle = cycle + 1
elseif day = 349 and year = 1998 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)!stem density data from Shafiq's
    cycle = cycle + 1
elseif day = 100 and year = 1999 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 165 and year = 1999 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 257 and year = 1999 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 310 and year = 1999 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)!stem density data from Shafiq's
data
    cycle = cycle + 1
elseif day = 19 and year = 2000 then
```

```
   lucerne harvest height = 50 (mm), plants = 700 (/m2)
    cycle = cycle + 1
elseif day = 57 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 700 (/m2)
    cycle = cycle + 1
elseif day = 90 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 143 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1

elseif day = 211 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 272 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 327 and year = 2000 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 42 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 66 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 108 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 192 and year = 2001 then
  lucerne harvest height = 50 (mm), plants = 500(/m2)
    cycle = cycle + 1
elseif day = 262 and year = 2001 then
   lucerne harvest height = 50 (mm), plants = 500 (/m2)
    cycle = cycle + 1
elseif day = 262 and year = 2001 then
   lucerne harvest height = 50 (mm)
   lucerne end_crop
endif
[sample.lucerne.parameters]
ll   =  .12  .13  .135 .17  .19  .20  .25  .30  .37  .38  ! Shafiq 08, evidence of extraction
xf   = 1.00  0.80 0.70 0.50 0.20 0.20 0.1  0.01  0.0  0.0  !Shafiq 08 root evidence
kl   = 0.09  0.08 0.06 0.03 0.01 0.01 0.01 0.01  0.0  0.0  ! !Shafiq 08 lower depths

[surface.irrigate.parameters]

! Manual irrigation scheduling
! ==========================
```

```
manual_irrigation = on
year =    1999  1999  1999  1999  1999  2000  2000  2000  2000  2000  2000  2000 2000
2000  2000  2000  2000 2000  2000 2000 2000 2000 2000 2000 2000 2000 2000 2000
2000 2000 2000 2000  2000 2000 2000  2000 2000 2000  2000 2000  2001  2001  2001
2001  2001  2001  2001  2001  2001()   ! year for application date
 day =     354   357   358   359   363   2     6     9     12    15    18    25    27    31    33    36
38   40    41   42   43   44   45   46   47   48   49   50   51   52   63   64    65   66   67    68
69   70    71   72     16     17     18    43     44     45     71     72     73  ()   ! day for application
!amount = 20.5  20.75 20.5  20.75 20.75 20.75 20.5  20.5  20.75 20.5  20.5  23.5 23.5
23.5  23.5  23.5  23.5 11.5  9    8.5  9.25 9    9.5  11.5 9    9.25 9.75 9    9.75 9.75 23.5
11.5  9    9    23.5  9    23.5 11.5  23.5  5    20    20    20    20    20    20    20    20    20
(mm) ! amount of irrigation applied
amount =  13.7  13.9  13.7  13.9  13.9  13.9  13.7  13.7  13.9  13.7  13.7  15.7 15.7  15.7
15.7  15.7  15.7  7.7  6.0  5.7  6.2  6.0  6.4  7.7  6.0  6.2  6.5  6.0  6.5  6.5  15.7  7.7  6.0
6.0  15.7  6.0  15.7  7.7  15.7  20    20    20    20    20    20    20    20    20 (mm) !66% of
2000 and 100% of 2001 applied
```

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