Water use efficiency of six dryland pastures in Canterbury

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Declaration

All of the data presented in this thesis was collected by the candidate except for

a) Soil water measurement during November 2008 – January 2009.

b) Sample preparation for nitrogen analysis.

A paper related to spring water use efficiency has been submitted to New Zealand Agronomy Society:

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Abstract

The annual and seasonal water use efficiency of six pasture combinations were calculated from the 'MaxClover' Grazing Experiment at Lincoln University. Pastures have been established for six years and are grazed by best management practices for each combination. Measurements for this study are from individual plots of four replicates of ryegrass (RG)/white clover (Wc), cocksfoot (CF)/Wc; CF/balansa (Bal) clover; CF/Caucasian (Cc) clover; CF/subterranean (Sub) clover or lucerne. Water extraction measurements showed soils for all dryland pastures had a similar plant available water content of 280±19.8 mm. Dry matter measurements of yield, botanical composition and herbage quality were assessed from 1 July 2008 until 30 June 2009. Lucerne had the highest annual yield of 14260 kg DM/ha/y followed by the CF/Sub at 9390 kg DM/ha/y and the other grass based pastures at ≤ 6900 kg DM/ha/y. All pastures used about 670±24.4 mm/y of water for growth. Lucerne had the highest annual water use efficiency (WUE) of 21 kg DM/ha/mm/y of water used (total yield/total WU). The WUE of CF/Sub was the second highest at 15 kg DM/ha/mm/y, and the lowest was CF/Wc at 9 kg DM/ha/mm/y.

The CF/Sub pastures had the highest total legume content of all grass based pastures at 21% and as a consequence had the highest annual nitrogen yield of 190 kg N/ha. This was lower than the monoculture of lucerne (470 kg N/ha). Ryegrass/white clover had the highest total weed component in all pastures of 61%.

For dryland farmers spring is vital for animal production when soil temperatures are rising and moisture levels are high. The water use efficiency at this time is important to maximize pasture production. In spring lucerne produced 8730 kg DM/ha, which was the highest dry matter yield of all pastures. The CF/Sub produced the second highest yield of 6100 kg/DM/ha. When calculated against thermal time, CF/Sub grew 5.9 kg DM/ºCd compared with lucerne at 4.9 kg DM/ºCd. The higher DM yield from lucerne was from an extra 400 ºCd of growth. The highest seasonal WUE of all pastures occurred in the spring growing period. Linear regressions forced through the origin, showed lucerne (1/7/08-4/12/08) had a WUE of 30 kg DM/ha/mm (R^2=0.98). Of the grass based pastures, CF/Sub produced 18 kg DM/ha/mm (R^2=0.98) from 1/7 to 10/11/08 from 270 mm of water used. The lowest spring WUE was 13.5 kg DM/ha/mm by CF/Bal pastures which was comparable to the 14.3±1.42 kg DM/ha/mm WUE of CF/Wc, CF/Cc and RG/Wc pastures.

During the spring, CF/Sub clover had the highest spring legume component of the grass based pastures at 42% and produced 120 kg N/ha. This was lower than the 288 kg N/ha from the monoculture of lucerne. Sub clover was the most successful clover which persisted with the cocksfoot.

Based on the results from this study dryland farmers should be encouraged to maximize the potential of lucerne on farm, use cocksfoot as the main grass species for persistence, rather than perennial ryegrass, and use subterranean clover as the main legume species in cocksfoot based pastures. By increasing the proportion of legume grown the water use efficiency of a pastur can be improved. When pastures are nitrogen deficient the use of inorganic nitrogen may also improve pasture yields particularly in spring.

Additional keywords; *Dactylis glomerata* L., *Lolium perenne* L., *Medicago sativa* L., *Trifolium ambiguum* L., *T. repens* L., *T. michelianum* L.

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List of Abbreviations

Abbreviation	Description	Units
DM	Dry matter	kg DM/ha
DUL	Drained upper limit	% v/v or mm
LL	drained lower limit	% v/v or mm
LSD	Least significant difference	
ME	metabolisable energy	MJ/kg DM
N%	nitrogen concentration	%
PAWC	plant available water holding capacity	mm
PET	potential evapotranspiration	mm
R^2	coefficient of determination	
SEM	standard error of the mean	
t	time	d
T_b	base temperature	ºC
Tmax	maximum temperature	ºC
Tmin	minimum temperature	ºC
Tt	thermal time	ºCd
VWC	volumetric water content	% v/v
WU	water use	mm
WUE	water use efficiency	kg DM/ha/mm
Y	yield	kg/ha or t/ha

1 General Introduction

In most countries, water resources for agriculture are limited, and therefore optimization of the use of water is essential. When irrigation is available, optimization strategies include temporal and spatial differentiation to provide an appropriate amount of water when it is required by the crop or pasture. When irrigation water is unavailable the duration and intensity of water stress influences crop and pasture production and plant survival (Grashoff *et al*., 2001). Under mild drought stress growth rates initially decrease due to reduced leaf expansion and therefore light interception. In more advanced stages of drought stress morphological changes and eventually leaf senescence and leaf death can occur (Jones and Lazenby, 1988). Water stress occurs when moisture lost through the combination of soil evaporation and plant transpiration exceeds that supplied by the soil and rainfall (Black *et al*., 1969). The dryland region of New Zealand is typically in the eastern shadow of the main divide of both islands. Rainfall may be 300 to 800 mm per year. Water stress occurs for pastures when long term average potential soil water deficit exceeds 100 mm (Salinger, 2003). Dry summers then result in severe soil moisture deficits. Stress is relieved by autumn rain which re-establishes the sward before cool winter temperatures restrict pasture growth (Radcliffe and Baars, 1987). Sheep and beef farm systems are dominant in these climate regions when topography prevents the use and restricts the availability of irrigation. In contrast, successful dairying occurs on ryegrass and white clover pastures as long as about 1200 mm of moisture as rain or from irrigation is available annually (Macfarlane and Sheath, 1984).

The overall aim of this research is to identify legume species that persist in cocksfoot swards to enhance overall productivity of pastures in summer dry environments. Specifically in this thesis, the soil water extraction patterns and pasture production from six dryland pastures are compared under sheep grazing. The annual and seasonal water use efficiencies of the six dryland pastures are compared from within the 'MaxClover' Grazing Experiment. The objective is to identify mechanisms that lead to differences in productivity among the pastures. Four of these pastures have cocksfoot as the sown grass because it is a persistent species commonly used in dryland regions. However, cocksfoot pastures are often nitrogen deficient (Peri *et al*., 2002b), because of their competitive ability in water extraction that restricts the growth of companion legume species.

This thesis is presented in five chapters. Chapter 1 is the general introduction. It is followed by a review of the literature in Chapter 2. The materials and methods from the single experiment are described in Chapter 3. The results are presented in Chapter 4 and discussed in general in Chapter 5.

2 Review of the Literature

Dry matter (DM) production is the product of a crop or pasture which comes from light interception, and efficiency of conversion of that light into carbon based products (Monteith, 1977). This chapter reviews current literature that describes dryland pasture species used in this study and then explains how their water use efficiency can be determined.

2.1 Dryland species

2.1.1 Ryegrass

Perennial ryegrasses (*Lolium perenne* L.) are the most widely grown cool-season grasses in the world (Langer, 1989). They have numerous desirable agronomic qualities. They establish rapidly (Camlin, 1981), have a long growing season, are high yielding under favorable environments when supplied with adequate nutrients, possess high nutrient content, and can be grazed or used for hay or silage (Mackinnon *et al*., 1988). Ryegrasses are suited to fertile, well-drained soils but can be grown on soils where it is too wet at certain times of the year for satisfactory growth of other grasses. Ryegrasses are heavy users of water and have shallow roots. Their performance is less than optimum during a drought or periods of extended low or high temperatures. Perennial ryegrass is the most important New Zealand grass species. It is used in pastures for grazing and for hay, because it is a highly nutritious stock feed. It is the principal grazing grass in New Zealand (Langer, 1989). Like many cool-season grasses, it is often infected by fungal endophyte which lives symbiotically within its leaves (Langer, 1989). Recent modifications of endophyte have reduced the negative impacts on animal health but maintained insect resistance particularly to weevils and beetles (Hume *et al.,* 2007).

In temperate climates, perennial ryegrass is usually grown with clovers, and it is considered the most suitable companion for white clover (Harris, 1987). However, in dryland moisture limited regions the dry matter yield of ryegrass/white clover (*Trifolium repens* L.) swards is low and pasture persistence is limited (Knowles *et al*., 2003). For example, Knowles *et al.* (2003) found that the percentages of white clover seedlings in five farms sampled in May after severe drought were less than 1% (Table 2.1). After there was some rain the percentages increased in August and October 2001 but were still less than 7% everywhere except North Otago.

2.1.2 Cocksfoot

In New Zealand, for many dryland farmers the most persistent grass species is cocksfoot (*Dactylis glomerata* L.), because it survives through dry periods. It is a persistent perennial grass that tolerates moisture stress, moderate soil fertility, insect attack and continual set stocking (Gregor, 1956). Cocksfoot is normally grown with legumes, such as white clover and more recently has been combined with Caucasian (*Trifolium ambiguum* L.), subterranean (*Trifolium subterraneum* L.), and balansa (*Trifolium michelianum* L.) clovers with varying degrees of success (Mills *et al.,* 2008a). Mills *et al.* (2008a) found that annual dry matter yields of ryegrass/white clover were lower than cocksfoot grown with these four clovers on dryland for four of the five measurement years (Figure 2.1) in the 'MaxClover' experiment at Lincoln University (Section 3.1). Over this period the ryegrass production dropped from 8 to 4 t/ha while the cocksfoot averaged about 6 t/ha in the final year.

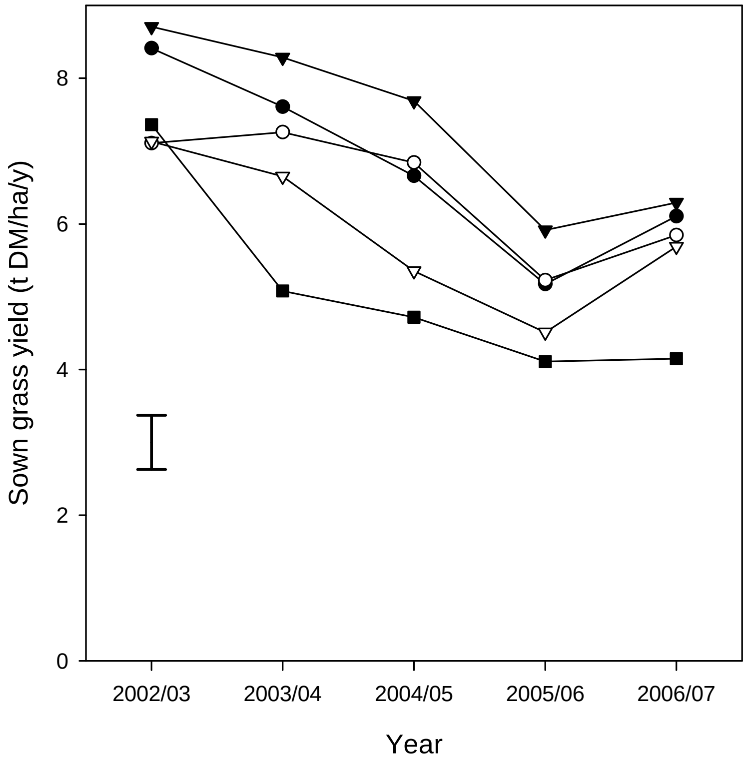

Figure 2.1 Annual dry matter yields (t/ha/yr) of the sown grass component of dryland CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽) and RG/Wc (■) pastures over five growth season (From Mills *et al.*, 2008a). The error bar is the maximum SEM. Full details of the acronyms are given in Table 3.1.

Cocksfoot also adds variety to the stock diet. Low seeding rates of 2-3 kg/ha are recommended, because cocksfoot can dominate pastures, reducing clover content (Stevens *et al.*, 1992) and thus total pasture quality due to reduced N availability (Peri *et al.*, 2002a). Cocksfoot is moderately slow to establish (Moot *et al.,* 2000) and has lower digestibility than ryegrass in unlimited water conditions. Cocksfoot has limited winter growth but higher summer growth than perennial ryegrass. Mills *et al.* (2008) found that in summer, lambs grazing ryegrass/white clover averaged 65 g/hd/d. In contrast, for cocksfoot based pastures the average was 90 g/hd/d. Furthermore, Mills *et al.* (2008b) showed that in most years (2005/06, 2006/07 and 2007/08) cocksfoot/sub clover produced spring liveweight production of 600-1100 kg LW/ha which was higher than ryegrass/white clover (600-800 kg LW/ha) (Figure 2.2). In the middle of summer, if there is any rain at all, cocksfoot greens up and recovers more quickly than ryegrass and this is its main attribute in a dryland system (Fraser, 1994).

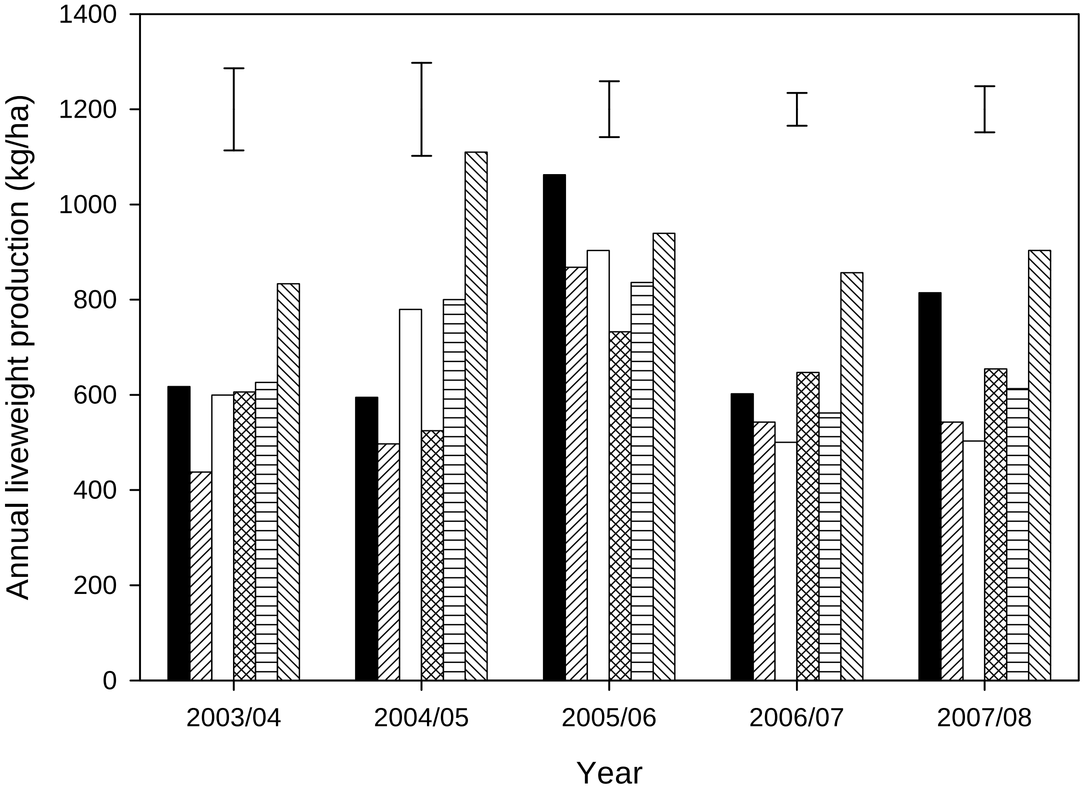

Figure 2.2 Total annual liveweight production (kg/ha) from dryland CF/Sub (■), CF/Bal (▨), CF/Wc (■), CF/Cc (⊠), RG/Wc (⊟) and Lucerne (▧) pastures. Error bars are LSD at P<0.05 for each year (From Mills *et al.,* 2008b). Full details of the acronyms are given in Table 3.1.

Brown, *et al.* (2006) stated that over time the growing of cocksfoot with white clover is unsuccessful because of the cocksfoot roots' higher ability to extract water during summer. This means white clover is out-competed and eventually the pasture becomes cocksfoot dominant. As a consequence the pasture becomes nitrogen deficient, loses palatability and subsequently production decreases. Annual clovers, such as subterranean clover, may be more suitable companion species for cocksfoot than white clover, because annual clovers grow in late winter and die in the summer. This means they can avoid the competition with cocksfoot during summer (Hyslop *et al.*, 2003).

Stevens *et al.* (1992) stated that cocksfoot is a pasture which can produce yield, survive and persist in drought conditions. It is also recommended for low to moderate fertility, summer dry regions (Baker *et al.*, 1985). Stevens *et al.* (1992) reported a ryegrass yield of 4.9 t/ha compared with 7.6 t/ha for cocksfoot. This was because cocksfoot produced 131% more dry matter than ryegrass in summer and 74% more in autumn. Peri *et al.* (2002a) found that a 10 year old cocksfoot dominant pasture produced a maximum yield of 28.6 t DM/ha/y under non limiting water and nitrogen conditions in Canterbury. This indicates cocksfoot has a similar potential annual yield to ryegrass. Mills *et al.* (2006) showed the main factor limiting cocksfoot production was N rather than water. Cocksfoot which was irrigated and with no nitrogen applied (I-N) produced an annual dry matter yield of 9.1 t/ha in 2004/05. In contrast, cocksfoot in dryland with nitrogen applied (D+N) produced an annual dry matter yield of 16.4 t/ha in the same period. Stevens and Hickey (2000) reported that cocksfoot gave the highest production four years after establishment out of several binary mixtures. Seasonal production of cocksfoot is generally less than ryegrass in spring, but the production increases in summer and autumn (Kemp *et al.*, 1999). However, management strategies also affect the growth rate of cocksfoot which usually decline at the time of maximum seedhead production, because of a reduction in the number of vegetative tillers and a change in partitioning priority associated with seed formation (Radcliffe and Baars, 1987).

2.1.3 White clover

White clover is an herbaceous perennial plant native to Europe, North Africa, and West Asia. It has been widely introduced as a pasture plant. It is low growing, with heads of white flowers, often with a tinge of pink or cream. Stems function as stolons, so white clover often forms mats with the stems creeping as much as 0.2 m a year (Langer, 1989).

White clover is an important pasture legume in New Zealand. It is a highly palatable, nutritious forage for all classes of livestock. White clover is commonly planted with cocksfoot, ryegrass, or tall fescue (Brock and Caradus, 1996). White clover thrives in a cool, moist climate in soils with ample lime, phosphate, and potash. In general, white clover is adapted to clay and silt soils in humid and irrigated areas. It grows successfully on sandy soils with a high water table or irrigated droughty soils when adequately supplied with phosphorus (P) and sulfur (S). White clover seldom roots deeper than 50 cm. This makes it adapted to shallow soils when adequate moisture is available (Brock and Kane, 2003). White clover requires high fertility and wet to moderately dry soils (Levy, 1970). However, growing it in dryland proves to be difficult, because of drought and competition that occurs for water among plants. Moreover, Sheath and Hay (1989) stated that white clover is only suited for dryland where there is a minimum of at least 750 mm of annual rainfall. Knowles *et al.* (2003) stated that in regions which had severe drought there was a large depression in white clover content in swards. For example, in North Otago when there was less than 10 mm of rainfall in March and April, the mean percentage of white clover seedlings was only 0.3% in May (Table 2.1). White clover initially produces a tap root that confers some drought tolerance. This dies after 12-18 months (Knowles *et al.*, 2003). It then requires frequent irrigation or rainfall to survive from adventitious roots at the nodes (Woodfield and Caradus, 1996).

Table 2.1 Table 2.1. Mean white clover seedling presence (% of cores with seedling), for 2-5 farms sampled after a severe drought in 2000/01 (± SEM) (From Knowles *et al.,* 2003).

	Post-drought							
Region	May 2001		June 2001		Aug 2001		Oct 2001	
Nth Otago	0.3	(±0.3)	1.3	(±1.3)	13.0	(±10.1)	9.0	(±3.1)
Sth Cant	0.8	(±0.5)	0.0	(±0.0)	1.3	(±0.6)	3.8	(±2.6)
Mid Cant	0.4	(±0.4)	1.6	(±1.2)	3.4	(±3.2)	6.0	(±3.2)
Marlb	0.6	(±1.5)	1.0	(±1.5)	3.3	(±5.5)	6.7	(±10.0)
Wairarapa	0.0	(±0.0)	0.0	(±0.0)	1.7	(±0.9)	2.0	(±0.8)

The regeneration of white clover in dryland pastures is often through seedling recruitment from seed in the soil. White clover is one of the perennial clovers which is widely used in mixed grass/clover pastures (Smith *et al.,* 1985), but requires sufficient summer rain to avoid permanent wilting and maintain persistence (Brock *et al.,* 2003).

2.1.4 Caucasian clover

Caucasian clover (*Trifolium ambiguum* L.) is a highly persistent perennial legume. Caucasian clover is reportedly productive and persistent in higher elevation areas (700 m a.s.l.) particularly if there is some summer rain fall (Watson *et al.*, 1998). Overall it is suited to temperate tableland areas receiving a minimum of 450 mm average annual rainfall. It is tolerant of cold conditions and drought. Caucasian clover requires well-drained soils with pH ($CaCl_2$) of 4.5 or greater, but will also tolerate intermittent waterlogging. It will tolerate low fertility conditions, but responds to fertilizer particularly P and S. Once established, Caucasian clover is tolerant of heavy continuous grazing and has persisted for over 20 years in elevated tableland regions (Woodman *et al*., 1992). Furthermore, Black *et al.* (2003) reported that Caucasian clover is more drought tolerant than white clover and it is also more productive than white clover under drought conditions on hill country and lowland regions (Figure 2.3). Black and Lucas (2000) found that Caucasian clover may persist with cocksfoot in summer, because it has a taproot and rhizomes.

A distinguishing feature of Caucasian clover is its strong underground root system, consisting of a dense network of rhizomes and taproots. It is this that enables Caucasian clover to survive drought and extreme cold. Caucasian clover spreads predominately via rhizomes, but may also increase in density by recruitment from seed. Leaf characteristics can vary significantly depending on a number of factors, including ploidy and grazing intensity (Scott, 1998). Leaflet size generally increases with ploidy, with diploid varieties having the smallest leaflets and hexaploid varieties the largest. However, this characteristic can be variable. Moreover, Caucasian clover has been shown to produce greater dry matter than white clover in mixed pasture under irrigated and dry conditions. For example, Black *et al.*(2003) found that in December 2001 dryland Caucasian clover produced 78 kg/ha/day compared with 50 kg/ha/day for white clover and, the advantage continued until mid March. After that, both clovers had growth rates of ~7 kg/ha/day. The greater production of Caucasian clover in spring and summer came from a higher photosynthetic rate of Caucasian clover than white clover irrespective of soil moisture.

2.1.5 Subterranean clover

Subterranean clover (*Trifolium subterraneum* L.) is an annual plant that has the ability to bury its seeds under the ground, and this is the basis of its name. It originated in the Mediterranean region, and is adapted to the Mediterranean climate of NZ region with a mean temperature of 7-13 ºC. Subterranean clover is a prostrate and tap-rooted plant. After self-pollination, the flowers bend over and grow into the soil. The sterile flowers form a burr, which is a network of barbs that anchor under the soil. This buries seeds to ensure regeneration of the stands in the following year. Seeds are purple to black colour and about 3 mm across, and they will germinate with the onset of overcast, wet conditions in the next autumn (Langer, 1989).

Subterranean clover is a winter-growing legume and is well adapted to sandy soils. It provides high quality protein rich forage when the feed value of the associated mainly summer-growing grasses is low. Moreover, subterranean clover germinates faster than other legumes in low temperatures (McWilliam *et al*., 1970) and has deep roots (Frame *et al*., 1998). It avoids summer dry conditions through its annual life cycle but can be susceptible to a ‘false strike’ if germination occurs too early in summer (Mills *et al.*, 2008b).

Moot *et al.* (2000) stated that subterranean clover was the fastest species of those tested to germinate at temperatures below 15 ºC. The rate of germination was 0.12 d^{-1}, while perennial ryegrass had an emergence rate of 0.06 d^{-1} at 15 ºC.

Subterranean clover requires careful grazing management in different seasons to ensure its survival in a sward. Moot *et al.* (2003) stated that after autumn rain, subterranean clover seeds in the soil will start their germination. The first grazing of subterranean clover sward should be done when the seedlings have six leaves. At this time, subterranean clover seedlings can survive grazing. Continue grazing until cool temperatures limit grass growth. In spring, during seed set, a low (<1000 kg DM/ha) post grazing pasture mass reduces subterranean clover seed set (Ates *et al.*, 2008). In contrast, in summer before subterranean clover regrows, hard grazing is required to reduce shading and competition for light and allow high numbers of seed to germinate. This is particular important in a moist summer when grass growth can be excessive (Ates *et al.*, 2008).

2.1.6 Balansa clover

Balansa clover (*Trifolium michelianum* L.) is an aerial seeding annual legume, capable of long term persistence in pastures. It is used for a variety of purposes such as in rainfed and irrigated pastures or as a hay, silage or green manure crop. Balansa clover is a species with broad environmental adaptation. It performs well on a range of soil types and textures. It tolerates a pH range of 5.0 - 8.6, although it has been shown to be more sensitive to low pH than subterranean clover (Evans *et al.*, 1990). Moreover, the species is well adapted to waterlogging and, once established, can withstand short periods of flood (Revell and Nutt, 2001). Further, balansa clover possesses moderate salinity tolerance. Rogers and West (1993) found that root growth of balansa clover increased with saline water-logging. There was a significant proportion of new growth occurring as adventitious roots. These roots contained a higher proportion of aerenchyma cells to facilitate oxygen transport than non-adventitious roots.

Balansa clover germinates in autumn with its main growth produced in late winter-spring, and then it senesces over summer. The sward matures and dies but regenerates from seed reserves in autumn following the summer drought. Its annual life cycle is also adapted to avoid summer drought (Rogers and Noble, 1991).

Monks *et al.* (2008) stated that balansa clover tolerated hard grazing after emergence from autumn to flowering in spring. A drawback is that wet summers and cool soil temperatures can reduce balansa clover recovery by inducing seed softening, promoting grass growth and increasing competition in the sward. They found that management affected balansa clover persistence. For example, the management of one stand involved no grazing in 2003 and limited flowering and seeding in 2004. From this management balansa clover persisted and produced enough seeds to re-establish 3 years later in 2007. A different stand was managed to contrast with this, and not allowed to set seed in 2004. The result was sufficient seed reserves from 2003 to re-establish for 2 years but not for 2006 or 2007 (Figure 2.3).

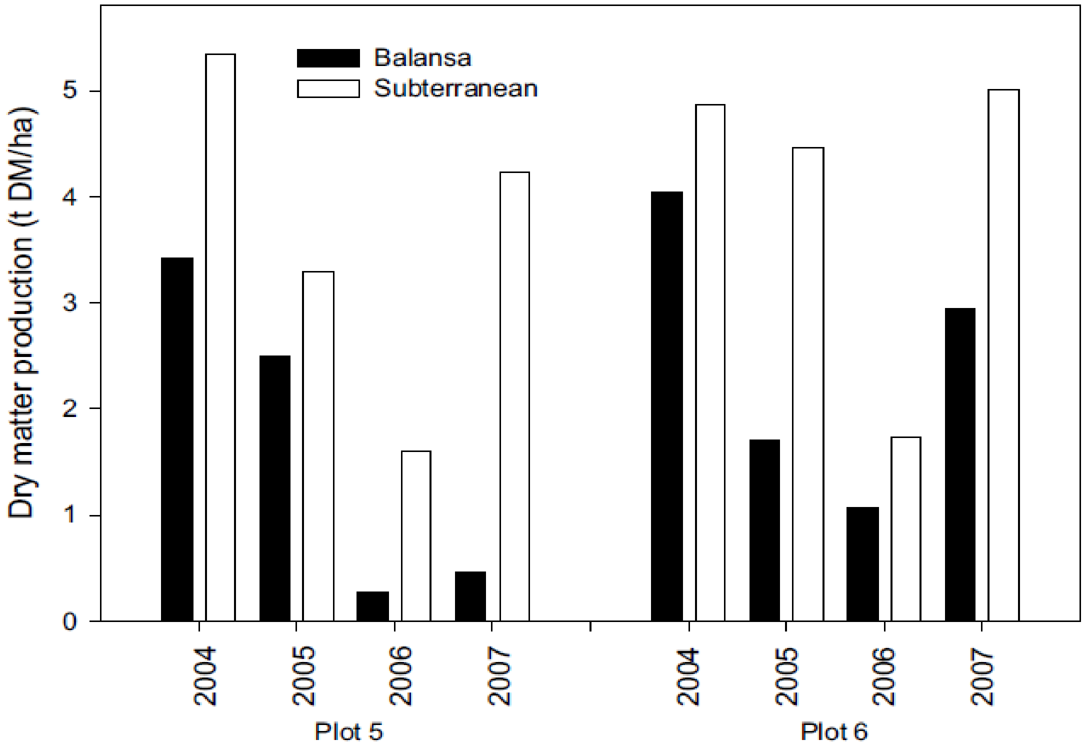

Figure 2.3 Total annual legume dry matter yield from years 2 to 5 from balansa or subterranean clover from two of the cocksfoot pastures (From Monks, *et al.*, 2008).

2.1.7 Lucerne

Lucerne or alfalfa (*Medicago sativa* L.) is a flowering plant in the pea family (Fabaceae) cultivated as an important forage crop. It is a cool season perennial legume living from 3 to 20 years, depending on variety, climate and management. It resembles clover with clusters of small purple flowers. The plants grow up to 1 metre, and have a deep root system sometimes stretching to 4.5 metres (Langer, 1989). This makes it flexible and more tolerant to drought than shallow rooted species. Lucerne is widely used in dryland pasture farming due to its ability to respond to summer rainfall, and access to moisture deep in soil profiles. For example, Crawford and Macfarlane (1995) measured changes in soil water status under lucerne pasture compared with a subterranean clover pasture. They found that the soil under lucerne pasture was much drier, particularly at 1.0 m. Moreover, Brown *et al.* (2003) found that lucerne extracted 358 mm of water in the driest season of 1997 to 1998, and it extracted water to at least a depth of 2.3 m. In contrast, chicory and red clover at the same site extracted 330 mm, only to 2.0 (Figure 2.4). These three species are drought tolerant but only lucerne persisted beyond the fourth growth season.

Lucerne has a tetraploid genome. The plant exhibits autotoxicity, which means that it is difficult for lucerne seed to grow in existing stands. Therefore, it is recommended that lucerne fields be rotated with other species before resowing (White, 1982). Lucerne is widely grown throughout the world as forage for cattle and sheep and is most often harvested as hay. It can also be made into silage, grazed, or fed as greenchop. In New Zealand, there has recently been a return to lucerne grazing particularly in dry areas (Avery *et al.*, 2008). When grown on soils where it is well-adapted, lucerne is the highest yielding of the temperate forage plants (Brown *et al.,* 2005).

Lucerne can be sown in spring or autumn, and gives the highest yields on well-drained soils with a neutral pH of 6.0–7.0. Lucerne used solely for conserving requires replacement of fertility and particularly potassium (K). Lucerne is moderately sensitive to salt levels in the soil (White, 1982). Sometimes, lucerne is considered 'insectary' due to the large number of insects it attracts, particularly if left to flower. Some pests such as sitona weevil, aphids and stem nematodes can reduce lucerne yields dramatically (Langer, 1989), but plant breeding and crop management have reduced their current impact.

Moot, *et al.* (2003) stated that in summer drought conditions water stress reduces pasture yield and also increases senescence of leaf, so in dry summers hard grazing should occur to reduce dry matter losses. They outlined a seasonally based grazing management package that has allowed greater flexibility in spring grazing management. Specifically, previous management recommendations advised farmers to defer the first spring grazing until flowering. The new recommendations showed that spring grazing could be triggered when stands reached ~0.3 m in height but flowering in late summer/autumn was critical to stand performance the following spring as it allowed replenishment of depleted root reserves. As a consequence ewes and lambs and cattle are now routinely grazing lucerne in spring on some dryland farms (Avery *et al*., 2008).

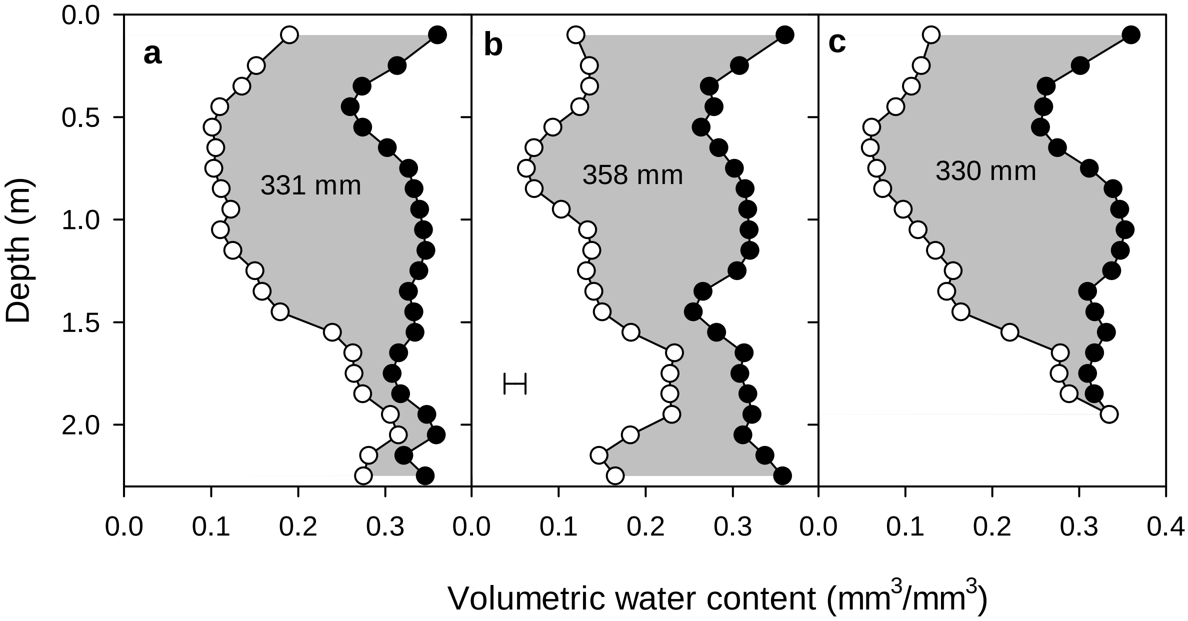

Figure 2.4 Volumetric water content of soil at upper (●) and lower (○) limits of a) chicory, b) lucerne and c) red clover water extraction measured to 2.3 m depth (From Brown *et al.*, 2003). The error bar is SEM of volumetric water contents.

2.2 Water use efficiency

Efficient use of water by agriculture is a complex subject. Water use efficiency (WUE) has been defined in several ways. In agronomy WUE is defined as the ratio of economic yield or the amount of biomass production relative to evapotranspiration (Copeland *et al.*, 1993) or the ratio of total dry matter (DM) accumulation to total water input to the system (Moot *et al.,* 2008). Engineers define irrigation WUE as the ratio of water beneficially used to irrigation water delivered to the field (Martin *et al.,* 2006). WUE is also defined as the ratio of a marketable unit of yield per unit of water used (Armstrong *et al.,* 2004). Enhancements in agricultural water use efficiency depend on productivity gains, and are described by consistent increases in outputs per unit input. Annual WUE can be calculated from measurements of total annual dry matter yield (kg/ha) and total water in the system (Equation 1):

Equation 1 WUE = Y/ (R+I+ASWC-D)

Where: Y is total dry matter yield/ha
R is rainfall (from Broadfields meteorological station)
I is irrigation, but this experiment is on dryland (irrigation = 0)
ASWC is available soil water content
D is drainage which can be calculated from water lost from the deepest soil layers in the absence of pasture growth

Water use efficiency also depends on soil texture and depth and rooting depth which differs between plant species. WUE of different plants grown in the same soil type may differ due to differences in their ability to extract moisture. For example, from Figure 2.4, lucerne extracted a total annual soil water supply of 358 mm. In contrast, chicory and red clover extracted approximately 330 mm (Brown *et al.*, 2003). Also the WUE of the same plant species grown in different soil types may differ due to the availability or storage capacity of the soil. For example, Moot *et al.* (2008) found that lucerne could extract more water from Wakanui than Lismore soils (Figure 2.5). The Lismore soil held 130 mm compared with 339 mm in the Wakanui. Thus if the soil contains 130 mm it will be at field capacity for the Lismore soil. Any additional rainfall could be expected to result in drainage from the Lismore soil but not the Wakanui. The WUE of pastures may also change over seasons. WUE is higher in spring, when temperatures are conducive to growth, but evapotranspiration rates and night temperatures are lower than in summer. WUE also increases when the canopy is closed and soil evaporation decreases. Moreover, WUE is also higher in C_4 than C_3 plants as there is more growth per mm of water due to less respiration, if temperatures are not limiting (Martin, 1984). Water use in spring is important for maximizing dryland pasture production. Growing lucerne or a combination between grass and legumes can increase the nitrogen content of some species and consequently their water use efficiency compared with monocultures (Moot *et al.* 2008). For example, lucerne produced a spring dry matter yield of about 6 t DM/ha at a rate of 24 kg DM/mm of water. For ryegrass/white clover the spring dry matter yield was less than 5 t DM/ha at rate of 20 kg DM/mm of water. Moot *et al.* (2008) also inferred that the higher herbage N content contributed to higher photosynthetic efficiency and higher dry matter yield which led to higher WUE.

Water use efficiency also depends on plant type within soil type. The availability of water in the soil for crops depends on root depth and proliferation. Normally, plants which have deeper roots extract more water than shallow rooted plants, because they have access to water from deeper in the soil profile. In contrast, a greater proliferation of roots (roots per unit soil volume) increases water extraction from a unit volume of soil before permanent wilting point occurs (Willatts, *et al.,* 1978). Moot *et al.* (2008) stated that lucerne can extract more water and can use water from deeper in the soil layer than perennial ryegrass. For example, lucerne extracted 328 mm of water to at least 2.3 m, but ryegrass extracted only 243 mm of water to a depth 1.5 m on a similar Wakanui soil (Figure 2.5). This is because the tap root of lucerne can extract more water from deeper in the soil than the fibrous perennial ryegrass. However, a fibrous root system is usually more capable of extracting water from the upper soil layers. Therefore, each root system has an advantage in different conditions. For example, in a cocksfoot and Caucasian clover sward, normally cocksfoot which has fibrous roots has a greater ability to extract water from the soil when there is water in the upper soil layers. Caucasian clover, which has a tap root, may extract more water than cocksfoot from deeper in the profile in summer (Black and Lucas, 2000). For example, the botanical composition of Caucasian clover in cocksfoot sward increased from about 20% in September to approximately 40% in December and February when the season changed from spring to summer. Caucasian clover may have been extracting water from beneath the cocksfoot rooting zone (Black and Lucas, 2000).

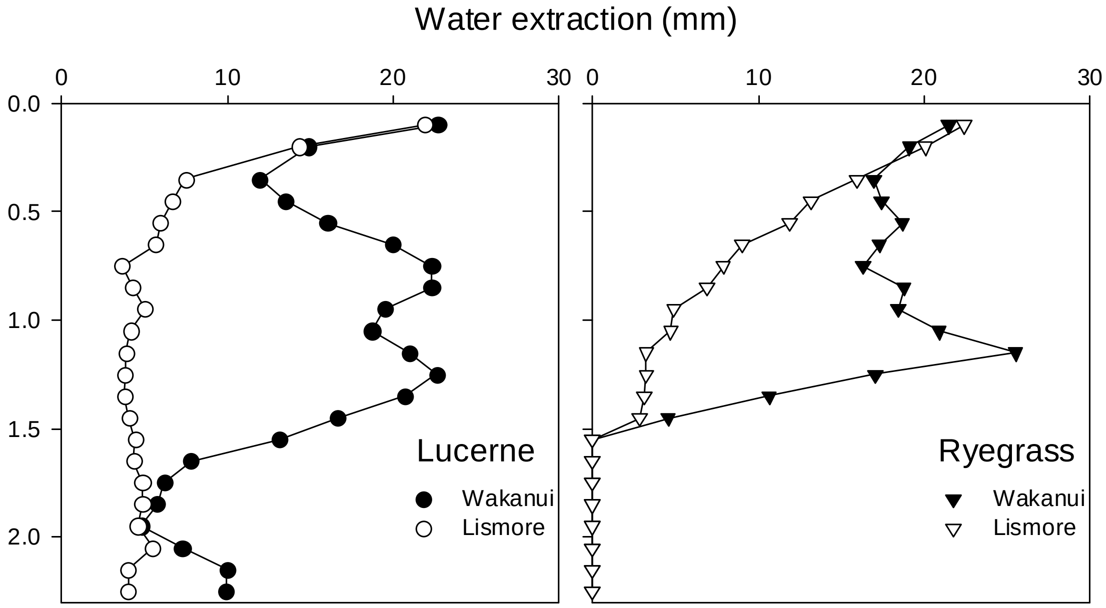

Figure 2.5 Water extraction (mm) from 0.2-3 m depth for lucerne and ryegrass on Wakanui or Lismore soil types (from Moot *et al.,* 2008).

Further, WUE of lucerne was reported by Paul (1991). He stated that the WUE of monoculture of lucerne was 14.1 kg DM/ha/mm of water used compared with WUE of lucerne/prairie and lucerne/phalaris (≤12.3 kg DM/ha/mm) when grown on a dryland Templeton soil at Lincoln University New Zealand from 20/3/91 to 7/4/91. Brown *et al.* (2003) also reported WUE of lucerne, chicory and red clover on Wakanui soil at Lincoln

University from 13/10/97 to 29/5/98. They found that all three species gave the similar WUE ~46 kg DM/ha/mm. For grass based pastures, Mills (2007) stated that WUE of pastures is affected by nitrogen content in the soil. She found that WUE of dryland and nitrogen fertilized (D+N) cocksfoot pasture ranged from a maximum of 81.2 kg DM/ha/mm (24/6/04) to a minimum 12.8 kg DM/ha/mm (16/3/05). In contrast, the WUE of dryland and non applied (D-N) cocksfoot pasture ranged from 30.6 to 6.9 kg DM/ha/mm. Moreover, McBeth (2004) reported that a combination pasture between ryegrass and Caucasian and white clovers could enhance WUE. She found that WUE of grass/clover (30 kg DM/ha/mm) was higher than pure clover (10 kg DM/ha/mm), but WUE between two clovers were not different (~18 kg DM/ha/mm) on Wakanui soil at Lincoln University, Canterbury, New Zealand from March to September 2004. This is because ryegrass pastures produced 2400 kg DM/ha more than pure clover pastures during the period. The differences in WUE of the pastures were related to differences in N content with the grass/clover pastures having a higher N content than pure grass swards (Moot *et al.*, 2008).

2.3 Soil moisture measurements

Accurate soil water measurement is an important part of assessing water use and water use efficiency. In this experiment the soil moisture content will be measured by neutron probe, time domain reflectometry (TDR) and Hydrosense. A neutron moisture meter (neutron probe) is one of the more accurate devices available for measuring the amount of moisture in the soil. The neutron moisture meter consists of two main components, a probe and a gauge. The probe contains a source of fast neutrons, and the gauge records the number of slow neutrons returned from the soil (Ghildyal and Tripathi, 1987). In using the neutron meter, a cased hole in the ground is necessary for lowering the probe to obtain readings. Neutron moisture meter measurements are correlated to soil types. The neutron moisture meter measures the total water content of a soil at a range of depths. Only a part of the water in a soil is available for plant use. The amount of water depleted from a soil (soil water deficit) is determined by subtracting the corrected neutron meter measurement from the total water-holding capacity of the soil (Karray *et al.,* 2008).

To measure the top 20 cm of soil time domain reflectometer (TDR) is used rather than a neutron probe**.** The TDR has the ability to accurately determine the permittivity (dielectric constant rate between two rods) of a material from wave propagation. Moreover, there is a strong relationship between the permittivity of a material and its water content. This means TDR has high performance to determine soil water content. TDR probes are usually between 10 and 30 cm in length and connected to the TDR via a coaxial cable (Topp *et al*., 1980).

Hydrosense also used to measure the top 20 cm soil moisture content. The Hydrosense is another simple form of TDR. It has two rods which are put into the soil. The microprocessor-controlled circuitry and two-line readout are contained in a splashproof enclosure that includes two integral membrane buttons used to operate the system. The parallel rods constitute a driven transmission line which is sensitive to dielectric permittivity and consequently water content (Topp *et al*., 1980).

2.4 Soil type

The water use availability also depends on soil type. This experiment will be done on a Templeton soil. Templeton soils have about 0.8-1.5 m of fine silt loam textured material overlying alluvial gravel. Silt loams are composed mostly of silt-sized particles with small amounts of sand and clay. The stony underlayer contains stones, gravel (Kohnke and Bertrand, 1959) and large sand particles or, irregularly shaped pieces of rock. In a sandy soil, there are large air spaces between the sand particles which allow water to drain very quickly (Kohnke and Bertrand, 1959).

2.5 How water, nitrogen and temperature affect plants

Cocksfoot growth with no CO_2 limitation is restricted by temperature, water (Radcliffe and Baars, 1987) and nitrogen status (Peri *et al.,* 2001). These factors influence seasonal production by limiting physiological processes (Peri *et al.,* 2002). The optimum temperature for photosynthesis is 20-22 ºC (Eagles, 1967) and a leaf water potential of -10.0 bar causes a reduction in cocksfoot growth (Jackson, 1974). Duru *et al.* (1997) reported that an herbage N value of 4.8% was an optimum herbage N for grasses for maximum growth. The N status also enhances the photosynthetic rate of individual leaves (Thornley, 1998). Peri *et al.* (2002) reported a maximum photosynthetic rate of cocksfoot at temperatures of 19-23 ºC and low temperatures caused a reduction in enzyme activities in chloroplasts rather than limitations on leaf gas exchange. Low temperatures consequently also reduces WUE. Peri *et al.* (2002) also reported that 5.2% to 5.9% and -0.1 to-1.2 bar were the optimum herbage N and optimum leaf water potential for maximum photosynthesis. Nitrogen deficiency reduced the photosynthetic potential of the leaf by decreasing protein content and activity (Evans, 1996). Peri *et al.* (2002b) stated that leaf nitrogen content which was between 3.3% and 3.8% was required to give at least 80% of the maximum potential photosynthetic capacity in cocksfoot. Once values fell below 2.6% the rate of photosynthesis was severely compromised. Water stress reduced photosynthesis by causing stomatal closure and a reduction in enzyme activity (Jackson, 1974).

2.6 'Max Clover' experiment in previous studies

This study builds on research in the 'MaxClover' Grazing Experiment at Lincoln University. This section summarises results of the experiment to date.

Mills *et al.* (2008a) reported that the total dry matter yields of six dryland pastures over five years were between 8.0 t/ha/y from CF/Cc (cocksfoot/Caucasian clover) pastures in 2005/06) and 18.5 t/ha/y from lucerne in 2004/05 (Figure 2.6). Lucerne produced higher ($P<0.001$) dry matter yield than the highest yield of grass based pastures in years 1, 2, 3 and 5 which were 13.1-18.5 t/ha/y. Surprisingly, CF/Sub (cocksfoot/subterranean clover) produced 16% more ($P<0.001$) DM than lucerne in 2005/06, but this was associated with a spring snow storm that flattened the lucerne crop. In all years, CF/Sub produced greater than or similar to CF/Wc (cocksfoot/white clover) and RG/Wc (ryegrass/white clover).

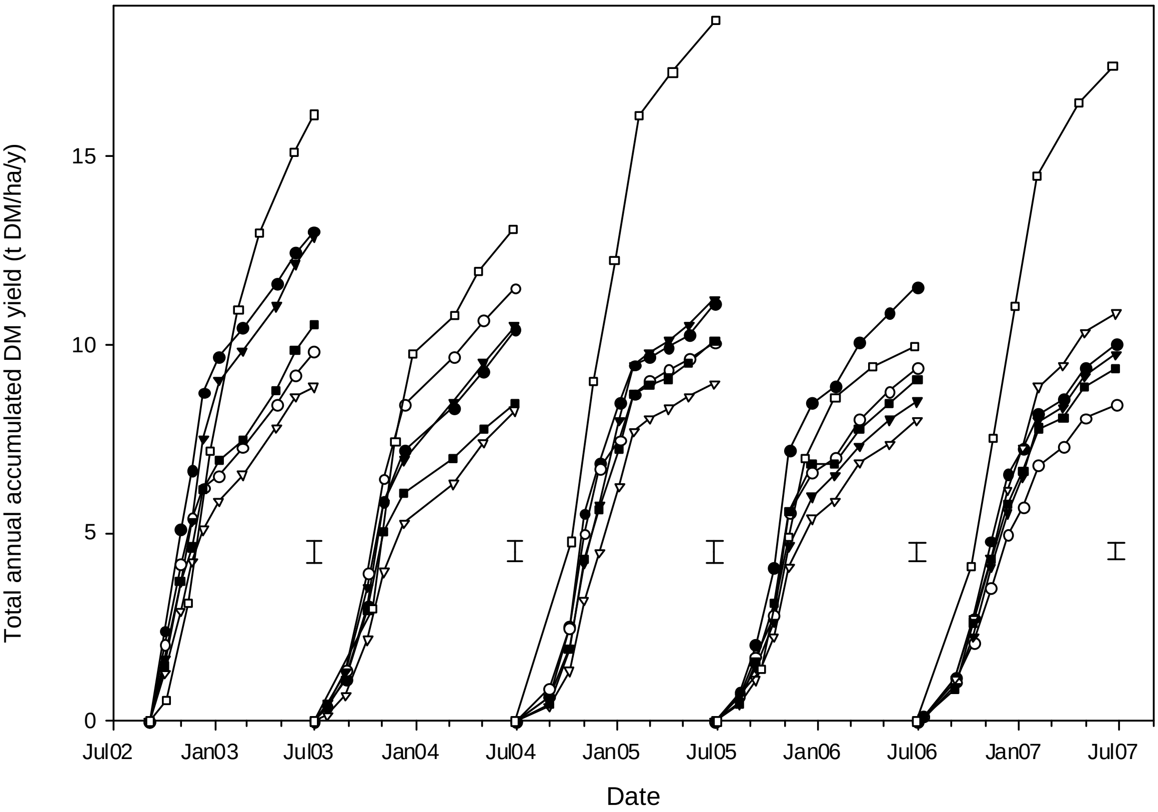

Figure 2.6 Total accumulated dry matter production of CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/WC (■) and lucerne (□) pastures of five growth seasons (2002-2007). Errors bar are SEM for total annual yields for each growth season (from Mills *et al.,* 2008a). Full details of the acronyms are given in Table 3.1.

Over 5 years, the mean daily growth rates of six dryland pastures ranged from no growth in RG/Wc pastures on 31/1/06 to a maximum of 111 kg DM/ha/d by CF/Wc in the first year. CF/Sub had the highest mean monthly growth rate in all grass based pastures from Years 2-5 (95-107 kg DM/ha/d). Moreover, pastures established with perennial legumes (CF/Wc, CF/Cc and RG/Wc) had higher growth rates than pastures established with annual legumes (CF/Sub and CF/Bal) in the summers of 2004/05 and 2006/07.

Further, Mills *et al.* (2008a) used thermal time to account for the seasonal response of the pasture growth using a base temperature of 3.0 ºC. They reported that CF/Sub grew at 8.3 kg DM/ha/ ºCd in spring which was higher ($P<0.05$) than the CF/Wc, CF/Cc and RG/Wc (≤6.5 kg DM/ha/ ºCd).

For the botanical composition of these six dryland pastures, the contribution of sown grass to total dry matter production declined. This was most apparent in RG/Wc where the sown grass yield decreased from 7.4 t DM/ha/y in year one to ≤4.7 t DM/ha/y in Years 3-5. For legume production, lucerne had the highest legume yield (9.5–17.3 t DM/ha/y). In grass based pastures, the clover content ranged from 4% (CF/Cc) to 40% (RG/Wc) over 5 years. In RG/Wc pastures weed content increased from 4% (Year 1) to 24% by Year 5.

Sheep liveweight gain was also reported from the six dryland pastures from 2003 to 2008 (Mills *et al.,* 2008b). Mills *et al.* (2008b) found that lucerne produced the highest liveweight in three years (2003/04, 2004/05 and 2006/07) and it was 33-42% higher than all grass based pastures. The superior animal production from lucerne occurred in most years, and reflected changes in summer. For example, the lambs grazing lucerne averaged 160 g/hd/d compared with only 65 g/hd/d for RG/Wc and 90 g/hd/d for cocksfoot based pastures over the summer. As a result, over the five years reported, the lucerne yielded 45-200 kg/ha more liveweight production annually compared with grass based pastures. Year to year variation generally reflected differences in DM production (Mills et al., 2008a) due to year-to year variation in environmental conditions.

Within this experiment the water use and nitrogen content of pastures has not been examined and these will form the basis of the current study.

3 Materials and Methods

3.1 Experimental site

The experiment was located at Lincoln University Canterbury, New Zealand (43º38'S, 172º28'E) on a Templeton silt loam soil which has 0.8-1.5 m of silt loam overlying alluvial gravel (Raeside and Rennie, 1974). Silt loam soils are productive and require minimum attention in terms of cultivation (Raeside and Rennie, 1974). This dryland grazing experiment was a randomised complete block design divided into 36 plots (6 treatments x 6 replicates). Four replicates were sown in February 2002 and two more were sown through autumn 2003. It was established with two perennial clovers (Caucasian and white) and two annual clovers (subterranean and balansa) sown with cocksfoot (CF). These four cocksfoot treatments are compared with a traditional ryegrass/white clover control and lucerne (Table 3.1). Each plot is 506 m^2 or 0.05 ha. The additional replicates increased the total area sown in each treatment to 0.3 ha. For this research, results from only the original four reps will be reported (Appendix 1) as neutron probe tubes had been installed for soil moisture monitoring in these replicates previously.

Table 3.1 Cultivar and seed sowing rate of six dryland pastures established in 2002 for the "MaxClover" Grazing Experiment at Lincoln University, Canterbury, New Zealand.

Species sown	Common name	Cultivar	Acronym	Sowing rate (kg/ha)
Trifolium michelianum	Balansa clover	'Bolta'	Bal	3.5
Trifolium ambiguum	Caucasian clover	'Endura'	Cc	5.9
Trifolium subteraneum	Subterranean clover	'Denmark'	Sub	10
Trifolium repens	White clover	'Demand'	Wc	3
Dactylis glomerata	Cocksfoot	'Vision'	CF	4
Lolium perenne	Ryegrass	'Aries AR1'	RG	10
Medicago sativa	Lucerne	'Kaituna'	Luc	5.7

3.2 Grazing management

The experiment is ongoing, and this study examined the period from 1/7/08 to 30/6/09.

Each pasture treatment is managed according to best current practice. This means grass treatments may be set-stocked or rotationally grazed while lucerne is strictly rotationally grazed (Moot *et al.*, 2003). The gazing management used for each pasture for the experimental period is given in Table 3.2. The clover treatments are grazed frequently in spring on 8 to 13 day rotations using either 2 or 3 paddock rotations to simulate set-stocking. Rotations were longer (16-21 days) in summer and autumn on the grass/clover plots. Grass plots in particular were grazed on a 6 plot, 21 day rotation in February/March to enhance cocksfoot carbohydrate storage. Lucerne is managed in a similar way to cocksfoot in late summer/early autumn except that the spelling time can be longer as there is no grass in the mixture. If the cocksfoot is spelled too long in autumn the grass nutritive value deteriorates to a point that lambs are reluctant to eat it. When pastures become dry in summer and have low grazing preference, dry ewes are used to graze the pastures prior to autumn rain.

Generally, all six treatments have a ‘clean up’ grazing at some stage from May to June and sheep are then removed from the experiment for at least 6 weeks. This is the period that ewes would normally be fed with winter crops such as turnips on a Canterbury dryland farm. Stocking rates may be 6 to 8 ewe hoggets per 0.3 ha farmlet initially but this is increased in mid-late September. Each grass based pasture started with hogget grazing in August and September followed by lamb grazing once they became available post-weaning. The six plot lucerne spring grazing rotation started on 8 September 2008 with 33 to 45 day grazing intervals.

Table 3.2 shows destocking of hoggets occurred in early October before lambs were introduced. Lambs 1 were the first group of lambs, and when they grew enough they were sent for slaughter. Lambs 2 were the second group of younger lambs which came in March 2009.

There has been weed control in lucerne plots. Spraying has occurred every second winter with a mixture of Gramoxone 250 and Atrazine 500 at 1.6 l/ha and 800 ml/ha. Gramoxone 250 contains 250g/litre of paraquat dichloride salt in the form of soluble concentrate, and

Atrazine 500 contains 510 g/litre atrazine in the form of a suspension concentrate. For the 2008/09 season only plot 12 was sprayed (14/07/2008).

Table 3.2 Grazing management of six dryland pasture treatments in the 'MaxClover" experiment at Lincoln University, Canterbury, New Zealand for 2008/09. Full details of the acronyms are given in Table 3.1.

Treatment	Graze period	Stock class	Date on	Date off	Grazing duration (days)
CF/Wc	1	Hoggets	22/8/2008	8/10/2008	47
CF/Wc	2	Lambs 1	21/10/2008	1/12/2008	41
CF/Wc	3	Lambs 1	23/12/2008	10/2/2009	49
CF/Wc	4	Lambs 2	3/3/2009	5/4/2009	33
CF/Wc	5	Lambs 2	21/4/2009	12/5/2009	21
CF/Cc	1	Hoggets	22/8/2008	8/10/2008	47
CF/Cc	2	Lambs 1	21/10/2008	1/12/2008	41
CF/Cc	3	Lambs 1	23/12/2008	10/2/2009	49
CF/Cc	4	Lambs 2	3/3/2009	5/4/2009	33
CF/Cc	5	Lambs 2	21/4/2009	12/5/2009	21
CF/Sub	1	Hoggets	22/8/2008	8/10/2008	47
CF/Sub	2	Lambs 1	21/10/2008	1/12/2008	41
CF/Sub	3	Lambs 1	23/12/2008	10/2/2009	49
CF/Sub	4	Lambs 2	3/3/2009	5/4/2009	33
CF/Sub	5	Lambs 2	15/4/2009	7/5/2009	22
CF/Bal	1	Hoggets	22/8/2008	8/10/2008	47
CF/Bal	2	Lambs 1	21/10/2008	1/12/2008	41
CF/Bal	3	Lambs 1	23/12/2008	10/2/2009	49
CF/Bal	4	Lambs 2	3/3/2009	5/4/2009	33
CF/Bal	5	Lambs 2	21/4/2009	12/5/2009	21
RG/Wc	1	Hoggets	22/8/2008	8/10/2008	47
RG/Wc	2	Lambs 1	21/10/2008	1/12/2008	41
RG/Wc	3	Lambs 1	23/12/2008	10/2/2009	49
RG/Wc	4	Lambs 2	3/3/2009	5/4/2009	33
RG/Wc	5	Lambs 2	21/4/2009	12/5/2009	21
Lucerne	1	Hoggets	8/9/2008	12/10/2008	34
Lucerne	2	Lambs 1	21/10/2008	21/12/2008	61
Lucerne	3	Lambs 1	31/12/2008	29/1/2009	29
Lucerne	4	Lambs 2	3/3/2009	3/4/2009	31
Lucerne	5	Lambs 2	18/5/2009	8/6/2009	21

3.3 Measurements

3.3.1 Pasture dry matter yield

Pasture dry matter (DM) yields were measured from 0.2 m^2 quadrats cut from 1140 x 760 mm exclosure cages in each grass pasture plot. These were shifted to a new site after each harvest approximately once a month. The herbage, cut to a height of ~30 mm, was then sorted into sown grass, sown legume, other grass, other legume, weeds and dead matter before drying at 65 ºC for at least 48 hours to constant weight. Sown clover and grass samples were then ground to a fine powder using a Cyclotec Sample Mill to pass through a 1 mm sieve. These were tested using near infrared spectroscopy (NIRs) for nitrogen content by the Lincoln University Analytical Laboratory. When sample sizes were small, due to low pasture growth rates, herbage samples of the same species from different replicates were combined to enable nitrogen measurements. From these nitrogen results, and the dry matter yield of the sample (kg/ha), the total nitrogen yield for the clovers and sown grass were calculated. The N% of the sown species (grass+clover) was calculated as a weighted mean (Equation 2) to accounted for differences in the proportions of sown components, present at a given harvest.

Equation 2: $(N\%_{Clover} \times Clover_{frct}) + (N\%_{Grass} \times Grass_{frct})$

Where $N\%_{Clover}$ is the N concentration in sown legume herbage, $N\%_{Grass}$ is the N concentration of the sown grass; $Clover_{frct}$ and $Grass_{frct}$ are the proportions of sown grass and sown clover present which sum to 1.0.

The monthly dry matter yields were accumulated to give annual dry matter yields (kg/ha/y). The yields were measured separately for each replicate and then averaged. Further, daily growth rates (kg/ha/day) were calculated by dividing the accumulated dry matter yields by the number of days between the cage cuts. Lucerne samples were measured from 5 x 0.2 m^2 quadrats per plot prior to grazing and grazing days were recorded. Lucerne samples were treated by the same method as grass samples to get the botanical composition and nitrogen results.

3.3.2 Environmental conditions

During the experimental period recorded annual rainfall was 767 mm which was 23% above the long-term mean (LTM) (Table 3.3). Specifically rainfall in July 2008 was 145 mm or more than double the long-term mean of 64 mm and in May 2009 rainfall was 171 mm compared with the LTM monthly rainfall of 50 mm. In contrast, the lower than average rainfall of 22 mm in October and 11 mm in November meant most plots had to be destocked for approximately 3 weeks from 1/12/08 (Table 3.2). Mean annual soil temperature (0.1 m) was 11% higher than the LTM (Table 3.3).

Table 3.3 Monthly rainfall (mm) and 0.1 m soil temperature (°C) recorded at the Broadfields Meteorological Station located 2 km north of the experimental site. Long-term monthly means (LTM) are for the period 1975-2002.

	Rainfall (mm)		Soil temperature (°C)	
Month	LTM	Actual	LTM	Actual
Jul ‘08	64	145	4.0	5.8
Aug	62	94	5.4	6.1
Sep	43	39	8.1	9.8
Oct	51	22	11.2	12.3
Nov	52	11	14.0	16.6
Dec	50	77	16.5	18.0
Jan ‘09	51	46	17.6	20.9
Feb	41	59	17.1	17.4
Mar	50	36	14.9	15.1
Apr	46	53	11.1	12.2
May	50	171	7.4	7.2
Jun	64	14	4.7	5.4
Annual	624	767	11.0	12.2

The period of pasture and environmental measurements was from 1 July 2008 to 30 June 2009. The annual period of the experiment was divided seasonally into three periods; spring, summer and autumn/winter. The spring period was defined as the period when pastures were non water limited and there was stock on plots. For grass based pastures this spring period was from 1/7/08 until they were destocked on 1/12/08. For analysis of pasture growth the last measurement date of cage cuts was used (10/11/08) prior to destocking. For lucerne the spring dates were from 1/7/08 until 10/12/08. The accumulated dry matter of grass based pastures in the summer period was from 11/11/08 to 2/3/09 and from 11/12/08 to 23/3/09 for lucerne. The summer period included the period of destocking in December, slow growth in January and destocking in February. For the autumn/winter period, plots were restocked but growth was slow. All grass based pastures were restocked on 3/3/09 and measured until 30/6/09. For lucerne, restocking occurred on 24/3/09 and measurements ceased on 30/6/09.

3.3.3 Soil moisture content

Soil moisture content was measured by Hydrosense from 13/8/08 to 24/10/08 to a depth of 0.2 m and changed to time domain reflectometry (TDR) from 30/10/08 to 30/6/09, because the ground was dried out, so it was difficult to put the hydrosense rods into the ground. A neutron probe (Troxler 4301) was used from 0.2 to 2.25 m (Section 2.2). From the period 13/8/08 to 30/6/09 measurements were taken weekly in spring, summer and autumn and fortnightly in winter. From these measurements temporal and spatial changes in the volumetric soil moisture content were observed for each plot and at each depth over time. For example, Figure 3.1 shows the changes in soil moisture content of a cocksfoot/sub clover pasture over the season. At the first measurement the top 0.2 m of soil had 34% soil moisture. The rainfall data for June and July (Table 3.3) suggest the profile was at or near field capacity at this time. This declined to <10% by the beginning of December when no growth occurred and plots were destocked (Table 3.2). Sporadic summer and autumn rainfall (Table3.3) then increased the soil moisture content and enabled some pasture growth. Rainfall recharged the top soil back to over 30% by the end of May.

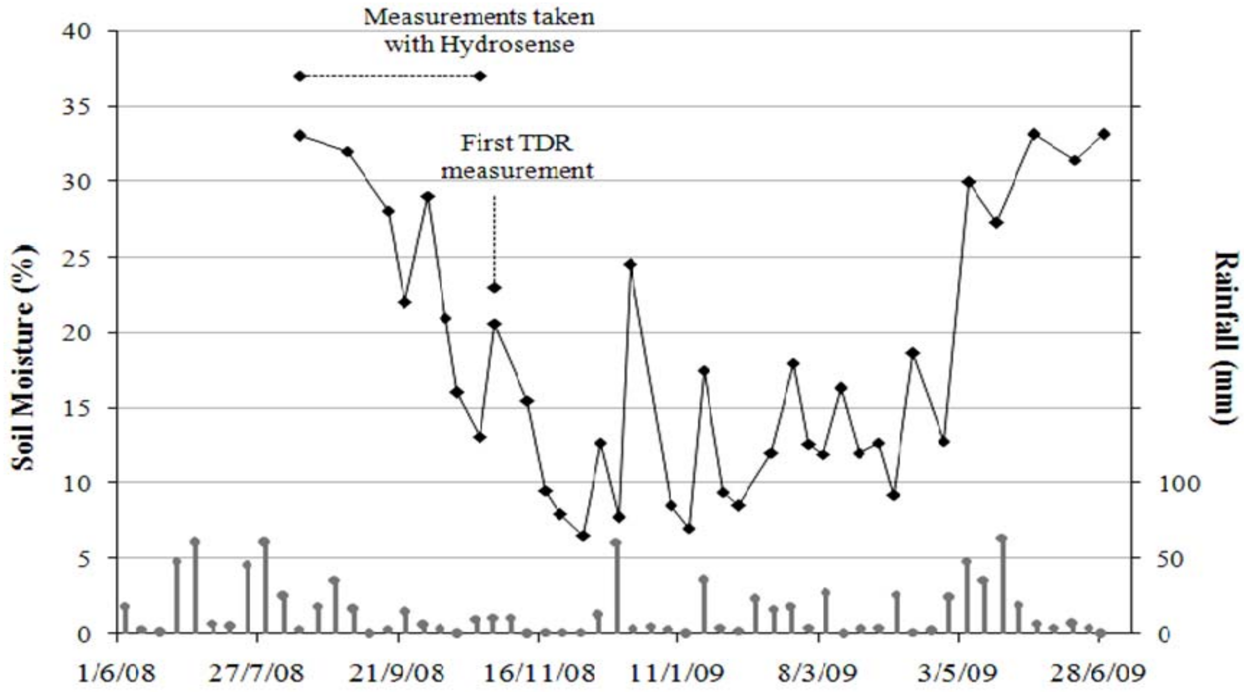

Figure 3.1 The percentages of the soil moisture in the 0-0.2 m profile of cocksfoot/sub clover in Plot 5 from 13/8/08 to 30/6/09 at Lincoln University Canterbury, New Zealand and accumulated weekly rainfall recorded (gray bars) from Broadfields Meteorological Station between 1/6/08 and 30/6/09.

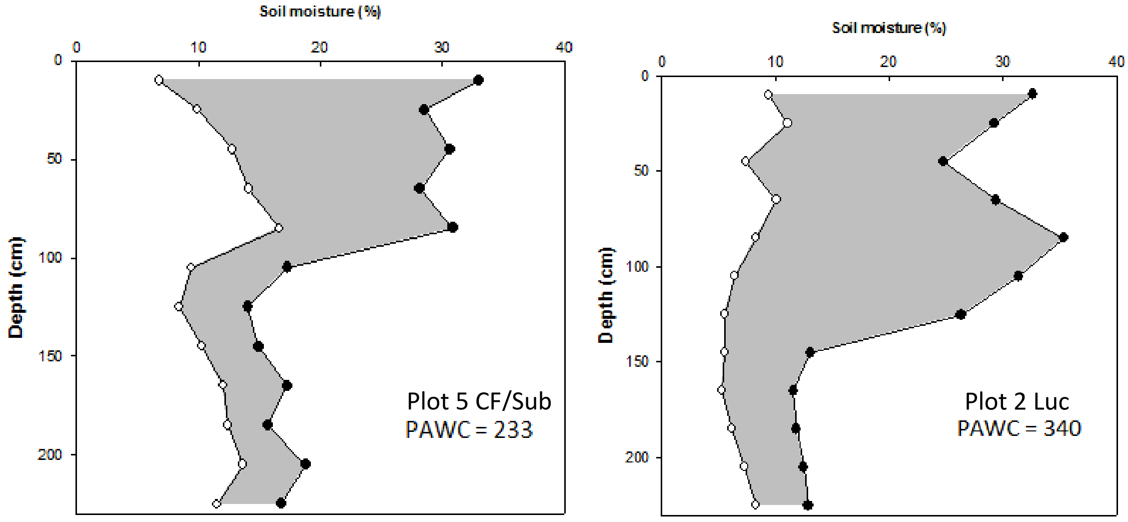

Figure 3.2 Water extraction (mm) from 0-2.3 m depth for cockfoot/sub clover (Plot 5 CF/Sub) and lucerne (Plot 2 Luc) pasture on Templeton silt loam at Lincoln University, Canterbury, New Zealand from 1/7/08 to 30/06/09. ● is drained upper limit (DUL) and ○ is the lower limit (LL). PAWC = total plant available water for the profile.

Similar measurements of soil moisture were undertaken for each plot and showed considerable spatial variation across the plots and with depth. To account for this the water holding capacity of each plot was determined. This enabled the actual water used from each plot to be calculated and related to pasture growth. To do this the drained upper limit (DUL) and lower limit (LL) of the soil in each plot for the depth of the profile was determined. For this study the DUL of each soil layer for each plot was calculated as the mean of the second and the third highest soil moisture readings for the plot from the 10 month measurement period. This conservative approach aims to avoid abnormally high readings that may occur before full drainage after heavy rainfall events. In most cases the DUL occurred in autumn 2009. Conversely, the lower limit was taken as the lowest recorded value for soil moisture, which was in mid-summer (January). Values for DUL and LL for Plot 5 at each depth are shown in Figure 3.2. Values for all other plots are given in Appendix 2.

3.4 Analysis

All statistical analyses were performed using Genstat (Version 11, VSN International Ltd, 2008). Least squares linear regression and analysis of variance with means separation based on least significant differences were used. No transformations were required of any variable.

3.4.1 Plant available water

The plant available water (mm/200mm depth) was calculated as the difference of the mean DUL and LL multiplied by the profile depth. For example, for Plot 5 (Figure 3.2), the calculation of the plant available water was 223 mm (gravels at ~1.0 m). In contrast, for a nearby lucerne crop in Plot 2 of Rep 1 the plant available water was 340 mm due to gravel being at 1.5 m depth. In this case, the plant available water between the two plots was different due to soil properties. In the top 0.2 m the top soil had a drained upper limit of over 30% and lower limits around 8% for all plots (Appendix 2). Below depths of ~1.0 m the drained upper limit was between 10 and 15% suggesting the presence of stones and sand and a lot less silt (Raeside and Rennie, 1974). The consequence is lower plant available water in each layer. The total plant available water for each individual plot is given in Table 3.4. The observed variability is common in such soils and is one of the reasons the actual water use was determined for individual plots. Analysis of variance showed no significant differences in plant available water among treatments or replicates (P<0.85). Figure 3.3 represents an example of the total soil water content in the full profile of the cocksfoot/sub clover (Plot 5) from 13/8/08 to 30/6/09. The change in soil moisture increased when rain fell and decreased due to plant root water extraction and drainage. Martin (1984) compared plant available water content and the soil moisture content and reported that plant available water accounted for about 50% of the maximum soil moisture stored in the profile at ~0-1.0 m soil depths.

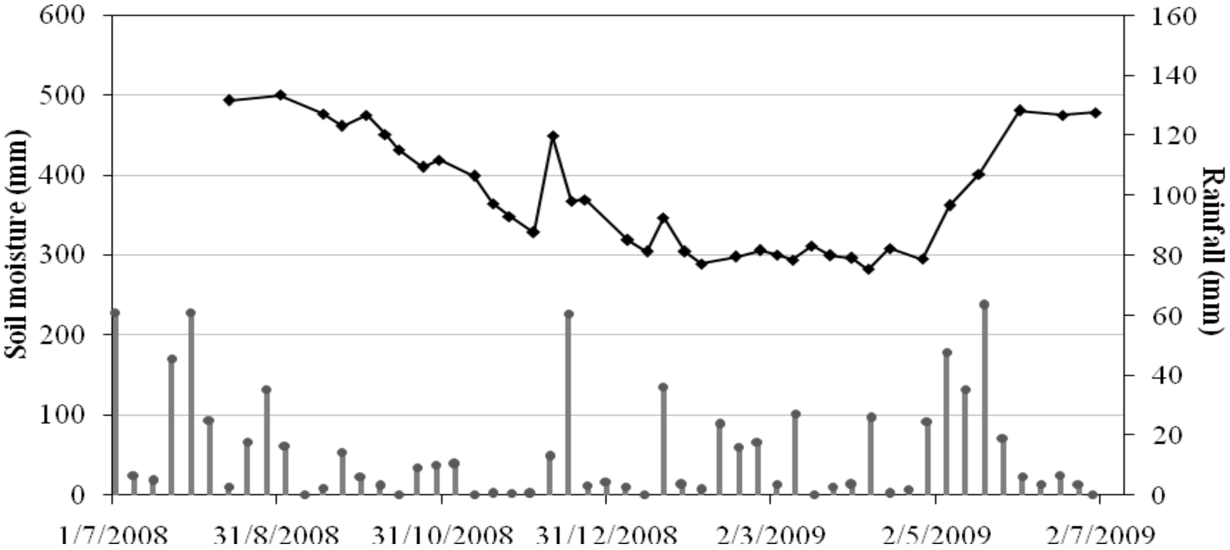

Figure 3.3 The soil water content (mm) in the full profile of CF/Sub pasture and accumulated weekly rainfall recorded in Plot 5 from 13/8/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand. The accumulated weekly rainfall (gray bars) was recorded from Broadfields Meteorological Station between 1/7/08 and 30/6/09.

Table 3.4 The annual plant water available (mm) of individual plots from 1/7/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1.

Treatment	Rep 1	Rep 2	Rep 3	Rep 4	Mean	SEM
CF/Bal	271	250	217	359	274	19.8
CF/Cc	220	263	203	439	281	
CF/Sub	245	242	268	347	275	
CF/Wc	306	264	227	417	304	
RG/Wc	278	202	207	384	268	
Lucerne	349	244	207	314	279	

The actual water use (WU) for each pasture was calculated using Equation 3.

Equation 3 $WU = P - \Delta SWC - D$

Where P is precipitation from rainfall measured at the Broadfields Meteorological Station (Table 3.3), ΔSWC is the change in soil water content (SWC) between successive soil moisture measurements and D is drainage. Drainage occurs when precipitation causes the SWC to exceed the DUL of the profile. A WU factor was calculated as the ratio between actual water use and Penman potential evapotranspiration. This factor was applied to daily PET to estimate daily water use between successive measurements.

The soil moisture values from each measuring date were used to calculate the actual plant water use of each pasture for each harvest date. The soil moisture measurements began on 13/8/08, but the pasture growth measurements started on 1/7/08. The water use prior to the first measurement was calculated from the accumulated PET value from the Broadfield website for 1/7/08 to 12/8/08 and was 41.6 mm. After that, the water use was calculated from successive soil moisture measurements. The water use of each plot was analysed in one-way ANOVA in Genstat. Table 3.5 shows the calculated annual accumulated water use of these six dryland pastures for each individual plot. The water use was similar ($P<0.82$) across treatments (668±24). The difference between the highest plant water use (695 mm) and the annual rainfall record (767 mm) suggests that there was approximately 100 mm of water lost from the system due to drainage and soil evaporation.

The annual water use efficiency (kg DM/ha/mm) of each pasture was calculated by using the final accumulated dry matter yield divided by the final accumulated water use for the period of interest. Seasonal WUE of each pasture was calculated by using regression analysis of dry matter accumulation against accumulated water use. These regressions were forced through the origin only in spring because accumulated DM was used thus, in summer and autumn/winter neither DM yield or water use were zero.

Table 3.5 The annual accumulated water use (mm) of six dryland pastures in individual plots from 1/7/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand. Full details of the treatment acronyms are given in Table 3.1.

Treatment	Rep 1	Rep 2	Rep 3	Rep 4	Mean	SEM
CF/Wc	663	623	622	715	656	24
CF/Cc	574	632	625	817	662	
CF/Sub	548	659	569	848	656	
CF/Bal	554	667	632	870	681	
RG/Wc	582	641	660	754	659	
Lucerne	640	684	695	759	695	

3.4.2 Thermal time

To examine the relationship between pasture yield and temperature (Mills *et al.,* 2006), daily thermal time values were calculated using temperature data from the Broadfields meteorological station. In its simplest form thermal time requires a daily maximum (Tmax) and minimum (Tmin) temperature (Equation 4) and a defined base temperature (t_b)

Equation 4 $$\text{Tt (°Cd)} = \frac{T\max + T\min}{2} - t_b$$

When daily minimum temperatures fall below t_b then a sinusoidal function is used to fit 8x3 hourly fractions of a day that exclude the periods when Tmin <Tbase (Jones and Kiniry, 1986). To explain the seasonal variation in pasture growth rates, the effect of temperature was determined using thermal time. Thus, the first step in these analyses was the calculation of t_b. This was determined by fitting linear regressions between accumulated yield and accumulated thermal time (using air temperature) with a range of base temperatures (0 to 8 ºC).. In most cases the highest coefficient of determination (R^2) was attained using t_b=0. Appendix 3 shows an example of the resulting coefficient of determination (R^2) against base temperature. The R^2 for the cocksfoot/white clover pasture declined as t_b was increased. For all analysis of thermal time including for lucerne, the base temperature was 0 ºC compared with the previously reported 3 ºC for pastures (Mills

et al., 2006) and 5 ºC for lucerne (Teixeira *et al*., 2009). Regression analysis of dry matter accumulation against thermal time (not forced through the origin) showed the x-axis had a range of intercepts. To account for the fact that the growing points of pastures are below ground a second analysis using soil temperature at 0.1 m depth from Broadfields station was used. These gave similar values of t_b= 0 ºC but a narrower range of x-axis intercepts, so the soil temperatures were used to calculate the thermal time accumulation.

Plate 1. Views of plots in the experiments on 26 February 2009.

Plate 2. A cage for collecting pastures dry matter yield on 21 June 2009.

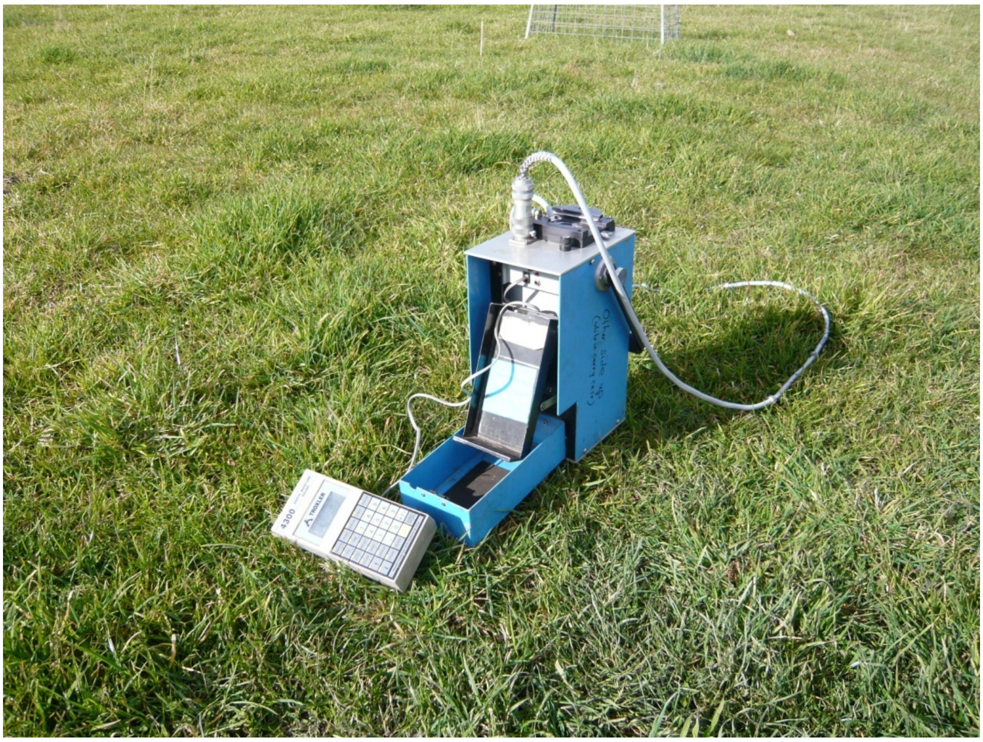

Plate 3. Neutron probe on 21 June 2009.

Plate 4. Time domain reflectometer (TDR) on 21 June 2009.

Plate 5. A combination of cocksfoot/sub clover pastures on 21 June 2009.

4 Results

4.1 Annual pasture dry matter yield

There were differences in the total annual dry matter yield among pastures (Figure 4.1). For the grass based pastures, CF/Sub had the highest (P<0.001) yield of 9390 kg DM/ha/y. The lowest yield was 5550 kg DM/ha/y for the CF/Wc compared with 6860 kg DM/ha/y in the CF/Bal. Overall, lucerne had the highest annual yield of 14260 kg DM/ha/y. The RG/Wc control yielded 6620 kg DM/ha/y.

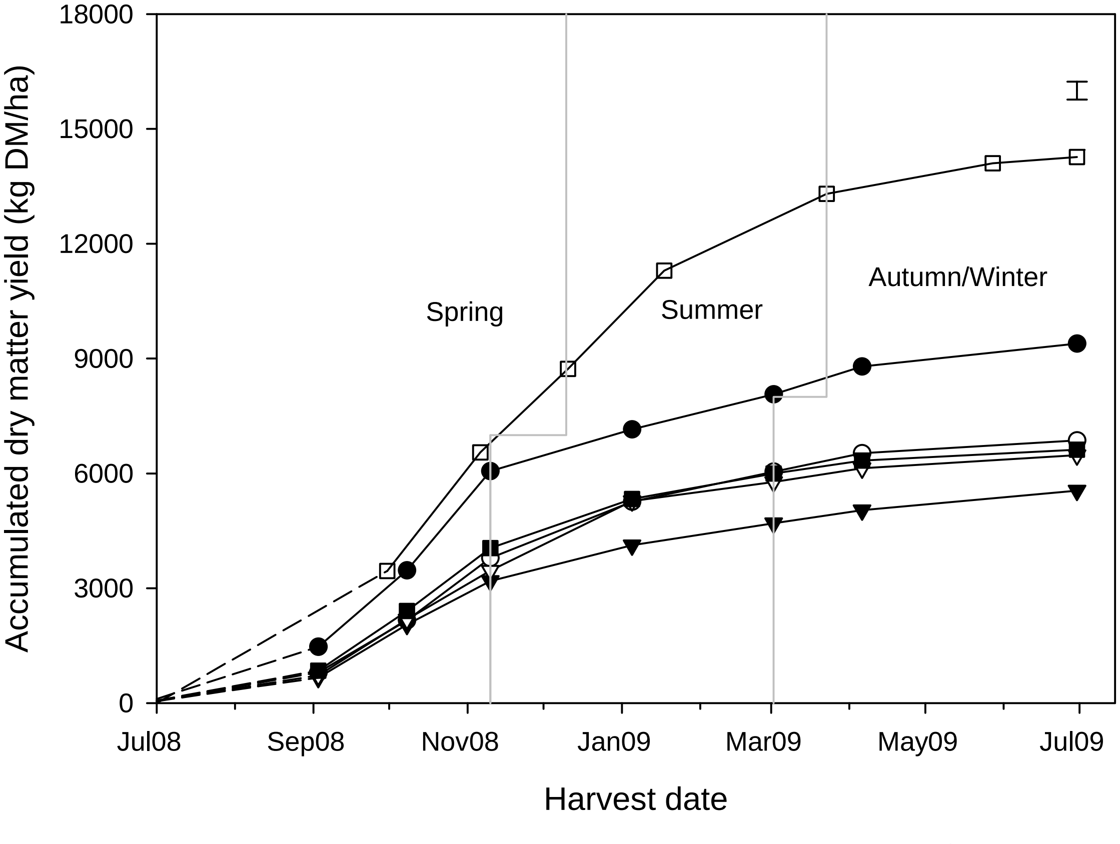

Figure 4.1 The total accumulated dry matter (DM) yield of CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and lucerne (□) pastures over the year from 1/7/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand. The error bar is SEM for final accumulated dry matter (on 30 June 09). Vertical gray lines separate the period of measurement into spring, summer, autumn/winter (Section 3.3.2) with a difference in the duration of each period between grass and lucerne pastures.

4.2 Mean daily growth rates

Mean daily growth also differed among pastures (Figure 4.2). For the initial spring period from 1/7/08 to 3/9/08, CF/Sub pastures grew at 21 kg DM/ha/d or almost double ($P<0.001$) the 11±1.4 kg DM/ha/d produced by all other grass based pastures. For October there was an indication ($P<0.1$) of a higher growth rate (57 kg DM/ha/d) for CF/Sub pastures compared with the other pastures. As spring progressed into November the CF/Sub pastures continued to show superior ($P<0.01$) production and grew at 74 kg DM/ha/d compared with 43±6.0 kg DM/ha/d for all other grass based pastures. Lucerne growth was comparable to the grasses in September and October. It increased to ~100 kg DM/ha/d in November and was 75 kg DM/ha/d in December and January. The duration of the spring phase, defined as when moisture was non-limiting (Section 3.3.2), occurred before a 50% reduction in daily growth rates of each pasture caused by drought stress.

Growth rates slowed in grass based pastures after the November harvest (10/11/08) and they were next harvested 56 d later (5/1/09). Over this period all grass based pastures averaged 24±6.5 kg DM/ha/d. In late summer/autumn (2/3/09) rain (Figure 3.1) alleviated soil water stress conditions and annual clover seedlings began to germinate. The cocksfoot pastures established with subterranean clover grew at 16 kg DM/ha/d compared ($P<0.05$) with 9 kg DM/ha/d for CF/Cc pastures, and at the same time lucerne grew approximately 43 kg DM/ha/d. By mid autumn (6/4/09) the CF/Sub pasture production of 21 kg DM/ha/d was double ($P<0.1$) the 10 kg DM/ha/d by perennial clover based pastures. The CF/Bal pasture was intermediate at 13.8 kg DM/ha/d. Early autumn production (24/3/09) by lucerne, was >30 kg DM/ha/d and this then decreased to ≤10 kg DM/ha/d until the final harvest on 30/6/09. For the autumn period (April to June 2009) the maximum growth rate of the grass based pastures was 7 kg DM/ha/d by the CF/Sub pastures which was higher ($P<0.05$) than the RG/Wc pastures which grew at 4 kg DM/ha/d.

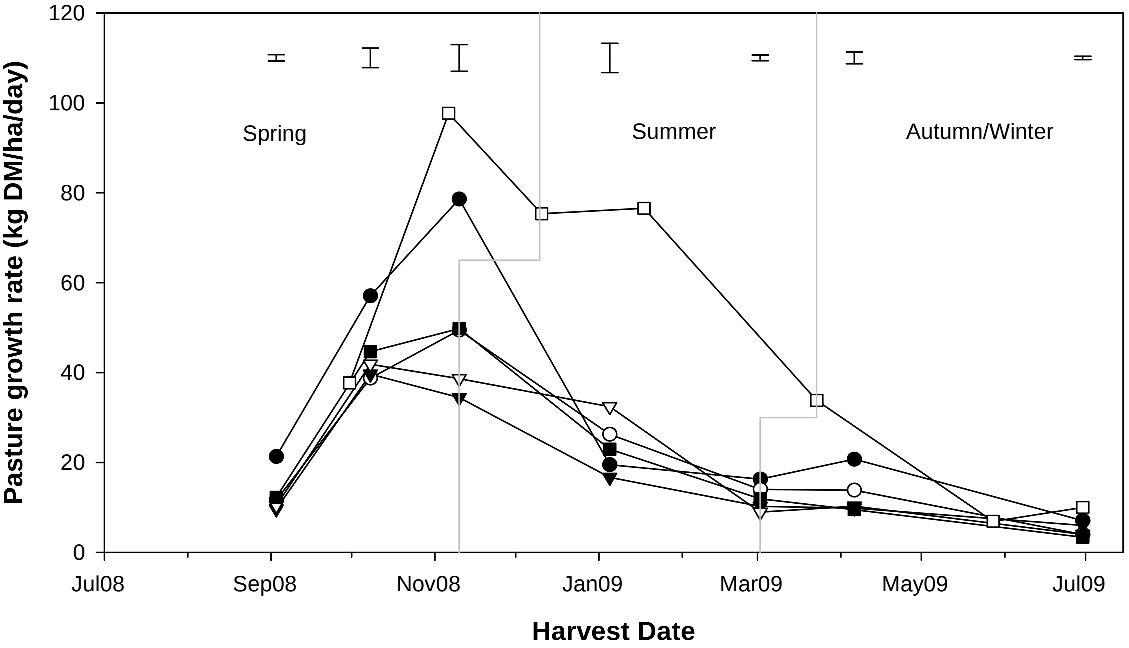

Figure 4.2 Mean daily growth rates of CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and lucerne (□) pastures at Lincoln University, Canterbury for regrowth cycles between 1/7/08 and 30/6/09. Lucerne mean daily growth rates are shown for reference but were excluded from the analysis because harvests were not made on the same day as those in grass based pastures. The mean daily growth rate of every pasture was calculated by dividing total dry matter yield by the number of days in the measurement period. Error bars are SEM for grass based pastures. Vertical gray lines separate the period of measurement into spring, summer, autumn/winter (Section 3.3.2) with a difference in the duration of each period between grass and lucerne pastures.

4.3 Thermal time

To remove the effect of temperature on dry matter production thermal time was calculated (Section 3.4.2). Figure 4.3 shows that the fitted regression equations of dry matter accumulation against thermal time gave an x-axis intercept of around 200 ºCd, which occurred on 3/8/2008. This value was different from ($P<0.05$) zero and suggests the pasture accumulation during winter (from 1 July 2008) was not linearly related to temperature.

4.3.1 Spring

The relationships between accumulated dry matter and thermal time were linear during late winter and early spring for all pastures and then the rate declined. For this initial non-water stressed spring period the growth rates among species were different. For the grass based pastures the CF/Sub had a spring growth rate of 5.9 kg DM/ºCd which was higher

($P \leq 0.001$) than other grass based pastures including RG/Wc at ≤4.1 kg DM/ha/°Cd. This higher rate for the CF/Sub led to a spring dry matter yield of 6100±270 kg DM/ha which was 50% higher ($P<0.001$) than for other pastures. Lucerne grew at 4.9 kg DM/°Cd and produced 8730 kg DM/ha in spring which was higher ($P<0.001$) than CF/Sub, because it grew at this rate for an extra 400 °Cd.

4.3.2 Summer

The growth rates of all pastures decreased in summer when water stress occurred. Lucerne had the highest ($P<0.001$) mean growth rate at 2.4 kg DM/ha/°Cd for 1854 °Cd and produced 4570±368 kg DM/ha over this period. For grass based pastures, the growth rates were similar and ranged from 0.7 kg DM/ha/°Cd for CF/Wc to 1.1 kg DM/ha/°Cd for CF/Cc pastures. These pastures produced less ($P<0.001$) dry matter than lucerne over the summer with yields between 1508 kg DM/ha for the CF/Wc and 2320 kg DM/ha for the CF/Cc, over the 2094 °Cd accumulated between 11/11/08 and 2/3/09.

4.3.3 Autumn/winter

The growth of most pastures in autumn/winter was also lower than in spring. However, there were differences in pasture growth rates among the six pastures. CF/Sub and lucerne had higher ($P<0.001$) growth rates at 1.1 kg DM/ha/°Cd than the other grass based pastures (≤0.72 kg DM/ha/°Cd). A higher ($P<0.01$) dry matter yield (1324 kg DM/ha) was measured for CF/Sub compared with all other pastures (748±106 kg/ha). Lucerne produced 962 kg DM/ha which was higher than RG/Wc (617 kg DM/ha), but similar to the other cocksfoot pastures (≤855 kg DM/ha). However, the yield accumulated during this period accounted for only ~10% of the total annual production from each pasture.

The regression equations, standard errors of the coefficients and the coefficients of determination of the regression of accumulated dry matter against thermal time in spring, summer and autumn/winter of six dryland pastures are given in Appendix 4.

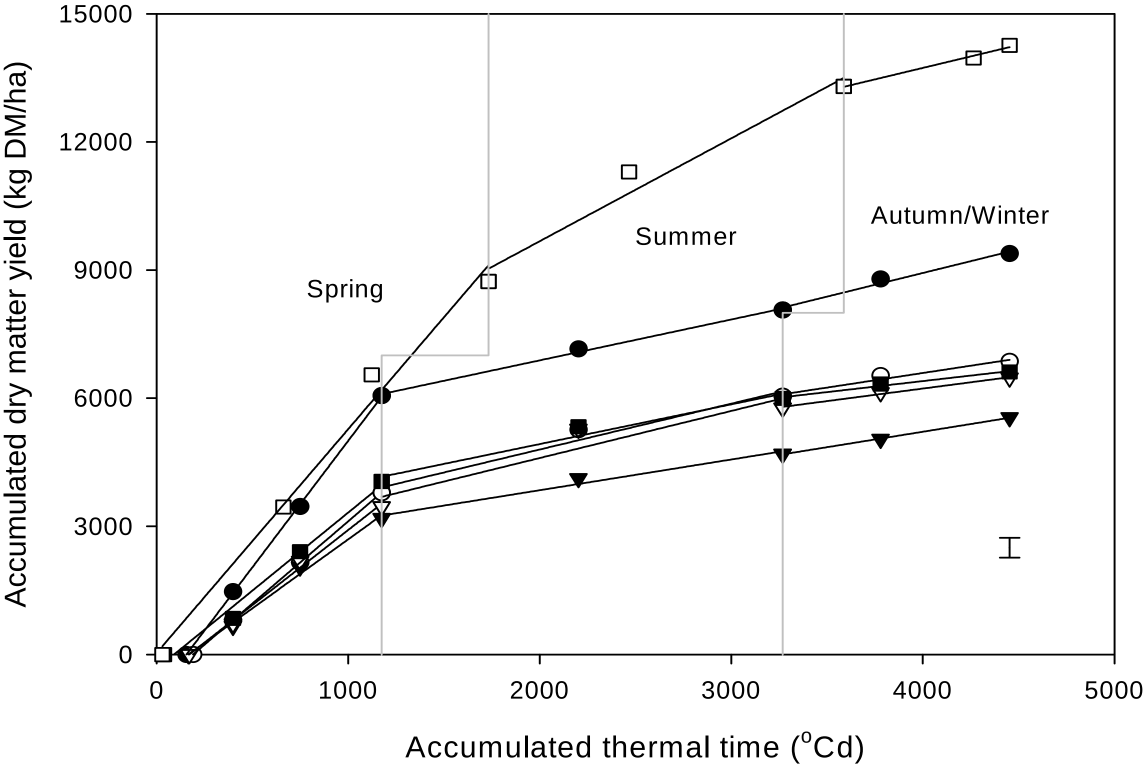

Figure 4.3 The total annual accumulated dry matter yields (kg/ha) of CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and lucerne (□) pastures against accumulated thermal time (Tt) calculated using 0.1 cm soil temperatures with a base temperature of 0 °C from 1/7/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand. The error bar is SEM for final accumulated dry matter (on 30 June 2009). Vertical gray lines separate the period of measurement into spring, summer, autumn/winter (Section 3.3.2) with a difference in the duration of each period between grass and lucerne pastures.

4.4 Water use efficiency (WUE)

From the annual accumulated dry matter yield (kg DM/ha) and annual plant water use (mm) the annual water use efficiency was calculated. Overall, lucerne had the highest annual WUE ($P<0.001$) of 20.6 kg DM/ha/mm of water used. Of the grasses, CF/Sub had an annual WUE of 14.7 kg DM/ha/mm of water used which was higher ($P<0.001$) than the other grass/clover combinations which ranged from 8.5 to 10.2 kg DM/ha/mm of water used. For all pastures the annual water used was calculated as 695 mm for lucerne and ≤681 mm for the grass based pastures (Figure 4.4). Table 4.1 shows these values and seasonal WUE of the six dryland pastures.

The regression equations, standard errors of the coefficients and coefficients of determination for regression of accumulated dry matter against accumulated water use in spring, summer and autumn/winter of six dryland pastures are given in Appendix 5.

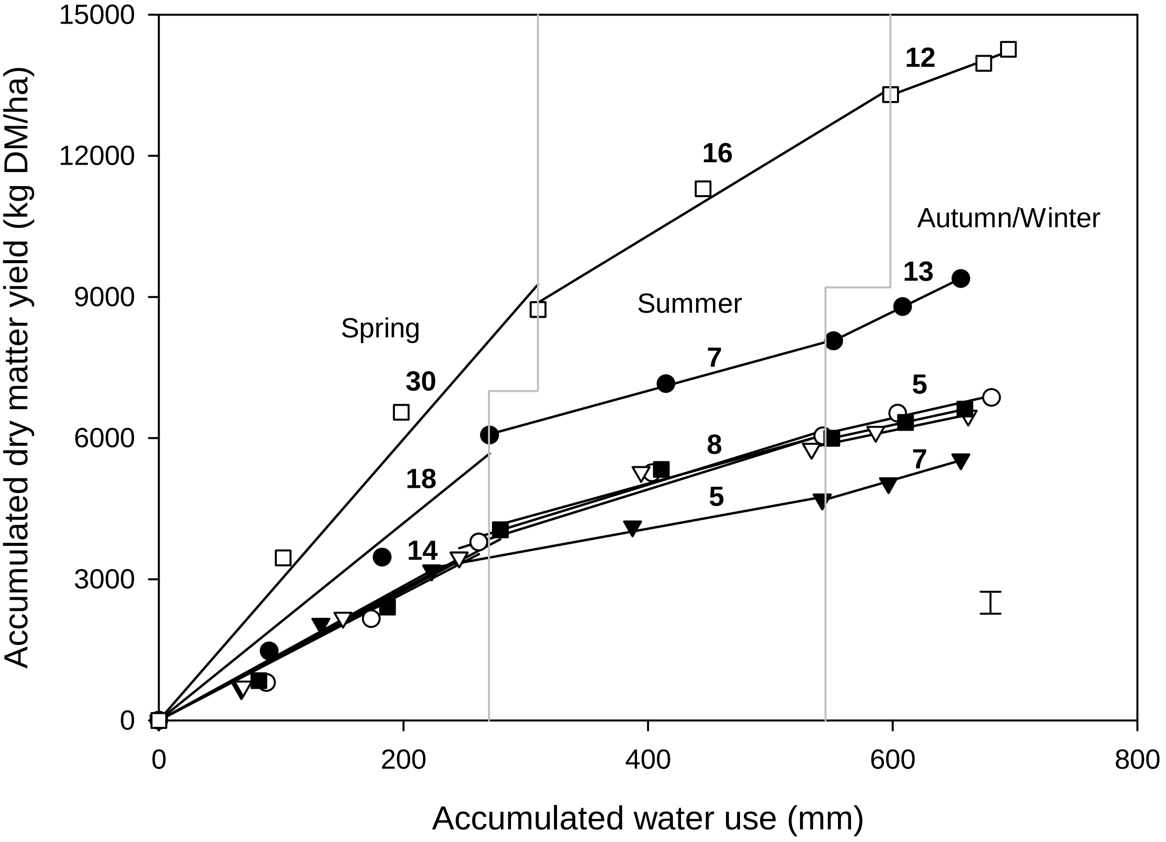

Figure 4.4 Total annual accumulated dry matter yields (kg DM/ha) of CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and lucerne (□) pastures against the annual water use (mm) from 1/7/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand. The error bar is SEM for final accumulated dry matter (on 30 June 2009). Vertical gray lines separate the period of measurement into spring, summer and autumn/winter (Section 3.3.2) with a difference in the duration of each period between grass and lucerne pastures. Values in bold show the WUE of the pastures. Full regression equations are presented in Appendix 5.

4.4.1 Spring

In the spring, when water was non limiting, lucerne had the highest WUE (P<0.001) at 30.1 kg DM/ha/mm of water used. For CF/Sub the total accumulated water use was comparable to the RG/Wc pastures (~280 mm) but its higher DM yield gave a calculated

WUE of 18.2 kg DM/ha/mm of water used. The spring WUE of ryegrass/white clover and cocksfoot dominant pasture mixes was 14.3±1.42 kg DM/ha/mm of water used.

Variation in species root depths affects their ability to take up water from the soil (Section 3.4.1). Analysis for each plot sometimes showed different plant water use even in adjacent plots probably due to different soil profiles (Appendix 6). In spring, for the grass based pastures, the lowest total accumulated water used was by the CF/Wc and CF/Cc pastures at ≤246 mm which was similar ($P<0.07$) to the 310 mm used by lucerne.

4.4.2 Summer

The WUE of all dryland pastures decreased in summer (Table 4.1) because of the effects of drought stress. The summer WUE ranged from 5.0 kg DM/ha/mm for CF/Wc to 9.3 kg DM/ha/mm of CF/Cc. Lucerne had the highest ($P\leq0.01$) WUE (16.1 kg DM/ha/mm) during summer from a similar ($P<0.86$) amount (~290 mm) of water used (Appendix 7). The WUE of CF/Sub pastures was 7.4 kg DM/ha/mm.

4.4.3 Autumn/winter

CF/Sub had a WUE of 12.6 kg DM/ha/mm of water used which was comparable ($P<0.06$) to lucerne (11.7 kg DM/ha/mm) and other grass based pastures (Table 4.1). All pastures used approximately 100 mm during this period (Appendix 8).

Table 4.1 The annual, spring, summer and autumn/winter water use efficiency (WUE) of six dryland pastures grown between 1/7/08 and 30/6/09 at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1.

Treatment	Annual WUE (kg DM/ha/mm)	Spring WUE (kg DM/ha/mm)	Summer WUE (kg DM/ha/mm)	Autumn/winter WUE (kg DM/ha/mm)
CF/Wc	8.5_{c}	14.5_{bc}	5.0_{b}	7.2_{ab}
CF/Cc	10.1_{c}	14.1_{bc}	9.3_{b}	5.5_{b}
CF/Sub	14.7_{b}	18.2_{b}	7.4_{b}	12.6_{a}
CF/Bal	10.2_{c}	13.5_{c}	8.1_{b}	6.3_{ab}
RG/Wc	10.1_{c}	14.3_{bc}	7.1_{b}	5.3_{b}
Lucerne	20.6_{a}	30.1_{a}	16.1_{a}	11.7_{a}
SEM	0.92	1.42	1.80	1.97

Note: Treatment means followed by the same letter are not significantly different at $\alpha=0.05$.

4.5 Botanical composition and Nitrogen concentration

4.5.1 Annual

Table 4.2 shows the botanical composition of the six dryland pastures. The sown grass component ranged from 19% for RG/Wc to 68% for CF/Wc. The legume component of the grass based pastures ranged from a minimum of 3% in the CF/Bal to a maximum of 21% in the CF/Sub. The RG/Wc had the highest weed content of 45% grass weeds and 16% of dicotyledonous (dicot) weeds. For other grass based pastures the grass weed component was ≤24% and the dicot weeds <7%. The lucerne plots contained about 10% weed, mainly yarrow (*Achillea millefolium*) and hawksbeard (*Crepis capillaris*).

Table 4.2 Annual botanical composition of six dryland pastures. Numbers within brackets are contributions of volunteer (unsown) white clover in each treatment. Values may not sum to 100% due to rounding. Lucerne was not included in the ANOVA so SEM and P values are for grass based pastures only. Full details of the acronyms are given in Table 3.1.

				Weeds (%)	
Treatment	Sown grass (%)	Legume (%)	Dead (%)	Grass	Dicots
CF/Sub	53.5_{ab}	21.4_{a}(1.7)	5.5_{c}	16.8_{b}	1.1_{b}
CF/Bal	61.6_{ab}	3.4_{d}(8.4)	9.1_{ab}	13.7_{b}	3.8_{b}
CF/Wc	67.8_{a}	8.3_{bc}	7.6_{bc}	13.6_{b}	2.7_{b}
CF/Cc	50.2_{b}	5.1_{cd}(7.8)	6.7_{c}	23.3_{b}	6.6_{b}
RG/Wc	19.0_{c}	9.9_{b}	10.1_{a}	45.2_{a}	15.8_{a}
Lucerne	-	86.6	3.2	-	10.2
Grand mean	50.4	9.6	7.8	22.5	6.0
SEM	4.80	1.56	0.73	4.46	1.92
P value	0.001	0.001	0.005	0.001	0.001

Note: Treatment means followed by the same letter are not significantly different at α=0.05.

Weeds were not estimated or included in the total N calculated from the pasture. For the cocksfoot grass based pastures, the inclusion of sub clover gave a higher ($P<0.001$) mean N% in the sown grass of 3.5% compared with the other treatments (Table 4.3). In contrast, RG/Wc had the lowest sown grass N% of 2.6% and the consequent grass N yield was only 34.5 kg/ha compared with over 100 kg/ha for sown grass in the cocksfoot pastures. For the legumes, the N% in all six dryland pastures ranged from 2.6% for balansa clover to over 4.0% for all other clovers. The highest ($P<0.001$) N yield was from the monoculture of lucerne at 471 kg/ha. Overall the CF/Sub had a sown species N yield of 188 kg/ha which was similar to CF/Wc (144) but higher (P<0.001) than CF/Cc (128), CF/Bal (118) and RG/Wc (73).

Table 4.3 Annual nitrogen concentration (N%) and corresponding annual N yields of the sown grass and legume components of the six dryland pastures at Lincoln University. The sown species N% is the weighted N concentration based on botanical composition from the sown grass and legume components (Equation 2, Section 3.31). Full details of the acronyms are given in Table 3.1.

Treatment	Grass (% N)	Legume (%N)	Grass N yield (kg/ha)	Legume N yield (kg/ha)	Sown species N%	Sown species N yield (kg/ha)
CF/Sub	3.5_{a}	4.3_{a}	137_{a}	51_{b}	3.6_{b}	188_{b}
CF/Bal	3.0_{c}	2.6_{b}	109_{ab}	9.3_{c}	3.1_{d}	118_{cd}
CF/Wc	3.1_{bc}	4.4_{a}	118_{ab}	25.6_{bc}	3.3_{c}	144_{bc}
CF/Cc	3.2_{b}	4.6_{a}	101_{b}	27.0_{bc}	3.4_{c}	128_{c}
Rg/Wc	2.6_{d}	4.2_{a}	34.5_{c}	38.1_{bc}	3.2_{cd}	73_{d}
Lucerne	-	3.9_{a}	-	471_{a}	3.9_{a}	471_{a}
Grand mean	3.1	4.02	100	103.7	3.42	187
SEM	0.06	0.37	9.38	13.1	0.06	15.7
P value	0.001	0.02	0.001	0.001	0.001	0.001

Note: Treatment means followed by the same letter are not significantly different at α=0.05.

4.5.2 Spring

The botanical composition of the six treatments at the last harvest date in spring (1/7/08 to 10/11/08) are shown in Table 4.4. In this rotation the sown grass component of these six year old pastures ranged from 29% for the RG/Wc pastures to 70% for the CF/Wc. The legume component of the grass pastures ranged from a maximum of 42% in the CF/Sub to ≤16% in all other grass pastures. The balance was predominantly from dicotyledonous (dicot) weed species such as dandelion (*Taraxacum officinale*) and storksbill (*Erodium cicutarium*) and unsown grasses such as goose grass (*Eleusine indica*) and barley grass (*Hordeum* spp.). The unsown grasses were especially prevalent in the ryegrass plots. Combining the botanical composition results and the herbage nitrogen percentage (N%) allowed the total nitrogen yield from each pasture to be determined for the sown species in the spring period (Table 4.5).

Table 4.4 Botanical composition of six dryland pastures at Lincoln University, Canterbury during the spring period (from 1/7/08 to 10/11/08 for grass based pastures and from 1/7/08 to 10/12/08 for lucerne). Numbers within brackets are contributions of volunteer (unsown) white clover in each treatment. Values may not sum to 100% due to rounding. Lucerne was not included in the ANOVA so SEM and P values are for grass based pastures only. The sown species N% is the weighted N concentration based on botanical composition from the sown grass and legume components. Full details of the acronyms are given in Table 3.1.

				Weeds (%)	
Treatment	Sown grass (%)	Legume (%)	Dead (%)	Grass	Dicots
CF/Sub	38.3_{cd}	$41.8_{a}(1.7)$	3.8	13.4_{b}	1.0_{b}
CF/Bal	57.8_{ab}	$6.5_{b}(8.3)$	6.0	14.0_{b}	7.4_{ab}
CF/Wc	69.8_{a}	10.5_{b}	4.5	11.7_{b}	3.6_{b}
CF/Cc	47.6_{bc}	$5.2_{b}(11.2)$	3.0	22.3_{b}	9.0_{ab}
RG/Wc	28.7_{d}	12.2_{b}	3.2	40.6_{a}	15.4_{a}
Lucerne	-	83.9	4.5	-	11.6
Grand mean	48.5	15.2	4.1	20.4	7.3
SEM	5.48	2.37	0.86	5.43	3.05
P value	0.002	0.001	0.15	0.014	0.05

Note: Treatment means followed by the same letter are not significantly different at α=0.05.

The nitrogen content of the grass in most cocksfoot pastures was higher (P<0.01) than in RG/Wc (Table 4.5). The nitrogen yield of grass from CF/Sub and CF/Wc pastures was 74.2 kg/ha and similar to CF/Bal and CF/Cc. All of these were higher (P<0.001) than from the ryegrass (24.4 kg/ha). The nitrogen concentration of the legumes was similar (P<0.51) at around 4±0.7%. However, lucerne produced a higher (P<0.001) nitrogen yield of 288 kg/ha than all other grass based pastures.

4.5.3 Summer

There were diffierences botanical composition in summer and corresponding nitrogen yield (Table 4.6). The sown grass component contributed 14% in the RG/Wc pastures compared with 65% in the CF/Sub pastures. The legume component of all grass based pastures was a maximum of 12% in the RG/Wc pastures. The lowest clover contents, 0.5% from the CF/Bal and 1.3% from CF/Sub, reflect the fact they had died in late spring to regrow from seed in autumn. Lucerne was 93% of the pasture at this time. The weed component in RG/Wc was over 66% with 37% of grass weeds and 19% of dicots weeds. The weed component of the CF/Sub pastures had increased from 14% in spring to 25% in summer.

Table 4.5 Nitrogen concentration (N%) and N yields (kg N/ha) of the sown grass and legume components of the six dryland pastures at Lincoln University in spring (1/7/08 to 10/11/08) for grass based pastures and from 1/7/08 to 10/12/08 for lucerne. The sown species N% is the weighted N concentration based on botanical composition from the sown grass and legume components. Full details of the acronyms are given in Table 3.1.

Treatment	Grass (% N)	Legume (%N)	Grass N yield (kg/ha)	Legume N yield (kg/ha)	Sown species (N%)	Sown species N yield (kg/ha)
CF/Sub	3.8_{a}	4.4	74.2_{a}	45.3_{b}	4.1_{a}	120_{b}
CF/Bal	3.3_{ab}	3.0	65.0_{a}	9.3_{b}	3.4_{abc}	74.3_{cd}
CF/Wc	3.5_{a}	4.2	74.2_{a}	16.3_{b}	3.6_{ab}	91.0_{bc}
CF/Cc	3.5_{a}	4.8	58.3_{a}	15.1_{b}	3.7_{ab}	73.4_{cd}
RG/Wc	1.9_{b}	3.6	24.4_{b}	19.1_{b}	2.4_{c}	43.5_{d}
Lucerne	-	4.0	-	288_{a}	4.0_{ab}	288_{a}
Grand mean	3.2	4.0	59.3	65.6	3.52	115
SEM	0.31	0.68	6.66	13.1	0.34	14.5
P value	0.007	0.51	0.001	0.001	0.04	0.001

Note: Treatment means followed by the same letter are not significantly different at α=0.05.

Table 4.6 Botanical composition during the summer period from 11/11/08 to 2/3/09 for grass based pastures and from 11/12/08 to 23/3/09 for lucerne. Numbers within brackets are contributions of volunteer (unsown) white clover in each treatment$^{(t)}$. Values may not sum to 100% due to rounding. Lucerne was not included in the ANOVA so SEM and P values are for grass based pastures only. Full details of the acronyms are given in Table 3.1.

				Weeds (%)	
Treatment	Sown grass (%)	Legume (%)	Dead (%)	Grass	Dicots
CF/Sub	64.9_{a}	1.3_{b} $(2.1^{(t)})$	6.9	22.8_{b}	2.1_{b}
CF/Bal	60.0_{a}	0.5_{b} $(10.7^{(t)})$	13.0	14.6_{b}	1.2_{b}
CF/Wc	62.7_{a}	8.4_{a}	8.8	17.0_{b}	3.1_{b}
CF/Cc	50.9_{a}	8.2_{a} $(7.7^{(t)})$	7.6	17.4_{b}	8.2_{ab}
RG/Wc	14.4_{b}	12.1_{a}	17.5	37.4_{a}	18.7_{a}
Luc	-	92.7	1.3	-	6.0
Grand mean	50.6	6.11	10.7	21.8	6.7
SEM	5.66	1.77	2.69	4.29	4.01
P value	0.001	0.002	0.08	0.02	0.05

Note: Treatment means followed by the same letter are not significantly different at α=0.05. $^{(t)}$ = contribution of unsown volunteer white clover.

Table 4.7 shows herbage nitrogen (N%) results and the total nitrogen yield of each pasture in summer. The RG/Wc had a N% in sown grass of 2.8% which was similar to the CF/Sub (2.9%). The RG/Wc grass N yield was only 8.0 kg/ha compared with between 25.4 and 34.0 kg/ha for the cocksfoot based pastures. Of the grass based pastures, the CF/Cc had the highest ($P<0.001$) legume N% at 4.4%, which was mainly from volunteer white clover followed by 4.1% and 3.8% of the CF/Wc and RG/Wc, respectively. The CF/Sub and CF/Bal pastures had no sown legume present, therefore no legume N yield. Lucerne had the highest ($P<0.001$) sown species N yield at 145 kg/ha, while the sown species N yield in all grass based pastures ranged ($P<0.001$) from 23.7 kg/ha in RG/Wc pastures to 40.8 kg/ha in the CF/Cc pastures.

Table 4.7 Nitrogen concentration (N%) and corresponding N yields (kg N /ha) of the sown grass and legume components of the six dryland pastures at Lincoln University in summer (from 11/11/08 to 2/3/09 for grass based pastures and from 11/12/08 to 23/3/09 for lucerne). The sown species N% is the weighted N concentration based on botanical composition from the sown grass and legume components. Full details of the acronyms are given in Table 3.1.

Treatment	Grass (% N)	Legume (%N)	Grass N yield (kg/ha)	Legume N yield (kg/ha)	Sown species N%	Sown species N yield (kg/ha)
CF/Sub	2.9_{a}	-	34.0_{a}	0.0_{c}	2.9_{b}	34.0_{b}
CF/Bal	2.4_{c}	-	27.8_{a}	0.0_{c}	2.4_{c}	27.8_{b}
CF/Wc	2.4_{c}	4.1_{b}	25.4_{a}	7.6_{b}	2.6_{c}	33.0_{b}
CF/Cc	2.6_{b}	4.4_{a}	30.9_{a}	9.9_{b}	2.9_{b}	40.8_{b}
RG/Wc	2.8_{ab}	3.8_{c}	8.0_{b}	15.7_{b}	3.3_{a}	23.7_{c}
Luc	-	3.4_{d}	-	145_{a}	3.4_{a}	145_{a}
Grand mean	2.6	2.6	25.2	29.6	2.9	50.6
SEM	0.06	0.04	4.68	2.85	0.08	5.65
P value	0.001	0.001	0.02	0.001	0.001	0.001

Note: Treatment means followed by the same letter are not significantly different at $\alpha=0.05$.

4.5.4 Autumn/winter

Table 4.8 shows that the sown grass component of the six dryland pastures contributed 9% in the RG/Wc compared with 70% in CF/Wc in autumn/winter. The legume component of grass based pastures ranged from a maximum of 11% in the CF/Sub to 2% in the CF/Bal pastures. The RG/Wc had a legume component of 5%, which had dropped from 12% in summer. This pasture also had the highest weed component (60% from grass weeds and 14% from dicot weeds). For the monoculture of lucerne, the legume component was 85%, and total weed content (including VWC) was 12%.

Table 4.8 Botanical composition of six dryland pastures during the autumn/winter period (from 3/3/09 to 30/6/09 for grass based pastures and from 24/3/09 to 30/6/09 for lucerne). Numbers within brackets are contributions of volunteer (unsown) white clover in each treatment$^{(t)}$. Values may not sum to 100% due to rounding. Lucerne was not included in the ANOVA so SEM and P values are for grass based pastures only. Full details of the acronyms are given in Table 3.1.

				Weeds (%)	
Treatment	Sown grass (%)	Legume (%)	Dead (%)	Grass	Dicots
CF/Sub	64.9_a	11.1_a ($1.3^{(t)}$)	6.7	15.8_b	0.2_b
CF/Bal	69.0_a	1.6_b ($6.3^{(t)}$)	9.9	12.3_b	0.9_b
CF/Wc	69.9_a	4.9_b	11.2	13.0_b	1.0_b
CF/Cc	53.5_a	1.8_b ($2.8^{(t)}$)	10.8	29.6_b	1.6_b
RG/Wc	9.1_b	4.5_b	13.1	59.9_a	13.5_a
Lucerne	-	84.7	3.2	0	12.1
Grand mean	53.3	4.7	10.4	26.1	3.4
SEM	6.08	1.80	1.84	6.40	2.49
Significance (P value)	0.001	0.02	0.23	0.001	0.013

Note: Treatment means followed by the same letter are not significantly different at α=0.05. $^{(t)}$ = contribution of unsown volunteer white clover.

Table 4.9 shows the herbage nitrogen percentage (N%) and the total nitrogen yield from each pasture. For all cocksfoot pastures the N% in the sown grass was between 3.3% and 3.6%. The ryegrass pasture had a N% in the sown grass of 2.6% ($P<0.001$) and a consequent N yield of only 2.1 kg N/ha. This was the lowest ($P<0.001$) grass N yield in all grass based pastures. CF/Sub had the highest ($P<0.001$) grass N yield at 28.7 kg N/ha. The CF/Sub had legume N% of 4.2% which was lower ($P<0.001$) than the CF/Wc, CF/Cc and RG/Wc. Lucerne had the highest ($P<0.001$) total and legume N yield of 39 kg N/ha. The

CF/Sub had a sown species N yield of 35 kg N/ha which was higher ($P<0.001$) than other grass based pastures where the N yield of sown species was ≤20 kg N/ha.

Table 4.9 Nitrogen concentration (N%) and corresponding N yields of the sown grass and legume components of the six dryland pastures at Lincoln University in autumn/winter (from 3/3/09 to 30/6/09 for grass based pastures and from 24/3/09 to 30/6/09 for lucerne). The sown species N% is the weighted N concentration based on botanical composition from the sown grass and legume components. Full details of the acronyms are given in Table 3.1.

Treatment	Grass (% N)	Legume (%N)	Grass N yield (kg/ha)	Legume N yield (kg/ha)	Sown species N%	Sown species N yield (kg/ha)
CF/Sub	3.6_{a}	4.2_{d}	28.7_{a}	5.8_{b}	3.7_{b}	34.5_{a}
CF/Bal	3.3_{c}	-	15.9_{b}	-	3.3_{cd}	15.9_{bc}
CF/Wc	3.3_{bc}	4.6_{a}	18.3_{b}	1.7_{cd}	3.4_{c}	20.0_{b}
CF/Cc	3.4_{b}	4.5_{b}	12.2_{b}	2.0_{cd}	3.4_{c}	14.2_{c}
RG/Wc	2.6_{d}	4.4_{c}	2.1_{c}	3.3_{c}	3.1_{d}	5.4_{d}
Luc	-	4.5_{b}	-	38.5_{a}	4.5_{a}	38.5_{a}
Grand mean	3.2	3.7	15.4	8.6	3.6	21.4
SEM	0.03	0.01	2.01	0.66	0.07	1.90
P value	0.001	0.001	0.001	0.001	0.001	0.001

Note: Treatment means followed by the same letter are not significantly different at $\alpha=0.05$.

5 General Discussion

The main aims of this research (Chapter 1) were to identify legume species that can persist in cocksfoot swards to enhance the overall productivity of dryland pastures. To do this dry matter yield, botanical composition, water use efficiency and nitrogen yield among pastures were compared for this 7th production year. This chapter discusses results in relation to previous work (Chapter 2) and quantifies the environmental factors which affected the pastures.

5.1 Pasture yields

The accumulated dry matter yields of these six dryland pastures in the 7th Year of the 'MaxClover' experiment differed. The annual yields were between 5550 kg DM/ha/yr by CF/Wc and 14260 kg DM/ha/yr from lucerne (Figure 4.1). The highest annual dry matter yield from lucerne is consistent with the previous results from this experiment (Mills *et al.*, 2008a). Mills *et al.* (2008a) found that lucerne had the highest annual dry matter yield over five years, and the lucerne annual dry matter yield in Years 1-5 was 13.1-18.5 t/ha/yr. In this 7th year, the lucerne produced an annual yield lower than Year 5 probably because the lucerne plant population is declining. Wynn-Williams (1982) showed that lucerne stands thin over time, regardless of sowing rate. Sowing rates of 5.6, 11.2 and 16.8 kg/ha gave plant densities of 90-160 plants/m^2 in the establishment year and this had declined to about 50 plants/m^2 in all pastures eight years later. Visual observation of the lucerne stands in this experiment indicates plots are beginning to show signs of weed invasion (Table 4.2) and more bareground is apparent. However, plant population was not measured in this study.

The CF/Sub pastures had the highest annual accumulated dry matter yield of all grass based pastures. It produced 9.4 t/ha/yr which was similar to the previous results (Mills *et al.*, 2008a) of 10.0 t/ha/yr in 2005/2006. The RG/Wc pastures produced 6.6 t/ha/yr and had the highest weeds component in all pastures (Table 4.2). This is also consistent with results from Mills *et al.* (2008a) who found that RG/Wc had the highest weed species yield since Year 2 (2003/04). The weed yield in the RG/Wc pastures increased each year (from 4% of total annual DM yield in 2002/03 to 23% by 2006/07), and in a commercial situation these pastures are probably now ready for renewal.

Cocksfoot based pastures with clovers other than sub clover had annual dry matter yields between 5.5 t/ha (CF/Wc) and 6.9 t/ha (CF/Bal). However, balansa clover did not persist in the cocksfoot sward. The balansa clover component was only 4%, although balansa clover yield from the first natural reseeding of annual clovers (2003/04) was double that of subterranean clover. This decline in balansa clover performance has been investigated fully in a PhD study by Monks (2009). He reported that balansa clover was out competed for water by cocksfoot, and it also had light competition from cocksfoot, particularly during seedling establishment. The cocksfoot canopy expands and shades the balansa seedlings which decreases the photosynthesis of the seedling. Monks (2009) also stated that the success of regeneration of balansa clover requires specialist management in the establishment year then about every 3 years. In the ‘MaxClover’ experiment the closing of the CF/Bal pastures for reseeding on 6 September allowed flowering after a February sowing, or no grazing in late May sowing both provided sufficient seed for successful re-establishment of the balansa clover over time. However, this management occurred in only 2 of the 6 replicates which compromised the overall balansa clover performance.

The seasonal pattern of DM production in these dryland pastures was quantified through differences in mean daily growth rates (Figure 4.1). These ranged from a minimum of 4 kg DM/ha/d in winter to a spring maximum of 100 kg DM/ha/d. The highest growth rates for all pastures occurred in spring when non water stressed. The CF/Sub pastures had the highest growth rate of all grass based pastures particularly from September to November (21 to 79 kg DM/ha/d). For other grass based pastures the highest mean daily growth rates also occurred in spring. Mills *et al.* (2006) found a similar pattern in mean daily growth rates of cocksfoot monocultures under dryland, non N fertilizer (D-N) conditions with the highest growth rates in spring. The growth rates decrease as pastures became water stressed. In this study the mean daily growth rates of all pastures decreased after December and did not increase again in autumn. Mills *et al.* (2006) reported a similar result from December 2004 to June 2005. The loss of yield in these pastures is caused by the effects of water stress which reduce leaf expansion, photosynthesis and consequently canopy expansion. Mills *et al.* (2008a) also found the highest mean daily growth rates of the dryland pastures from Years 1-4 occurred from CF/Sub pastures (95-107 kg DM/ha/d) in late spring. Moreover, pastures which established with perennial legumes (CF/Wc, CF/Cc and RG/Wc) had higher growth rates than those with annual legumes (CF/Sub and CF/Bal) in summer, because the annual legumes died before re-establishment from seed in autumn.

Effectively, the annual and seasonal variability of dry matter production is related to the timing of rainfall and the ability of pastures to use the available soil moisture. For the spring period, the growth of lucerne declined in December compared with November for the grass based pastures. It appears that the lucerne tap root insulated the crop from water stress in early summer (Moot *et al.,* 2008) by extracting more water from deeper in the soil profile (Figure 4.3). Further, the yield of all pastures in autumn did not increase after summer. This was probably because of the decrease in soil temperature in autumn. By the onset of autumn rain in May (Figure 3.1), the soil temperature had dropped to 7.2 ºC which limited mean daily growth rates, because of reduced leaf appearance rates, leaf area index development and photosynthetic rate (Mills, 2007).

5.2 Temperature

To take account of seasonal fluctuations in mean daily growth rates, caused by variations in temperature, thermal time (Tt) was quantified. The base temperature for all pastures was 0 ºC based on 0.1 m soil temperatures with an optimum temperature for pasture growth set at 25 ºC (Peri *et al.,* 2002b). This base temperature was also used by Hutchinson *et al.* (2000) to compare annual values of pasture production in Southland.

The annual growth rates of the six dryland pastures ranged from 1.2 kg DM/ha/^{o}Cd to 3.2 kg DM/ha/^{o}Cd (Figure 4.3). However, the seasonal values are more important than annual, particularly when water is non-limiting, because water stress reduces canopy expansion, leaf size and tiller population of pastures (Mills, 2007). The highest growth rates of all pastures occurred in spring and ranged from 3.5 kg DM/ha/^{o}Cd (CF/Cc) to 5.9 kg DM/ha/^{o}Cd (CF/Sub) (Figure 4.3). In each case the fitted regression equation indicated an x-axis intercept of around 200 ºCd, which translated to 3/8/2008. This value was different from zero (1/7/08) and suggests the pasture accumulation during winter (from 1 July 2008) was not linearly related to temperature. This probably reflects the low pasture covers at this time with the hard autumn grazing removing herbage to below the critical leaf area index. An apparent lag phase was also reported by Fasi *et al.* (2008) for dryland pastures growing in the Lees Valley, Canterbury. This suggests further work is required to identify the mechanism responsible for the lag period and to identify a trigger point to commence linear accumulation with thermal time for it to be used in a predictive manner.

Surprisingly, the lucerne grew at a rate comparable (4.9 kg DM/ha/^{o}Cd) to the CF/Sub pastures throughout the early spring growth period despite its reputation for slow growth at this time (Mills *et al.*, 2008a). Moreover, lucerne produced a higher spring dry matter yield than CF/Sub, due to its additional 400 ^{o}Cd of growth (Figure 4.3). The additional yield of high quality feed (Brown and Moot, 2004) would support higher live-weight gain and consequently meat yield per hectare (Mills *et al.*, 2008b) than the traditional pasture combinations. Equally, the greater yield from the CF/Sub pastures supports the recommendation for this combination to be used in dryland pastures to complement lucerne productivity (Brown and Moot, 2004; Mills *et al.*, 2008a).

5.3 Water availability and Water use efficiency

In these dryland conditions, there were differences in plant available water content in the soil and the root extraction depth, both of which contributed to differences in the annual water use and WUE (Table 4.1). The annual PAWC of soils for all pastures was 280±19.8 mm, and all pastures extracted 670±24.4 mm of total water use. Lucerne had the highest annual WUE at 20.6 kg DM/ha/mm, followed by CF/Sub at 14.7 kg DM/ha/mm. This is because lucerne produced a higher yield (Figure 4.4) and extracted more water than grass based pastures (Table 3.5) (Moot *et al.*, 2008). Plant available water content was different in each plot, because of the soil characteristics which reflects the gravel layers in the soil. Figure 3.2 shows examples between Plot 5 which was a shallow plot and Plot 2 which had deeper soil. The gravel layer in Plot 5 began below about 1.0 m depth, but it started below about 1.5 m in Plot 2. As a consequence the plant water available content was 254 vs. 349 mm (Appendix 2). Therefore, calculated WUE required actual plant water use to be determined. Water stress had different effects on pastures. Figure 4.2 shows the effects of water stress occurred later for lucerne than grass based pastures with a lucerne growth rate of a 75 kg DM/ha/d through to January. The grass based pastures had lower growth rates at under 30 kg DM/ha/d due to less water extraction because of shallower roots (Moot *et al.*, 2008).

The highest WUE for all pastures occurred in spring, because of lower temperatures and lower vapour pressure deficits compared with summer. Therefore more water is used for growth rather than evaporation. Lucerne had a spring WUE of 30 kg DM/ha/mm of water used. The CF/Sub pastures produced 18 kg DM/ha/mm. These values were consistent with results from Moot *et al.* (2008) which also showed that lucerne a higher spring WUE than ryegrass/white clover and a monoculture of ryegrass. For cocksfoot pastures, Moot *et al.* (2008) reported that CF/Sub in dataset 5 (a dryland experiment in its experiment year at Lincoln University) had a spring WUE of 37 kg DM/ha/mm which was higher than the CF/Sub WUE in the current study. The differences may reflect the age of pastures.

In summer, the WUE of the six dryland pastures decreased (Figure 4.4), and the WUE of the grass based pastures ranged from 5.0 kg DM/ha/mm (CF/Wc) to 9.3 kg DM/ha/mm (CF/Cc). Lucerne and CF/Sub had WUE of 16.2 and 7.4 kg DM/ha/mm, respectively. Most pastures were affected by water stress, so there was little growth in summer and any rain that fell (Figure 3.1) was usually as events less than 20 mm and thus ineffective (Moot *et al.,* 2008). Lucerne was less affected by water stress in summer, because of its deep tap root (Mills *et al.,* 2008a). As expected the WUE of annual clover pastures declined in summer, because the clover component died after setting seed (Costello and Costello, 2003).

The lower autumn/winter than spring WUE of most pastures was consistent with a temperature limitation to pasture growth. When 171 mm of rain fell in May, the mean soil temperature had declined to 7.2 ºC. This compares with an October mean of 12.3 ºC. For CF/Sub the spring WUE was 18.2 kg DM/ha/mm, but in autumn/winter only 12.6 kg DM/ha/mm. These results highlight the importance of spring to dryland farms. The seasonal WUE of all species is highest in the most favourable atmospheric conditions and when soil moisture is readily available (Moot *et al.,* 2008). Peri *et al. (*2002) stated that temperature influences seasonal production by limiting the physiological processes, such as photosynthesis. Eagles (1967) reported that the optimum temperature for photosynthesis of cocksfoot is 20-22 ºC. This was similar to the 19-23 ºC of Peri *et al.* (2002) which was the optimum temperature for a maximum photosynthesis rate of cocksfoot. They also stated that low temperatures caused a reduction in enzyme activities in the chloroplasts rather than limitations on leaf gas exchange.

These results suggest the combination of dry conditions and declining soil temperatures makes autumn a more risky period for pasture production than spring. Effectively, dryland farmers should look to maximize favourable spring conditions through using appropriate species, for example lucerne and sub clover, or using nitrogen fertilizer.

5.4 Nitrogen status

The differences in WUE within each season of these six dryland pastures were probably caused by herbage nitrogen concentration. This directly affects the photosynthetic efficiency per unit leaf area (Peri *et al.,* 2002b), and higher rates of photosynthesis are gained per unit of water used. This leads to higher dry matter production. There were differences in botanical composition, particularly legume component (Table 4.2) of the pastures which contributed to differences in the total nitrogen yield (Table 4.3). As expected, from Table 4.3, the total annual legume contribution of the lucerne was higher than grass based pastures. Lucerne produced 471 kg N/ha. The CF/Sub pastures had the highest legume component of all grass based pastures (21%) and a sown species N yield of 188 kg N/ha. The result of this was that lucerne had higher annual WUE than CF/Sub. For RG/Wc pastures the annual legume content (12%) meant sown species yielded only 73 kg N/ha. These results explain the continued decline in the ryegrass pastures and the relative superiority of the cocksfoot after seven years (Mills *et al.*, 2008a). The influence of herbage N concentration on WUE was supported by Moot *et al.* (2008). They stated that higher herbage N content contributed to higher photosynthetic efficiency and higher dry matter yield which led to higher WUE. In their work, the N fertilised pastures had a WUE of 36 kg DM/ha/mm, but unfertilised pastures had a WUE of only 17 kg DM/ha/mm.

In spring, for all of the cocksfoot pastures, the N% in the sown grass was between 3.3 and 3.8% (Table 4.5). These values are consistent with those found by Peri *et al.* (2002b) and are in the range which was required to give at least 80% of the maximum potential photosynthetic capacity in cocksfoot. Once values fell below 2.6% the rate of photosynthesis was severely compromised. This relationship also happens in ryegrass which had the lowest herbage N of 1.9% and a consequent N yield of only 24 kg N/ha. The low N% at this time is likely to reflect the inclusion of reproductive seedheads, which contain more structural material of lower N%, in samples sent for analysis. This is supported by previous work which showed in the Nov/Dec regrowth cycles the proportion of reproductive structures accounted for ~25% of ryegrass harvested (2003/04 and 2004/05 growth seasons, A. Mills, unpublished data). This was almost double the amount of reproductive structures found in cocksfoot pastures which typically produce the majority of reproductive seedheads in summer months. Rainfall was also 20-40% below the long-term average in three of the four months prior to this harvest the development of soil moisture stress may have also restricted uptake of N as the soil dried leading to N deficiency in ryegrass. This phenomenon may not have been observed in the cocksfoot because it has been shown previously to have almost four times more root length in the top 0.25 m compared with ryegrass (Evans, 1978) and hence a greater surface area for water and nutrient uptake. It was therefore unexpected that the total dry matter yield and water use efficiency of the RG/Wc pasture was similar to that of several of the cocksfoot based pastures. This suggests that the annual weed grasses (predominantly barley grass (*Hordeum* spp.) and *Bromus* spp.) that had invaded these pastures were growing DM at a similar rate to the cocksfoot. Without determination of the N% of these components it is difficult to know exactly how much N was harvested from this treatment but the total of 44 kg N/ha calculated from sown species underestimates the total N yield.

In contrast, the superior spring clover content (42%) in the CF/Sub pastures resulted in the highest total nitrogen yield of 120 kg/ha from grass based pastures. These results highlight the importance of nitrogen availability to maximise the WUE of dryland pastures. In most cases, spring dry matter production of dryland pastures is nitrogen limited and the highest response of yield to applied N can be expected at this time (Fasi *et al.*, 2008). The main impact of nitrogen deficiency is to reduce leaf area. Many species adjust their leaf size to maintain nitrogen concentrations above critical levels that affect photosynthesis. This probably explains why the herbage N% are usually conservative within the range of 3-4% found in this study. On its own herbage N concentration do not reflect whether the pasture would respond to additional N fertiliser or not.

The benefits of managing dryland pastures to maintain a legume in the system are frequently directly related to the herbage quality of feed on offer (Litherland and Lambert, 2007). Indirectly, the increased water use efficiency means each unit of actual water use results in a higher DM yield, particularly in spring. The additional benefit of a pure legume can be gauged from the lucerne pastures which produced spring yield of 288 kg N/ha or about 30 kg N/t DM. This is similar to the generalized figure for nitrogen fixation of 25 kg N/t DM produced (Peoples and Baldock, 2001). The higher value possibly represents the added input of soil N from these grazed pastures. Regardless of the source, the availability of nitrogen in spring pastures is crucial to maximise the efficient use of the limited water storage capacity of the soil in dryland regions. The resulting increase in water use efficiency at the canopy level leads to higher dry matter yields through a faster rate of dry matter accumulation per unit of thermal time before the dry summer.

6 Conclusions

Based on the results from this study dryland farmers should be encouraged to:

1) Maximize the potential of lucerne on farm.

2) Use cocksfoot as the main grass species for persistence rather than perennial ryegrass.

3) Use subterranean clover as the main legume species in the cocksfoot based pasture. The inclusion of white clover may be of benefit in summer moist years.

4) When pastures are nitrogen deficient in spring consider the use of nitrogen fertilizer to maximize water use efficiency and yield.

7 References

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9 Appendices

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Rep 1	Rep 2	Rep 3	Rep 4
1 CF/Wc	7 CF/Sub	13 RG/Wc	19 Lucerne
2 Lucerne	8 CF/Bal	14 CF/Sub	20 CF/Cc
3 CF/Bal	9 CF/Wc	15 CF/Cc	21 RG/Wc
4 RG/Wc	10 CF/Cc	16 CF/Bal	22 CF/Wc
5 CF/Sub	11 RG/Wc	17 Lucerne	23 CF/Bal
6 CF/Cc	12 Lucerne	18 CF/Wc	24 CF/Sub

Appendix 1 Layout of plots in the Lincoln University 'Max Clover' Grazing Experiment established in 2002.

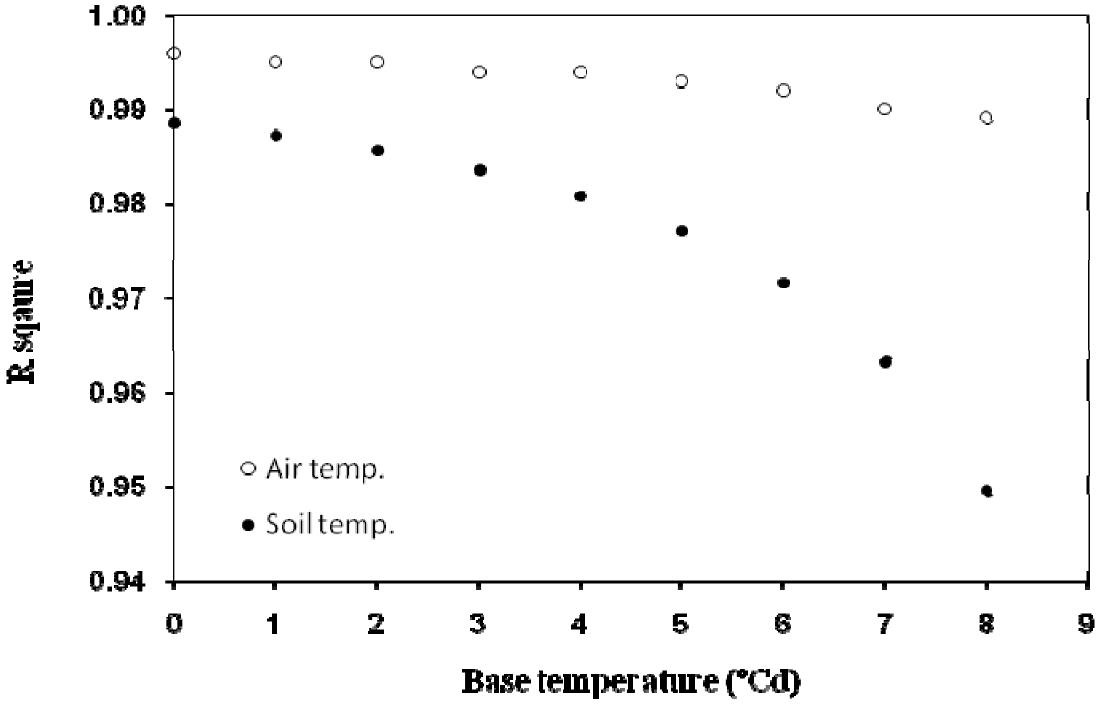
Appendix 2 Values of drained upper limit (DUL) (mm), lower limit (LL) (mm) and plant available water content (PAWC) (mm) of all plots from 13/8/08 to 30/6/09 at Lincoln University, Canterbury, New Zealand.

	Plot 1		Plot 2		Plot 3		Plot 4		Plot 5		Plot 6	
Depth (cm)	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL
10	6.5	33.0	9.4	32.7	7.2	33.2	6.7	33.3	6.8	33.1	5.9	32.2
25	9.5	30.2	11.1	29.3	7.6	26.0	12.3	29.8	10.0	28.6	7.9	28.9
45	9.2	26.3	7.5	24.8	6.2	19.6	11.1	26.5	12.8	30.7	9.8	25.8
65	7.1	25.3	10.1	29.5	14.0	28.2	10.0	27.6	14.2	28.2	6.4	19.3
85	5.2	23.4	8.3	35.4	15.9	31.3	6.7	23.0	16.6	30.9	8.3	20.5
105	5.3	26.3	6.5	31.4	6.9	22.1	7.2	16.3	9.4	17.3	7.0	14.5
125	5.5	17.5	5.5	26.4	9.6	23.5	8.6	15.8	8.5	14.1	7.7	13.9
145	6.3	10.9	5.5	13.1	25.2	31.5	11.1	24.4	10.3	15.0	8.7	12.0
165	7.0	14.8	5.3	11.6	10.7	16.4	10.1	16.8	12.0	17.3	8.7	11.4
185	7.3	12.8	6.2	11.9	9.4	14.2	10.3	16.2	12.4	15.7	8.6	11.3
205	8.5	12.0	7.3	12.5	10.5	14.8	12.7	17.3	13.7	18.8	8.9	11.4
225	8.8	12.7	8.3	12.9	10.6	14.2	14.2	18.2	11.6	16.8	9.0	11.4
PAWC (mm)	306		349		271		278		254		220	

	Plot 7		Plot 8		Plot 9		Plot 10		Plot 11		Plot 12	
Depth (cm)	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL
10	7.0	33.2	6.6	33.2	5.3	32.2	6.4	32.8	7.2	33.2	7.2	28.9
25	10.9	30.2	11.0	31.0	10.4	30.1	9.0	29.8	11.4	32.0	10.4	28.6
45	13.3	30.6	12.3	31.3	12.5	30.6	9.6	29.8	13.3	29.8	8.6	24.4
65	15.3	27.2	12.9	27.5	13.0	28.9	11.3	26.8	17.6	27.1	9.2	27.1
85	9.5	24.0	15.3	28.8	15.3	29.4	8.6	28.1	27.7	31.4	4.6	13.7
105	7.4	18.2	16.6	29.2	8.3	20.2	7.8	13.8	26.0	35.1	5.1	15.6
125	8.1	13.5	8.0	13.4	7.3	15.2	9.0	14.9	24.2	30.6	6.3	12.2
145	9.7	14.5	9.4	14.5	9.6	14.9	7.8	12.8	7.8	11.7	6.4	13.3
165	8.8	13.5	9.9	13.9	15.3	23.1	11.7	17.7	7.8	11.1	6.7	13.5
185	9.0	12.9	10.1	13.7	8.7	12.8	12.6	17.2	7.7	10.8	6.4	11.3
205	9.4	13.1	9.2	13.3	9.8	13.3	12.1	16.2	7.3	9.8	6.7	11.8
225	11.0	14.8	6.2	8.5	9.7	12.4	11.8	15.3	7.8	10.1	6.3	11.1
PAWC (mm)	241		250		264		263		202		244	

	Plot 13		Plot 14		Plot 15		Plot 16		Plot 17		Plot 18	
Depth (cm)	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL
10	6.2	31.2	6.5	32.7	7.5	33.9	5.8	34.1	8.4	30.3	6.4	32.0
25	7.4	25.9	9.1	30.0	8.8	27.3	8.7	28.8	9.7	25.5	7.9	27.8
45	5.6	20.3	7.3	22.7	8.5	27.4	8.5	24.0	6.9	16.6	6.3	20.8
65	5.4	22.3	7.4	21.4	9.5	22.5	11.0	25.5	9.0	28.9	6.6	30.1
85	5.2	21.5	7.1	23.5	6.4	11.7	7.3	11.9	7.1	13.0	21.2	34.4
105	5.2	19.9	11.2	29.8	7.1	12.6	7.8	13.7	6.3	11.1	8.3	12.3
125	5.6	23.4	20.0	30.0	8.9	14.1	8.4	13.7	6.1	12.1	7.0	11.4
145	5.6	21.1	29.2	32.8	8.8	12.1	9.7	14.5	6.4	11.4	7.1	10.5
165	5.1	14.8	30.7	33.8	7.1	11.0	9.1	13.5	6.8	11.9	6.9	9.4
185	5.2	8.9	23.6	29.7	7.1	9.5	10.1	14.1	7.1	12.1	7.2	10.0
205	5.4	8.7	29.2	31.5	6.6	8.7	9.0	12.1	6.4	10.7	8.0	10.3
225	5.5	9.5	12.0	15.1	6.2	8.1	9.0	12.7	7.3	12.7	9.1	11.9
PAWC (mm)	309		268		203		217		207		227	

	Plot 19		Plot 20		Plot 21		Plot 22		Plot 23		Plot 24	
Depth (cm)	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL
10	8.5	30.0	8.4	33.3	7.8	32.7	8.7	34.1	7.4	33.4	6.9	34.1
25	10.0	28.7	11.3	30.7	11.3	30.4	11.5	32.3	9.4	30.0	10.3	30.0
45	7.0	22.3	10.8	26.5	9.2	24.9	7.8	26.9	7.1	25.5	7.0	19.6
65	5.1	17.6	6.4	23.3	5.8	21.3	6.8	28.3	5.4	17.3	4.8	17.2
85	8.2	29.0	7.8	24.2	7.5	26.7	8.5	28.9	4.7	23.9	4.3	23.4
105	5.7	29.2	4.1	23.2	7.8	31.3	8.6	32.3	6.4	31.0	6.6	33.1
125	7.3	34.1	4.1	31.9	8.4	32.7	9.8	36.0	9.3	32.1	11.7	30.1
145	6.4	17.5	8.9	35.0	7.1	23.9	6.8	24.5	7.8	25.2	7.2	30.3
165	5.8	10.0	7.9	33.8	5.0	15.2	6.3	26.1	5.7	12.2	6.0	17.0
185	6.3	9.6	6.6	23.7	4.9	14.3	6.3	17.5	7.5	16.8	5.2	8.7
205	6.7	9.5	7.3	17.1	5.4	14.9	6.5	12.4	6.0	10.6	5.8	7.7
225	6.8	8.4	7.1	14.1	7.2	18.9	7.2	10.0	9.8	14.5	10.0	14.1
PAWC (mm)	314		439		384		417		359		347	



Appendix 3 The coefficient of determination (R^2) of the regression of dry matter yield against thermal time using different base temperatures from 0-8 °C for cocksfoot/white clover using air temperature and soil temperatures at Lincoln University, Canterbury, New Zealand from 1/07/08 to 30/06/09.

Appendix 4 The regression equations, standard errors of the coefficients and the coefficients of determination for the regression of accumulated dry matter against thermal time in spring, summer and autumn/winter of six dryland pastures at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1

	Spring	
Treatment	Equation	R^2
CF/Sub	y = 5.9±0.12x – 922.0±96.33	0.99
CF/Bal	y = 3.9±0.10x – 732.3±8.42	0.99
CF/Wc	y= 3.2±0.36x – 535.9±307.38	0.98
CF/Cc	y = 3.5±0.34x – 601.9±281.35	0.98
RG/Wc	y = 4.1±0.17x – 759.3±140.72	0.99
Lucerne	y = 4.9±0.54x – 282.8±581.97	0.98

	Summer	
Treatment	Equation	R^2
CF/Sub	y = 1.0±0.06x + 4972.3±140.56	0.99
CF/Bal	y = 1.1±0.20x + 2648.8±476.18	0.96
CF/Wc	y= 0.7±0.10x + 2407.1±255.09	0.98
CF/Cc	y = 1.1±0.38x + 2396.0±890.08	0.90
RG/Wc	y = 0.9±0.18x + 3068.1±427.35	0.96
Lucerne	y = 2.4±0.46x + 4855.6±1260.71	0.96

	Autumn/Winter	
Treatment	Equation	R^2
CF/Sub	y = 1.1±0.15x + 450.5±576.91	0.98
CF/Bal	y = 0.7±0.13x + 3861.4±485.47	0.97
CF/Wc	y = 0.7±0.02x + 2320.4±87.41	0.99
CF/Cc	y = 0.6±0.06x + 3879.9±214.89	0.99
RG/Wc	y = 0.5±0.06x + 4335.0±249.80	0.98
Lucerne	y = 1.1±0.11x + 9434.0±453.37	0.99

Appendix 5 The regression equations, standard errors of the coefficients and the coefficients of determination for the regression of accumulated dry matter against accumulated water use in spring, summer and autumn/winter of six dryland pastures at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1. Regressions forced through the origin in spring but not summer or autumn/winter.

	Spring	
Treatment	Equation	R^2
CF/Sub	y = 18.2±1.16x	0.98
CF/Bal	y = 13.5±0.89x	0.97
CF/Wc	y = 14.5±0.73x	0.98
CF/Cc	y = 14.1±0.51x	0.99
RG/Wc	y = 14.3±0.65x	0.98
Lucerne	y = 30.1±1.39x	0.98

	Summer	
Treatment	Equation	R^2
CF/Sub	y = 7.4±0.26x + 4152.5±112.55	0.99
CF/Bal	y = 8.1±1.38x + 1800.7±578.57	0.97
CF/Wc	y = 5.0±0.57x + 2181.2±234.43	0.98
CF/Cc	y = 9.3±2.49x + 1676.2±1016.38	0.91
RG/Wc	y = 7.1±1.43x + 2161.6±611.78	0.96
Lucerne	y = 16.1±1.71x + 3979.8±799.23	0.99

	Autumn/Winter	
Treatment	Equation	R^2
CF/Sub	y = 12.6±0.07x + 1035.2±43.29	1.0
CF/Bal	y = 6.3±0.99x + 2893.5±610.50	0.97
CF/Wc	y = 7.2±0.65x + 569.80±391.19	0.99
CF/Cc	y = 5.5±0.64x + 2922.9±383.35	0.99
RG/Wc	y = 5.3±0.11x + 2877.0±66.36	0.99
Lucerne	y = 11.7±1.05x + 7521.4±689.03	0.99

Appendix 6 Spring plant water use (mm) of six dryland pastures in individual plots from 1/7/08 to 10/11/08 for grass pastures and from 1/7/08 to 10/12/08 for lucerne, at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1.

Treatment	Rep 1	Rep 2	Rep 3	Rep 4	Mean	SEM	Significance
CF/Wc	225	239	265	164	223	18.8	0.07
CF/Cc	269	255	256	202	246		
CF/Sub	244	273	341	230	272		
CF/Bal	256	247	313	235	263		
RG/Wc	235	235	286	361	279		
Lucerne	280	316	354	291	310		

Appendix 7 The summer accumulated water use of individual plots from 11/11/08 to 2/3/09 for grass based pastures and from 11/12/08 to 23/3/09 for lucerne at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1.

Treatment	Rep 1	Rep 2	Rep 3	Rep 4	Mean	SEM	Significance
CF/Wc	329	262	246	440	319	27.2	0.86
CF/Cc	181	286	220	466	288		
CF/Sub	208	304	223	391	281		
CF/Bal	211	314	239	361	281		
RG/Wc	241	265	301	276	271		
Lucerne	319	265	219	349	288		

Appendix 8 Autumn/winter accumulated water use (mm) in individual plots from 3/3/09 to 30/6/09 for grass based pastures and 24/3/09 to 30/6/09 for lucerne at Lincoln University, Canterbury, New Zealand. Full details of the acronyms are given in Table 3.1.

Treatment	Rep 1	Rep 2	Rep 3	Rep 4	Mean	SEM	Significance
CF/Wc	109	122	111	111	113	14.4	0.37
CF/Cc	123	92.0	149	149	128		
CF/Sub	115	112	73.0	116	104		
CF/Bal	113	97.0	145	197	138		
RG/Wc	106	140	72.0	117	109		
Lucerne	41	103	122	119	96		