Dry matter production and water use of lucerne and perennial ryegrass under dryland and irrigated conditions

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In dryland regions of New Zealand lucerne is sown as an alternative species to the most common pasture of perennial ryegrass and white clover. This is to maximise dry matter production and water use efficiency. This experiment compared the dry matter production of lucerne and perennial ryegrass pastures under full irrigation, irrigation every two weeks, irrigation every three weeks or no irrigation (dryland) on a Templeton silt loam and Eyre soil. Fully irrigated lucerne and perennial ryegrass had the highest dry matter yield of 18.7 t DM/ha. Unirrigated lucerne and perennial ryegrass had the lowest dry matter yields of 4.65 t DM/ha and 8.29 t DM/ha. The fully irrigated lucerne grew at the fastest rate of 6.69 kg DM/ha/˚Cd across the whole season. Unirrigated lucerne grew 3.03 kg DM/ha/˚Cd until soil moisture limited growth. After this point growth slowed to 0.39 kg DM/ha/˚Cd. Irrigated lucerne had the highest water use efficiency of 34.5 kg DM/ha/mm compared with 22.5 kg DM/ha/mm for all perennial ryegrass pastures and 11.2 kg DM/ha/mm for unirrigated lucerne. The low yield of unirrigated lucerne was unexpected and probably caused by an application of Glyphosate in June 2012. This experiment shows that lucerne could be sown instead of a perennial ryegrass/white clover pasture under irrigation due to higher dry matter production.

Keywords: Alfalfa, Glyphosate, *Lolium perenne, Medicago sativa*, thermal time, water use efficiency, yield

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1 INTRODUCTION

Agricultural products make up 58% of merchandise export revenue in New Zealand (Ministry for Primary Industries, 2011). The majority of agriculture is based around a pastoral system. Therefore it is important to ensure that this sector maintains high productivity annually. This can be achieved by maximizing the efficiency with which plants use resources, that impact on yield , such as temperature and light (Brown, 1999).

In New Zealand in the past 13 years much of the flat land on the Canterbury Plains and on the eastern side of the main mountain ranges has been irrigated and converted to dairy farming (Martin *et al.*, 2006; Moot *et al.*, 2008; Moot, 2012). Irrigation covers 364 000 ha in Canterbury which is 70% of the irrigated land in New Zealand (Moot *et al.*, 2010). This has caused sheep and beef properties to intensify in more marginal hill and high country areas (Moot *et al.*, 2008; Moot *et al.*, 2010; Moot, 2012). Dryland environments are characterized by the inability of rainfall to match summer evapotranspiration rates in most years (Moot, 2012). These often receive annual rainfall of 300-800 mm and experience potential soil moisture deficits between 200-600 mm. This makes them unsuitable for dairy production. Total water holding capacity of the soil is also variable. It ranges from less than 100 mm on stony Lismore soils to 380 mm on deep Wakanui soils. Potential evapotranspiration (PET) generally exceeds rainfall from September to April which produces a long term average potential soil moisture deficit of 430 mm/yr in April (Tonmukayakul *et al.*, 2009). This deficit is relieved by autumn rainfall which re-establishes the sward before the temperature drops below critical levels for pasture growth. The majority of pasture growth in these regions occurs in spring when soil moisture is at, or near, field capacity and soil temperatures are rising. The efficiency with which pastures use the available water, particularly in spring, is therefore an important contributor to annual pasture yields. Species that have high spring growth and water extraction should be sown (Brown *et al.*, 2003, 2005a; Moot *et al.*, 2008).

The most common pasture mixture in New Zealand's pasture based agriculture is a combination of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) (Brown *et al.*, 2005a). However, this pasture has low productivity when soil moisture is limiting, especially in summer and autumn periods, due to its shallow root system which means that it is less suitable for dryland environments (Brown *et al.*, 2003, 2005a). This can also cause clover content to be reduced in the sward which causes the grass to become nitrogen deficient. There is often a reduction in herbage quality in summer, which reduces stock performance (Brown *et al.*, 2005a). This drop in herbage quality is due to an increase in reproductive development which causes a decline in metabolisable energy (ME) and crude protein (CP) content.

An alternative pasture species for a dryland environment is lucerne (*Medicago sativa* L.). Lucerne has been promoted as a suitable legume for dryland systems in New Zealand for over 100 years (Moot, 2012). It has the potential to increase productivity in dryland environments due to its deep tap root which increases the amount of plant available water, through the drier months, and its ability to use this water more efficiently than grass (Moot *et al.*, 2008) because it can fix nitrogen (Brown *et al.*, 2003, 2005a). Lucerne is summer active but it has limitations of minimal cool season activity, slow early spring production and a lack of persistence (Brown *et al.*, 2005a). This can be overcome by appropriate autumn grazing and winter herbicide management (Moot *et al.*, 2003). Lucerne may also provide increased production under irrigated and high summer rainfall conditions as it provides a high quality feed when ryegrass quality is declining due to its reproductive growth.

The objective of this study was to measure the dry matter production and water use of second year stands of lucerne and perennial ryegrass under irrigated and dryland conditions. Productivity and daily growth rate will be assessed in relation to species and irrigation treatments. Differences in yields will be discussed in relation to crop physiology including thermal time requirements, water extraction and water use efficiency. The nitrogen and ME content of each species under each irrigation treatment will also be examined to quantify herbage quality. From this information recommendations will be made on the suitability of each species under irrigated and dryland conditions. This dissertation is presented in six chapters, beginning with a literature review, followed by materials and methods, results and discussion. In chapter 6, a general discussion will describe the practical implications of these findings in the wider context of pastoral farming in New Zealand.

2 REVIEW OF THE LITERATURE

2.1 Perennial ryegrass

Perennial ryegrass is the most widely used temperate grass in New Zealand (Charlton and Stewart, 2006). This is due to its reputation for high dry matter production over a wide range of fertile soils and its ease of establishment and management. It also has the ability to withstand treading and hard grazing. Perennial ryegrass is most commonly used in pastures for grazing and hay production due to it being a highly nutritious stock feed (Tonmukayakul *et al.*, 2009). However, perennial ryegrass performs poorly in hot, dry conditions compared with other deeper rooted species (Charlton and Stewart, 2006). Some ryegrass cultivars are also susceptible to grass grub damage (*Costelytra zealandica*) and to infections by crown (*Puccinia coronata* Corda, (1837)) and stem rust (*Puccinia graminis* Pers., (1794)) disease which lowers feed quality especially during humid summers (Parry *et al.*, 1992).

Perennial ryegrass is most commonly sown with white clover. This mixture is unsuitable for dryland pasture production in low rainfall (<750 mm/yr) environments (Mills and Moot, 2010). This is due to unreliable production from its shallow root system and low persistence (Moot, 2012). Perennial ryegrass only contributed 19% to total dry matter in year 7 of a ryegrass/white clover pasture compared with 40% for the more drought tolerant cocksfoot (*Dactylis glomerata* L.) in a cocksfoot/subterranean clover (*Trifolium subterraneum* L.) pasture (Mills and Moot, 2010).

2.2 Lucerne

Lucerne or alfalfa, as it is known in North America, is an erect growing, perennial legume that produces stems from the crown of the plant (White and Hodgson, 1999; Charlton and Stewart, 2006). Lucerne is suitable for sheep, cattle or deer production but should be rotationally grazed to maintain persistence and to reduce the likelihood of the crown being grazed (Mills and Moot, 2010). It is commonly used in dryland systems due to its large taproot extracting water from deep soil layers (Charlton and Stewart, 2006). This makes it drought tolerant and gives it the ability to continue to have a high dry matter yield throughout summer. Lucerne should be grown on the deepest, well drained soils on flat to rolling land to take advantage of the deep tap root (Mills and Moot, 2010). Lucerne plants can grow up to 1 m tall and have a deep tap root reaching up to 4.5 m deep (Langer, 1989).

Lucerne is most commonly grown in pure stands on soils with high fertility levels. Optimum yield is produced on soils that are well drained and have a pH greater than 6.0 (Charlton and Stewart, 2006). The area of lucerne in New Zealand peaked at 220 000 ha in 1975 and has since declined by 54% (Douglas, 1986). Lucerne establishes most successfully when spring sown but requires careful seedbed preparation and may require herbicide application to control fast establishing annual weeds (White and Hodgson, 1999; Charlton and Stewart, 2006). However, lucerne is resistant to grass grub (McKenzie *et al.*, 1990) and able to produce over 20 t DM/ha on well drained, high fertility soils (White and Hodgson, 1999).

A larger area is sown to lucerne than any other tap-rooted perennial forage crop in New Zealand (White and Hodgson, 1999). The main areas where lucerne is grown are the east coast of the North and South Islands, Central Otago, the Volcanic Plateau, Bay of Plenty and South Auckland. The amount of lucerne grown declined dramatically in the 1970s (Moot, 2012). A survey in the 1970s showed that 67% of dryland farmers in the South Island grew lucerne but it averaged less than 20% of their farm (Kirsopp, 2001). This differs from the recommended land use of 40-60% for maximum liveweight gain (White, 1982). This decline in the use of lucerne was due to the perception that lucerne management is inflexible especially in spring when animal demand is high. This has resulted in lucerne being used more as a conserved forage for hay and silage. More recently, experiments have redefined spring management of lucerne (Moot *et al.*, 2003). Current recommendations advise famers to introduce ewes with lambs at foot to lucerne when lambs are about two weeks old to create a feed wedge. From here the goal is to maximise lamb liveweight gain. Gains of 308 g/head/day pre-weaning have been recorded on a farm in Marlborough with a 580 mm rainfall (Avery *et al.*, 2008).

The most suitable pasture for a dryland system will meet three criteria: the quantity and quality of spring feed must meet animal requirements, the pasture can efficiently use the water stored in the soil profile and the pasture must be able to survive, recover and persist through periods of drought to avoid costs associated with frequent pasture renewal (Mills and Moot, 2010). Lucerne could therefore be sown in this environment as it meets all of the criteria as shown in the following sections. Despite the importance of lucerne and perennial ryegrass there are few direct comparisons of their growth or response to irrigation and temperature.

2.3 **Pasture growth and yield**

2.3.1 Spring growth and yield

To maintain the viability of dryland systems exposed to periodic moisture stress it is important to use available water resources efficiently within spring to maximise annual production (Mills and Moot, 2010). In spring, temperatures are rising and soil moisture is usually non-limiting in New Zealand due to winter rainfall refilling the soil profile. Maximising dry matter production at this time provides feed to allow stock to reach prime condition and be sold before the summer water deficit sets in. It also allows for the conservation of forage which can then be fed throughout periods of feed deficit in summer or winter. Lucerne has been shown to out produce perennial ryegrass in summer. For example lucerne dry matter yields ranged from 3-7 t DM/ha from September to November under dryland conditions on a Templeton silt loam in the sixth and seventh years of the ‘MaxClover’ grazing experiment (Figure 2.1) (Mills and Moot, 2010). A ryegrass/white clover pasture under the same conditions yielded 2-6 t DM/ha. Lucerne in the sixth year of the ‘MaxClover’ grazing experiment grew at a rate of 100 kg DM/ha/day in November compared with 43 kg DM/ha/day for a ryegrass/white clover pasture (Tonmukayakul *et al.*, 2009).

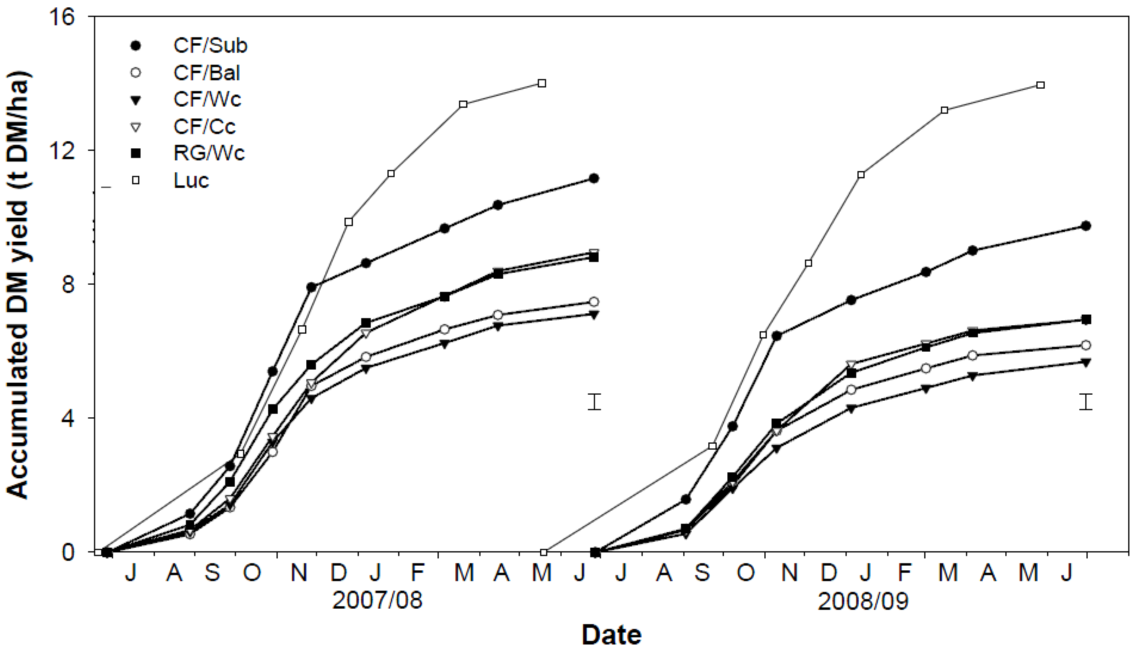

Figure 2.1 Total accumulated annual dry matter yield of six dryland pastures for year six (2007/2008) and year seven (2008/2009) of the 'MaxClover' grazing experiment on a Templeton silt loam at Lincoln University, Canterbury. Error bars are SEM for total annual dry matter yield (From Mills and Moot, 2010).

Lucerne grew for longer at a higher rate in spring (Tonmukayakul *et al.*, 2009). Spring in this environment can be quantified as the period when moisture is non-limiting therefore growth rates are increasing up to a maximum. In summer dry regions lucerne has access to a greater amount of water due to its long taproot. A ryegrass/white clover pasture would be expected to extract only a small amount of water from a depth greater than 1 m (Brown *et al.*, 2005a). Lucerne also begins growth later than ryegrass in early spring as it has to remobilise root reserves. Therefore it has more water available for a longer period and uses that water more efficiently over the season which extends the spring phase of maximum growth. In 2007/2008 lucerne had a reduction in daily growth rates on the 9 December 2008 compared with one month earlier on the 10 November 2008 for a ryegrass/white clover pasture (Figure 2.2) (Mills and Moot, 2010). Growth began for both pastures in August but lucerne took longer to reach its maximum growth rate compared with perennial ryegrass.

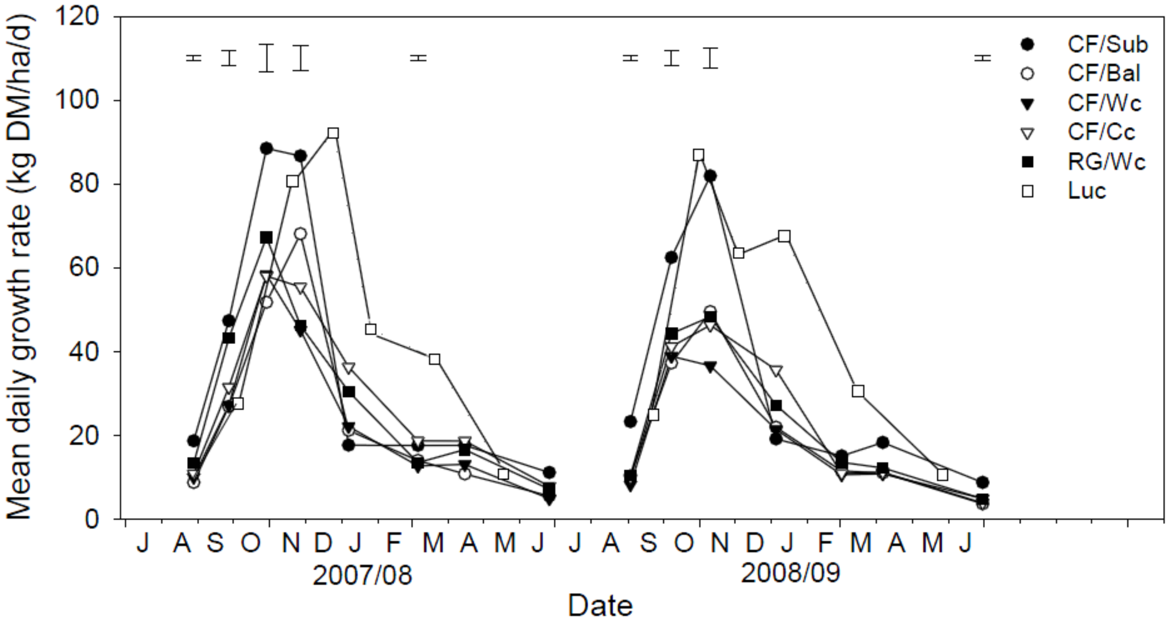

Figure 2.2 Mean daily growth rate of six dryland pastures for year six (2007/2008) and year seven (2008/2009) of the 'MaxClover' grazing experiment on a Templeton silt loam at Lincoln University, Canterbury. Error bars are SEM for rotations where treatment differences occurred (From Mills and Moot, 2010).

2.3.2 Annual dry matter growth and yield

Lucerne had higher annual yields than a perennial ryegrass pasture in the 'MaxClover' grazing experiment (Mills and Moot, 2010). This was due to higher growth rates from October to May. In the first four years of the experiment lucerne produced the highest DM yields of 13.1-18.5 t DM/ha/yr through higher daily growth rates particularly during periods of water stress in summer (Mills *et al.*, 2008). The ryegrass/white clover pasture yielded an average of 9 t DM/ha/yr in comparison. Even after six years, lucerne still had a higher yield than the ryegrass/white clover pasture. Tonmukayakul *et al*. (2009) showed that growth in that sixth year slowed from a maximum in November. The ryegrass/white clover pasture had a growth rate of 24 kg DM/ha/day in January compared with 77 kg DM/ha/day for lucerne. This contributed to the annual yield of 8.7 t DM/ha for lucerne compared with 4.0 t DM/ha for the ryegrass/white clover pasture. In the seventh year of the 'MaxClover' experiment lucerne had an annual yield of 14 t DM/ha compared with 8 t DM/ha for a ryegrass/white clover pasture (Figure 2.1) (Mills and Moot, 2010). Lucerne reached maximum growth rates of 92 kg DM/ha/day in December 2007/08 compared with 50 kg DM/ha/day in November 2008/09 for the ryegrass/white clover pasture

(Figure 2.2). This shows that lucerne was able to maintain its advantage over the ryegrass based pasture for seven years. Douglas (1986) reported that lucerne yields in New Zealand range from 6.5 to 28.0 t DM/ha/yr and average 40% higher than grass based pastures in dryland regions. In an experiment reported by Brown *et al*. (2005a) lucerne had a linear growth rate of 70-100 kg DM/ha/day from November to January compared with 40 kg DM/ha/day for a ryegrass/white clover pasture in Canterbury. Dryland lucerne also had an annual dry matter yield of 12.7 t DM/ha on a Templeton fine sandy loam in Canterbury (McKenzie *et al.*, 1990).

Dryland lucerne had a higher yield than chicory (*Cichorium intybus* L.; Ch) or red clover (*Trifolium pratense* L.; RC) in a five year experiment at Lincoln University on a Wakanui silt loam (Brown *et al.*, 2003). This was due to higher growth rates in September when soil moisture was not limiting growth and from December to May when water was limiting growth (Brown *et al.*, 2005a). This was consistent with results from Mills and Moot (2010). The higher growth rates were due to the greater persistence of lucerne and extracting water from a greater depth (Brown *et al.*, 2003). This increased the amount of plant available water. Dryland lucerne also used water more efficiently because early in the season (spring) when the lucerne had its highest growth rates, the lower air temperature and vapour pressure deficits (represents humidity) increase water use efficiency (WUE). Therefore a higher yield was produced from less water reserves than the same amount of water use (WU) during a period when air temperature was higher. This also indicated lucerne had higher cool season activity contributing to the higher yield. The mean annual production of lucerne was 20 t DM/ha. Lucerne pastures comprised of 94% lucerne in the final year of this five year study. The average growth rate for lucerne in November was 70-80 kg DM/ha/day compared with 40-50 kg DM/ha day for a white clover/ryegrass pasture. The summer growth rate for lucerne was 50-80 kg DM/ha/day compared with 15-30 kg DM/ha/day for a nearby ryegrass/white clover pasture (Hayman and McBride, 1984). The annual yields of 13.4-21.3 t DM/ha for lucerne were almost double the annual yield of 8.5 t DM/ha for the ryegrass/white clover pasture (Black, 2004; Brown *et al.*, 2005a). The ryegrass/white clover pasture extracted 243 mm of water to a depth of 1.5 m compared with the lucerne which extracted 328 mm to a depth of 2.3 m. This highlights the superiority of lucerne over other deep rooting species in dryland conditions.

Lucerne also had higher yields than chicory and red clover under irrigated conditions due to greater cool season activity and higher growth rates in September and from February to May (Brown *et al.*, 2005a). Irrigated swards are more susceptible to weed invasion as weeds are more competitive due to an abundance of moisture not limiting growth. This highlights the sensitivity of lucerne to inappropriate management. Lucerne had persistence of 55% of the botanical composition of the sward. Annual yields of lucerne were 25 t DM/ha. This was consistent with irrigated and dryland lucerne yields exceeding 20 t DM/ha on soils of high available water capacity as reported by Hoglund *et al*. (1974) and Douglas (1986). Growth rates for lucerne were 15 kg DM/ha/day higher than chicory and red clover in September and 10-30 kg DM/ha/day higher from March to May (Brown *et al.*, 2005a). This also highlights the superiority of lucerne over other deep rooting species in irrigated conditions.

Seasonal changes in the above ground growth rate of lucerne are due to consistent changes in the allocation of dry matter between roots and shoots (Teixeira *et al.*, 2007). Lucerne remobilises carbohydrate and nitrogen from roots in spring to begin growth. Therefore in autumn it allocates nutrients to roots to replenish reserves for the following spring. This explains the increase in growth in spring in 2007/08 and the reduction in growth rate in autumn in Figure 2.2.

A perceived disadvantage of lucerne is a lack of winter activity and slow early spring production (Moot, 2012). However this can be overcome to some extent by appropriate autumn grazing and winter herbicide management (Moot *et al.*, 2003). Lucerne should be grazed in late June/early July to remove any residual biomass and overwintering aphids (Douglas, 1986). This graze should be followed 7-10 days later by appropriate contact and residual activity herbicides. The crop should then be spelled until spring and growth should continue in the following season as usual.

Perennial ryegrass was reported to have poor yield and be unsuitable to a dryland environment due to poor persistence by Mills and Moot (2010). This occurred due to the invasion of unsown annual and perennial weed species. The decline in persistence and yield of perennial ryegrass was also due to the invasion of Argentine stem weevil (*Listronotus bonariensis*) and other pests from periodic drought and an inability to access moisture stored further down the profile than 0.8 m. This is similar to the extraction depth of 0.9 m found by Hayman and Stocker (1982) for a ryegrass pasture. Regardless of the reasons, perennial ryegrass failed to persist in a dryland environment therefore its continual use in similar environments is questionable (Mills and Moot, 2010).

2.4 Thermal time

During periods when moisture is non-limiting, growth rates can be related to thermal time (Tonmukayakul *et al.*, 2009). This allows for comparisons between species to be made. Thermal time (also known as heat units or growing degree days (˚Cd)) is calculated as the mean temperature minus the base temperature below which no growth occurs (Equation 1) (Black *et al.*, 2006). Lucerne had a growth rate of 5.7 kg DM/˚Cd compared with 4.1 kg DM/˚Cd for a ryegrass/white clover pasture when a base temperature of 0 ˚C was used by Tonmukayakul *et al*. (2009). A ryegrass/white clover pasture grew 6.5 kg DM/ha/˚Cd in spring in an experiment by Mills *et al*. (2008) with the use of a base temperature of 3 ˚C.

Equation 1 **Thermal time (˚C d) =** $\sum\left[\left(\frac{T_{max}+T_{min}}{2}\right)-T_b\right]$

Temperature causes a seasonal effect on crop growth that cannot be changed through alterations in management (Mills *et al.*, 2006). The main limitation to pasture growth when water was not limiting was shown to be N availability. The impact of changes in seasonal temperature and nitrogen application can therefore be quantified in relation to Tt to predict responses in pasture production. The difference between the two regressions in Figure 2.3 shows the effect of N on yield. This is due to a decrease in photosynthetic efficiency and leaf area expansion when N is limited. Irrigated pastures which had N applied had a higher accumulated dry matter yield at the same accumulated thermal time (7.0 kg DM/˚Cd) compared with irrigated cocksfoot without N (3.3 kg DM/˚Cd).

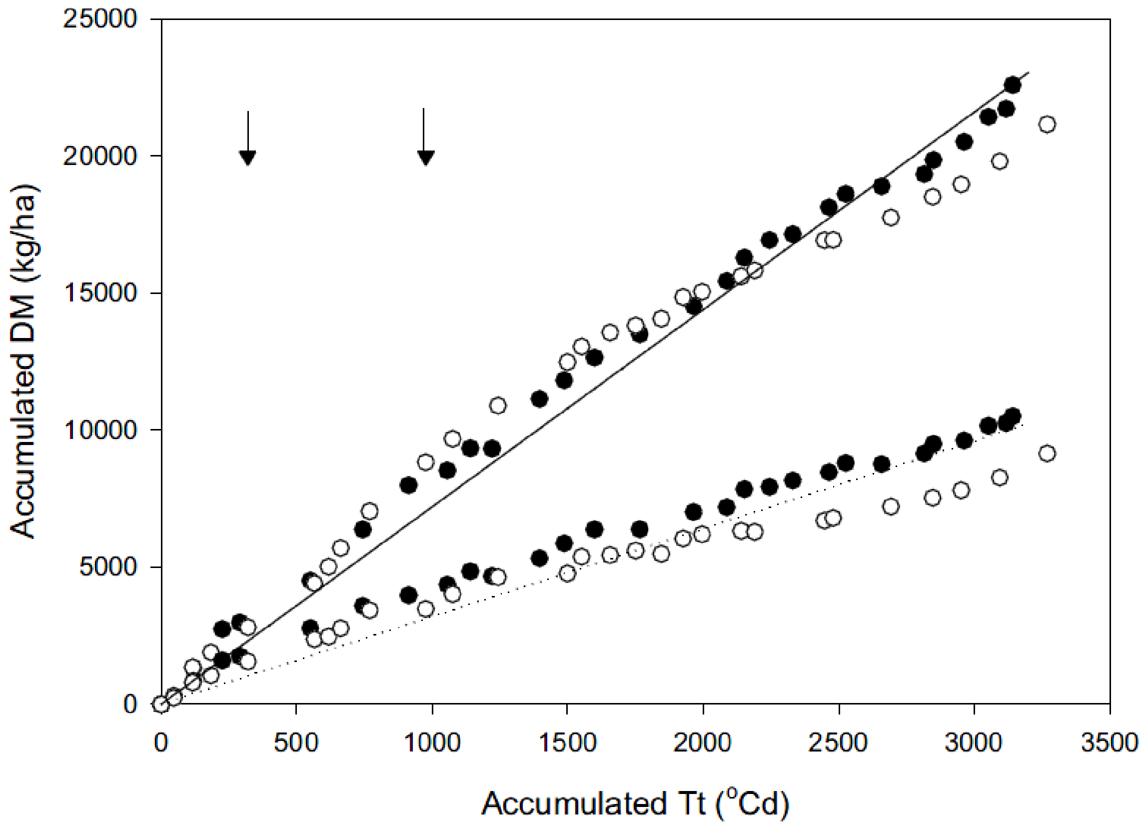

Figure 2.3 Accumulated thermal time (Tt, ˚Cd) against accumulated dry matter yield (kg/ha) for 2003/04 (closed symbols) and 2004/05 (open symbols) of irrigated +N (—) and irrigated –N (·····) 'Wana' cocksfoot pastures with a base temperature of 3 ˚C at Lincoln University, Canterbury, New Zealand (From Mills *et al.*, 2006).

2.5 **Soil water**

Soils in Canterbury vary considerably in their depth to gravel which affects soil water holding capacity which largely determines dry matter production under dryland conditions (Tonmukayakul *et al.*, 2009). For example, plant available water for a cocksfoot/subterranean pasture was 223 mm compared with 340 mm in a nearby lucerne plot within the same replicate (Figure 2.4).

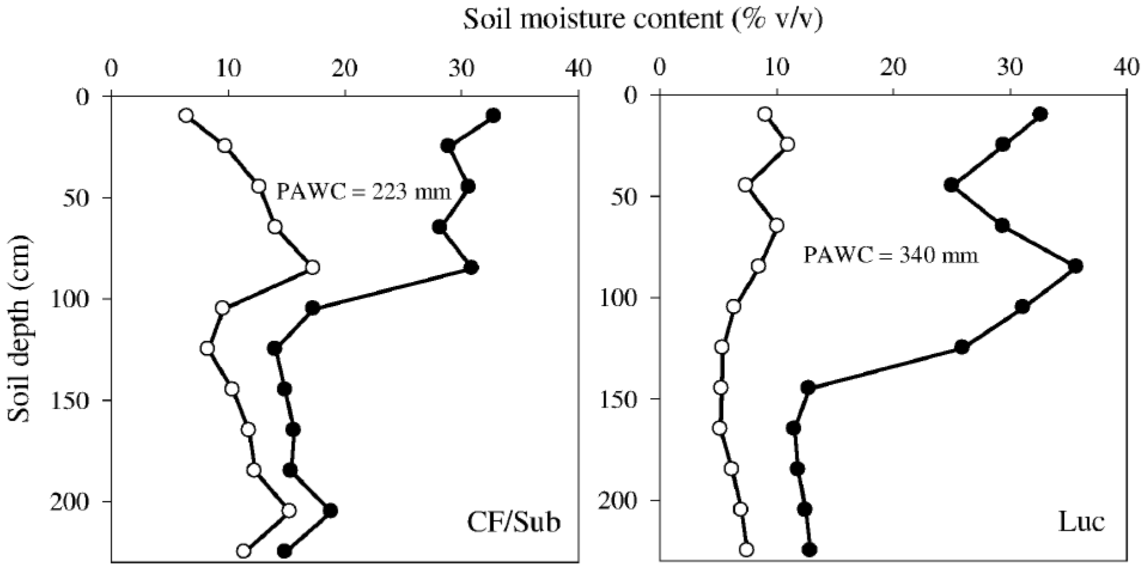

Figure 2.4 Soil moisture content (%v/v) for each 0.2 m soil layer from 0-2.3 m depth under a cocksfoot sub clover and lucerne pasture grown on a Templeton silt loam soil at Lincoln University, Canterbury. Where DUL (●) is the drained upper limit and LL (○) is the lower limit from the 1 July 2008 to 18 June 2009 (From Tonmukayakul *et al.*, 2009).

Water holding capacity of the variable soils in Canterbury can also fluctuate considerably with depth (Tonmukayakul *et al.*, 2009). This impacts on the amount of plant available water and therefore how much water the plant can extract and use to produce dry matter. The water content of a soil is the total amount of water that a soil can hold. The plant available water is the proportion of this that the plant can access and extract and this varies across soil types. On a silt loam the available water is about 50% of the total soil water content (McLaren and Cameron, 1996). The drained upper limit of a soil or field capacity is when the soil is at saturation point (McLaren and Cameron, 1996). The lower limit of the soil is when it has reached permanent wilting point. Between the drained upper limit and the lower limit is the plant available water. However, all of this water is not equally available. Generally the first 50% of water is readily available. Once this has been used by the plant it has reached the critical limiting deficit where water stress commences. The water between the critical limiting deficit and the lower limit is harder for the plant to access. Moisture content of a Templeton silt loam soil at field capacity is

33.8% v/v and 15.5% v/v at permanent wilting point. Figure 2.4 shows that in the top 0.2 m of the top soil there was a drained upper limit of over 30% and lower limit of 8% (Tonmukayakul *et al.*, 2009). Below depths of 1.0 m the drained upper limits were between 10 and 15% indicating the presence of stones and a lot less silt at depth which lowered the plant available water in each layer.

Water supply is made up of soil water extraction and rainfall (Brown *et al.*, 2003). Therefore species that are able to extract water from a greater depth, such as lucerne, are less affected by reductions in within season rainfall. This is because rainfall makes up less of their water supply, compared with grass, provided the soil water content is fully recharged over winter. Lucerne roots often reach in excess of 3 m depth, therefore even on soils of low plant available water capacity, the deep tap root may provide water for one to two weeks more growth than a perennial ryegrass/white clover pasture.

2.5.1 Potential soil water deficit

The extent to which water supply limits pasture growth during a season is described by the potential soil water deficit (PSWD) (Brown *et al.*, 2003). The PSWD is the amount of water that is required to bring the soil back to field capacity determined by PET and rainfall (Equation 4). The actual soil water deficit (SWD) is calculated from actual plant water use and rainfall. The SWD is higher in dryland than irrigated pastures and varies annually. In a dryland system SWD is dependent on the ability of winter rainfall to refill the soil profile. If the profile is not completely refilled then this causes the SWD in the following season to be greater. In irrigated conditions the SWD is dependent on the ability of rainfall and irrigation to refill the soil profile. Under dryland conditions lucerne had a higher soil water deficit than chicory or red clover because it was reliant on rainfall which is less consistent than irrigation (Brown *et al.*, 2005a). Lucerne had a higher SWD than other deep tap rooted species. The higher mean SWD for lucerne shows the potential for it to extract more water. The highest SWD was in the 1997/98 season, when lucerne had a maximum deficit of 407 mm. This was due to incomplete soil water recharge in the previous winter. In 1998/99, 2000/01 and 2001/02 the maximum SWD for lucerne was >350 mm due to a dry season. The smallest SWD was in the 1999/00 season when lucerne had a maximum SWD of 250 mm due more rainfall than the average season. The SWD for lucerne only reached zero in the spring of the 2000/01 season.

Therefore, actual SWD that a plant experiences is dependent on the season and irrigation level (Martin, 1990). In spring, SWD is similar between dryland and irrigated pastures due to the soil profile being rewetted over winter. As the soil dries out in summer, the SWD increases to a higher level in dryland than irrigated pastures because irrigated pastures get a consistent supply of water over the seasons. Soil water deficits to a depth of 1.05 m in unirrigated ryegrass/white clover pastures grown in Canterbury were similar to irrigated pastures in spring, but 40% higher in summer and then twice as high in autumn.

Water extraction depths are also dependent on the SWD of the soil (Martin, 1990). This is a likely trend because a plant will extract water from the top soil first as this is the easiest water to access. Once it has used all of the water in the top soil it will start to extract water from further down the soil profile up to the depth that the roots reach. When the SWD was less than 128 mm in an experiment by Martin (1990) on a Templeton silt loam, a ryegrass/white clover pasture extracted water from the top 450-600 mm. When the soil deficits were higher, up to a maximum of 190 mm water was extracted down the full depth of the measured profile to 1.05 m.

The critical soil moisture deficit reduces growth earlier in dryland than irrigated pastures (Martin, 1990). On a Templeton silt loam pasture production began to decline when the SWD exceeded 90 mm to a depth of 1.05 m or 30% of the water holding capacity of the soil. Therefore under irrigated conditions the soil water was able to be maintained above the critical soil moisture deficit due to regular applications of water. Dryland pastures are reliant on rainfall therefore if rainfall is irregular the critical soil moisture content will be exceeded. Dryland pastures grew at a similar rate to irrigated pastures when the soil moisture deficit was less than 90 mm. At a soil moisture deficit of 80-100 mm, dry matter accumulation in the dryland pastures reduced to less than that of irrigated pastures. This shows that dry matter production of irrigated pastures was unaffected by the critical water deficit.

2.6 **Water use efficiency**

There are multiple definitions for water use efficiency. The most commonly used in agronomy is the ratio of total dry matter (DM) accumulation to total water input in a system (Moot *et al.*, 2008) or the ratio of the amount of biomass produced to potential or measured evapotranspiration (PET) (Martin *et al.*, 2006). For irrigation systems WUE is defined as the ratio of water beneficially used to irrigation water delivered. WUE can also be defined as the ratio of marketable unit yield per unit water used. To increase WUE a balance between supply and demand is required under irrigated conditions. In dryland conditions the available water capacity of the soil and depth of extraction determine annual WUE (Moot *et al.*, 2008).

2.6.1 Soil type

The advantage of a species with deep roots is most recognised on a deep soil (Hayman and McBride, 1984; Moot *et al.*, 2008). This is due to deep rooting species being able to use a substantial amount of winter rainfall stored in the soil profile (Section 2.5). Figure 2.5 shows that on a deep Wakanui silt loam soil, dryland lucerne had an annual WUE of 40 kg DM/ha/mm which was a result of extracting 328 mm of water to a depth of at least 2.3 m (Moot *et al.*, 2008). On the same soil, ryegrass had a WUE of 18 kg DM/ha/mm as a result of extracting 243 mm of water to a depth of 1.5 m. On a stony Lismore soil, a ryegrass/clover pasture extracted 129 mm of water to a depth of 1.5 m resulting in a WUE of 16 kg DM/ha/mm. On a stonier Lismore soil, lucerne extracted 131 mm of water to a depth of 2.3 m resulting in the same WUE as ryegrass on this type of soil (16 kg DM/ha/mm). The soil type in the current experiment is a mixture of an Eyre and Templeton soil (Section 3.1). Therefore WUE is expected to be closer to the Lismore soil rather than the Wakanui silt loam.

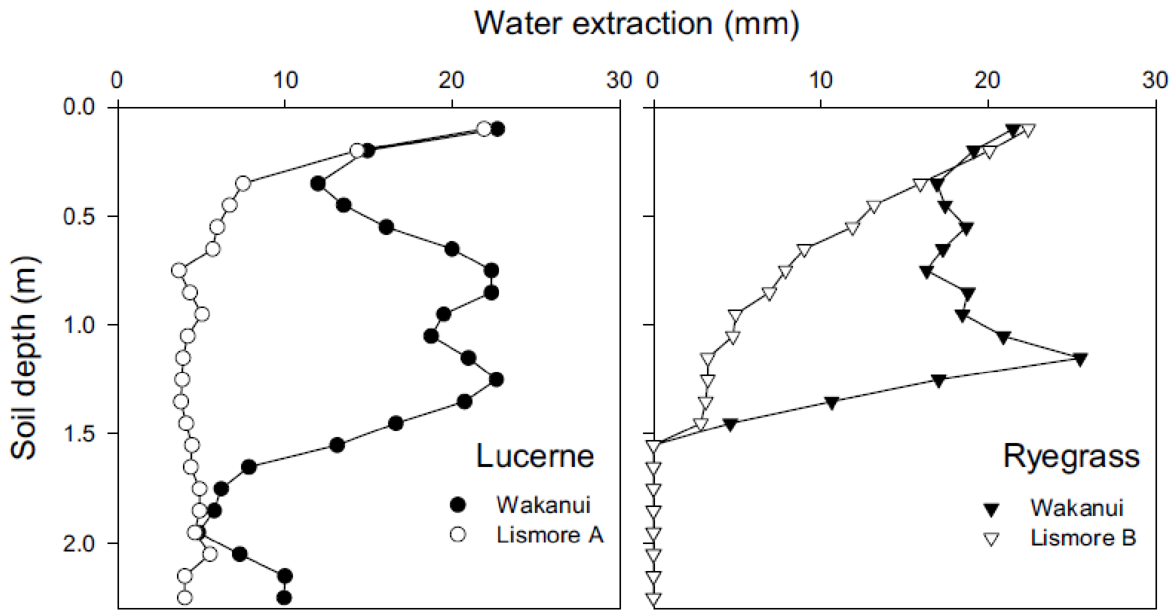

Figure 2.5 Water extraction for lucerne (circles) and grass based pastures (triangles) from each 0.1 m soil layer from 0-2.3 m depth on a deep Wakanui silt loam and a Lismore very stony loam (A) and Lismore stony loam (B) from Lincoln and Ashley Dene, Canterbury, New Zealand (From Moot *et al.*, 2008).

2.6.2 Species

Water use efficiency differs across species (Moot *et al.*, 2008). This can be demonstrated in the spring period when WUE of all species is at its highest due to favourable atmospheric conditions and a high amount of available soil water. The higher WUE for legumes is due to their higher herbage N content from biological N fixation. Irrigated perennial ryegrass in an experiment by Parry *et al.* (1992) had a WUE of 22.3 kg DM/ha/mm on a Wakanui silt loam using 400 mm of water to a depth of 0.8 m. Lucerne had a WUE of 30 kg DM/ha/mm compared with 14 kg DM/ha/mm for a ryegrass/white clover pasture on a Templeton silt loam soil (Tonmukayakul *et al.*, 2009). Figure 2.6 shows that a lucerne monoculture had a WUE of 24 kg DM/ha/mm compared with 20 kg DM/ha/mm for a perennial ryegrass/white clover pasture and 13 kg DM/ha/mm for a perennial ryegrass monoculture on a Templeton soil (Moot *et al.*, 2008). Clover monocultures had a higher WUE (30-40 kg DM/ha/mm) than their binary mixtures (23-37 kg DM/ha/mm) and the ryegrass monoculture had the lowest WUE of 15 kg DM/ha/mm on a Templeton soil.

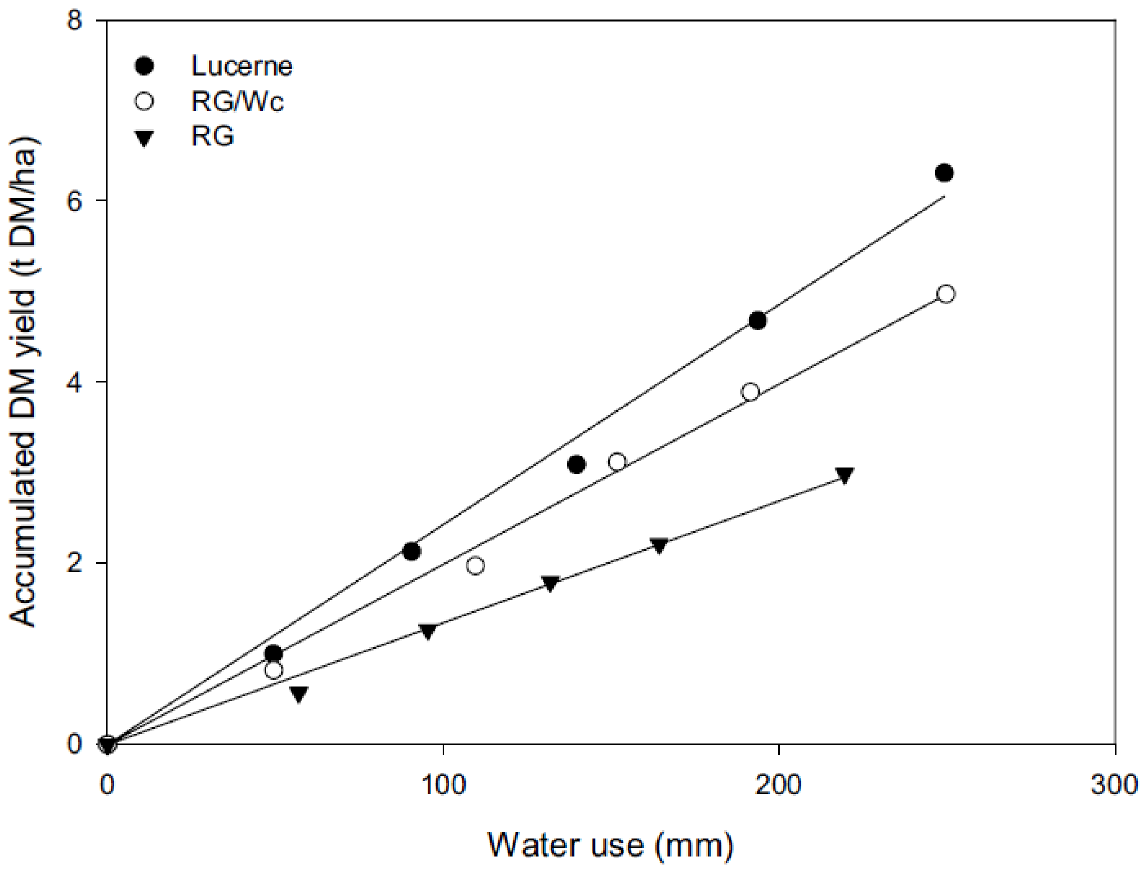

Figure 2.6 Accumulated dry matter yield (t DM/ha) and spring water use (mm) for spring for lucerne, perennial ryegrass/white clover (RG/Wc) and perennial ryegrass (RG) with a WUE of 24, 20 and 13 kg DM//ha/mm on a Templeton silt loam soil at Lincoln, Canterbury (From Moot *et al.*, 2008).

Hayman & McBride (1984) compared irrigation experiments across a number of Canterbury locations with contrasting soil types. At three sites, data were recorded for both grass based and lucerne pastures over five years (Martin *et al.*, 2006). To maintain maximum WUE no irrigation would be used but this would not optimize pasture production. Farmers can increase WUE by applying water evenly, avoiding over application of irrigation, scheduling irrigation and using efficient forage species such as lucerne. This is due to differences in losses from soil evaporation, drainage and run off. The five year means (Table 2.1) show that lucerne received slightly fewer irrigations than pasture because it had access to more water so did not require irrigation as frequently. Lucerne had a 13% higher yield under the top three irrigation treatments and up to 50% more yield without irrigation. This was due to a higher WUE across irrigation treatments of 18.0 to 9.6 kg DM/ha/mm.

Table 2.1 The five year mean dry matter yield (t DM/ha), number of irrigations and WUE (kg DM/mm water applied) of a ryegrass/white clover pasture and lucerne sward averaged over three soil types in Canterbury using data from Hayman & McBride (1984). ASM is available soil moisture content (From Martin *et al.*, 2006).

		Dryland	Irrigated at -10% ASM	Irrigated at 0% ASM	Irrigated at 25% ASM	Irrigated at 50% ASM
Pasture	Yield (t DM/ha)	6.4	9.2	10.7	11.3	11.8
	Irrigations		3	4	6	9
	WUE (kg DM/mm)	12.9	11.9	12.1	10.5	8.5
Lucerne	Yield (t DM/ha)	9.7	11.2	12.0	12.9	13.5
	Irrigations		2	3	5	9
	WUE (kg DM/mm)	18.0	15.0	14.3	11.9	9.6

2.6.3 Season

WUE differs across seasons (Moot *et al.*, 2008). The seasonal differences reflect how soil moisture deficit, soil evaporation and drainage affect pasture growth. Within a year, ryegrass had a WUE that ranged from 3 to 22 kg DM/ha/mm (Figure 2.7). The highest WUE of 22 kg DM/ha/mm was between September and January. This then decreased to 3 kg DM/ha/mm through the driest months of February to April, due to an increase in temperature and a low amount of available water. Although 70 mm of rain fell through this period the WUE did not change as the pasture had dried off and the water was lost as soil evaporation with minimal pasture recovery. This water loss often occurs in dryland environments due to high soil evaporation rates in the summer. The combination of warm soil and low pasture cover causes rapid soil evaporation of the first 10-20 mm of any rainfall event. In early April, 120 mm of water fell which restored the soil to near field capacity. However, it took the pasture another three weeks to regain full ground cover and for WUE to increase. For the May-June period WUE was 18 kg DM/ha/mm. After this, temperature began to limit pasture production and, of the 178 mm of rain that fell some was lost as drainage due to the low water holding capacity of the soil. This reduced the

WUE to 9 kg DM/ha/mm. This shows the disadvantages of ryegrass in a dryland system as it had a lower WUE in spring and summer compared with lucerne. Lucerne was able to maintain a high WUE in summer due to its ability to extract water from depth. Therefore if rain does fall it is able to utilise it more efficiently than ryegrass to grow a higher yield.

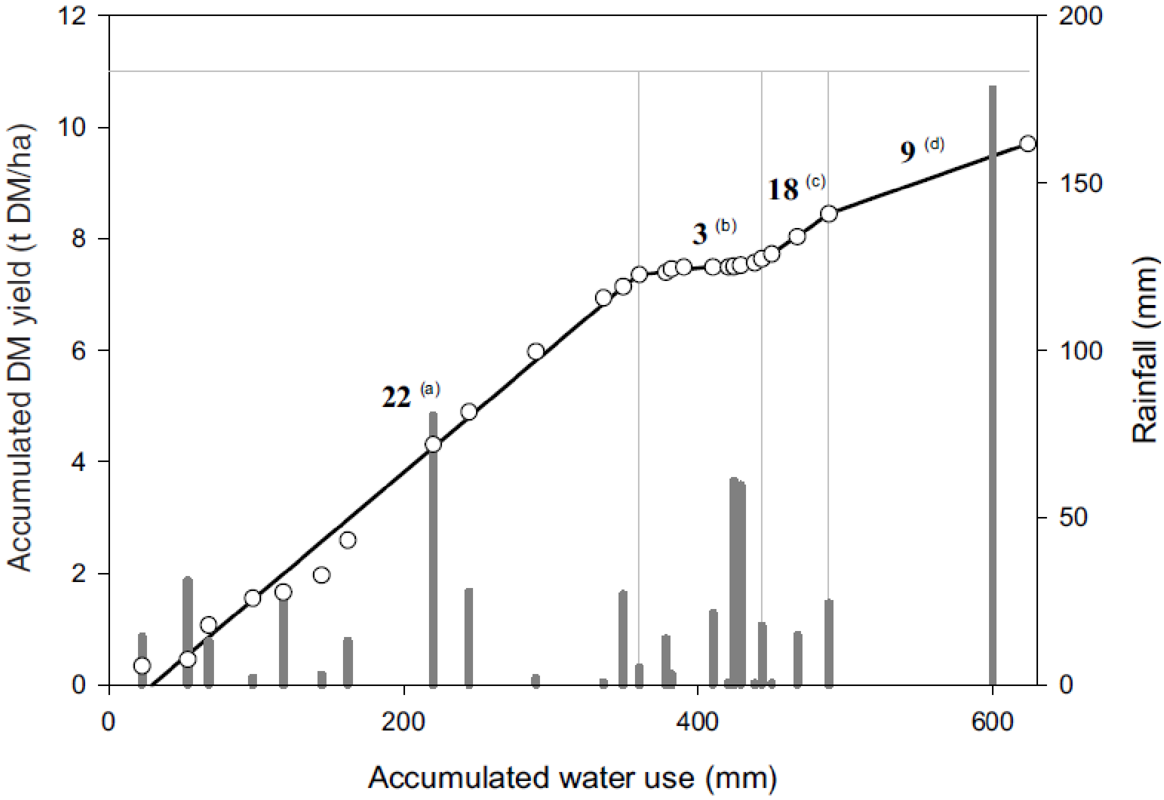

Figure 2.7 Accumulated dry matter yield (t DM/ha) and accumulated water use (mm) for a year long period for a dryland perennial ryegrass pasture on a Lismore very stony loam soil at Ashley Dene, Canterbury, New Zealand. Dark grey bars represent rainfall (mm) and the light grey lines show periods of different WUE: (a) had a WUE of 22 kg DM/ha/mm (17/9/2002-23/1/2003), (b) was 3 kg DM/ha/mm (23/1-29/4/2003), (c) was 18 kg DM/ha/mm (29/4-12/6/2003) and (d) was 9 kg DM/ha/mm (13/6-16/9/2003) (From Moot *et al.*, 2008).

2.7 Nitrogen and quality parameters

Nitrogen (N) is required to maximise photosynthetic rates and WUE (Mills and Moot, 2010). This is due to nitrogen being an essential plant element. Nitrogen supply from the soil is frequently inadequate to meet the high requirement from crops (Sun *et al.*, 2008).

Low leaf nitrogen limits leaf expansion, reducing light interception, growth and potentially yield (Mills and Moot, 2010). The addition of N fertilisers overcomes this problem in grasses but in dryland areas of New Zealand the use of top dressed inorganic nitrogen fertilisers is generally uneconomic (Fasi *et al.*, 2008). The response of dry matter production to N application in perennial ryegrass was ～20 kg DM/kg N. Therefore pasture production and quality are determined by the proportion of legume able to be maintained in the sward (Moot, 2012). Applying phosphorous and sulphur fertilisers is considered a cost effective alternative to increase N availability as this increases symbiotic N fixation, without the environmental issues from increased applications of nitrogen fertilisers (Sun *et al.*, 2008). Biological nitrogen fixation rates can range between 100-300 kg/ha/yr for grass/clover pastures in New Zealand. A generalized figure in New Zealand for N fixation is 25 kg N/t DM produced (Peoples and Baldock, 2001; Lucas *et al.*, 2010). The average annual N content of ryegrass was 2.7% compared with 3.9% for lucerne (Mills and Moot, 2010). The reduction in N content of their perennial ryegrass was due to the invasion of unsown annual and perennial weed species. The yield of the sown perennial ryegrass in the seventh year of the study was only 2.4 t DM/ha/yr. Moot *et al*. (2008) found that the N content of cocksfoot green herbage was 4.2% when nitrogen was applied compared with 2.9% with no N. The yield of the cocksfoot pasture increased from 6.3 t DM/ha when N was not applied to 15.7 t DM/ha with applied nitrogen, which highlights the importance of nitrogen to a dryland pasture that is usually N limited (Mills *et al.*, 2006).

The main consequence of limited N is plants decrease leaf size (Tonmukayakul *et al.*, 2009). This is so that the plant can maintain N concentrations above critical levels that affect photosynthesis. The N concentration below which photosynthesis is affected was found to be 2.6% for cocksfoot. This explains why herbage N concentration is usually within the range of 3-4% (Peri *et al.*, 2002).

Because of its effects on photosynthesis and leaf extension, nitrogen also impacts on WUE (Moot *et al.*, 2008; Moot, 2012). Ryegrass monocultures had the lowest WUE of 15 kg DM/ha/mm which was increased to 20 kg DM/ha/mm when WC was included (Moot *et al.*, 2008). A cocksfoot monoculture with applied nitrogen had a WUE of 38 kg DM/ha/mm compared with 17 kg DM/ha/mm when no N was applied.

N also affects pasture quality. Crude protein and metabolisable energy were at least double in cocksfoot pastures containing N (3.2-4.2 t/ha/yr and 178 GJ ME/ha/yr) than without N (1.0 t/ha/yr and 69 GJ ME/ha/yr) (Mills *et al.*, 2006). Annual CP increased by 30% from 2003/04 to 2004/05 in the pastures with N but there was no change in the treatments without N. This trend was also seen for ME which increased by 7% in the +N treatments. Lucerne had a ME content in utilised herbage of 10.9-11.6 MJ/kg (Brown *et al.*, 2005a). Lucerne had a CP content of 29%. The average ME content of ryegrass was ～11.7 MJ/kg DM compared with 11.0 MJ/kg DM for lucerne (Mills and Moot, 2010).

2.8 Conclusions

- Lucerne had a higher dry matter yield than other deep rooting species and a ryegrass/white clover pasture therefore it should be planted on deep soils to realise the yield advantage from having greater access to water. Lucerne roots can grow in excess of 3 m when there are no barriers to root penetration which can provide the plant with one or two weeks more growth than a ryegrass/ white clover pasture.
- The yield advantage of lucerne over a perennial ryegrass/white clover pasture was due to high mean daily growth rates from October to May. Lucerne had a linear growth rate of 70-100 kg DM/ha/day from November to January compared with 40 kg DM/ha/day for a ryegrass/white clover pasture in Canterbury.
- The high dry matter production of lucerne could also be quantified using thermal time. Lucerne had a growth rate of 5.7 kg DM/˚Cd compared with 4.1 kg DM/˚Cd for a ryegrass/white clover pasture.
- WUE also affected dry matter production and can be maximized by the use of legume monocultures such as lucerne or management that encourages clover production within a pasture. This is because N increases the photosynthetic efficiency per unit leaf area. A lucerne monoculture had a WUE of 24 kg

DM/ha/mm compared with 20 kg DM/ha/mm for a perennial ryegrass/white clover pasture and 13 kg DM/ha/mm for a perennial ryegrass monoculture on a Templeton soil

- The use of strategic applications of N (150 kg N/ha/yr) on grass based pastures can also be beneficial in increasing WUE and quality of a pasture if economically feasible. ME increased by 7% when N was applied to a cocksfoot pasture.

3 MATERIALS AND METHODS

3.1 **Location and Site History**

This experiment was set up and run by Plant and Food Research and located on the AgResearch farm, Lincoln, Canterbury, New Zealand (43˚37’16” S 172˚28’15” E, 18 m a. s. l.) (Plate 1) (Minchin *et al.*, 2011). The soil type is a mixture of Eyre silt loam (Pallic Orthic Brown Soil; Udic Haplustept loamy skeletal) and Templeton moderately deep silt loam soil (Immature Pallic Soil; Udic Haplustepts) Full descriptions and classifications were given by Hewitt (1998) and Soil Survey Staff (1998). The shallow Eyre soil is well drained with 110 mm of total available water per metre of soil and a potential rooting depth of 0.7-1 m (Landcare Research, 2012). It has a top soil depth on average of 300 mm to gravel with more than 2% stones in the top soil (Minchin *et al.*, 2011). The moderately deep Templeton silt loam is moderately well drained with 129 mm of total available water per metre of soil and a potential for unlimited rooting depth (Landcare Research, 2012).

The experimental site was sown in ‘Conquest’ wheat (*Triticum aestivum* L.) for the 2010-11 season (Minchin *et al.*, 2011). The wheat was harvested using a small plot harvester, before the straw was baled and removed on the 17 February 2011. The plots were then sprayed using an ATV sprayer with 3 L/ha Glyphosate (720 g/ha) and 20 g/ha of Tribenuron-methyl (750g/kg) in 200 L/ha water on 24 February 2011. The wheat stubble in the experimental area was mown prior to the sideroll irrigation being set up on 28 February 2011. Pre sowing irrigation of 40 mm was applied on the 1 March 2011. The entire site then had Glyphosate (360 g/L) applied at a rate of 3 L/ha using the ATV sprayer on the 8 March 2011 prior to the lucerne being sown. All ryegrass fallow plots and the area surrounding the experiment were also sprayed with 3 L/ha Glyphosate (360 g/L) in 200 L/ha water on the 21 March 2011 prior to the ryegrass being sown.

Plate 1 Aerial view of the complete experimental area at AgResearch farm, Canterbury, New Zealand on the 22 January 2013.

3.2 **Experimental Design**

The experimental area is 24 x 68 m with an eight metre fallow strip down the centre (Plate 1). Within this area there are 32 plots, each 32 m^2 (8 x 4 m). These were split into four replicates of eight treatments. Each of the replicates had four plots sown in lucerne and four in ryegrass with each of the four plots having one of four irrigation treatments applied (Appendix 1). The treatments for the 2012/13 season were: full replacement of evapotranspiration (ET) twice a week (Monday and Thursday; irr 1) or once every two weeks (Thursday; irr 2) or once every three weeks (Thursday; irr 3) or no irrigation (dryland; dr). Irrigation began on the 1 November 2012 for the second year of the experiment. In the first year (2011/12) the irrigation treatments were: irrigated twice a week to replace ET (Monday and Thursday), once a week to replace ET (Thursday), once every 15 days to replace ET (Thursday) or no irrigation. The design was based on the previous wheat experiment and used previous irrigation treatments and the physical 'block' as blocking factors, leading to a latinised row by column design.

3.3 **Sowing and Establishment**

The lucerne plots were sown on the 10 March 2011 using a Taege 13 coulter (150 mm row) direct drill from North to South with two drill widths per plot at a rate of 14 kg/ha of coated seed. The lucerne seed used in this experiment was Pioneer pelleted seed '54V09' which included an inoculant, molybdenum, fungicide and insecticide (Superstrike) in the lime based coating. The first sign of emergence from the lucerne plots was on the 15 March 2011. Methiocarb (7.5 kg/ha) was broadcast, to control slugs and snails (*phylum Mollusca*), on the same day across all of the lucerne plots at a rate of 10 kg/ha. The lucerne crop was at the 4th true leaf stage on the 19 April 2011.

The ryegrass was sown on the 24 March 2011 using the same method as for the lucerne plots. The ryegrass seed sown was 'Grasslands Samson' perennial ryegrass at a rate of 25 kg/ha. The first sign of emergence for the ryegrass was on the 5 April 2011.

Neutron probe tubes were installed in each plot on the 18 April 2011 to a depth of 1.5 m. Neutron probe (CPN 503DR Hydroprobe) readings were taken at seven depths down to 1.5 m, 200 mm apart, starting at 300mm. Readings were taken every two weeks over the growing season (September to May) and once a month throughout winter (June to August). Photos were taken at 45˚ for a percent cover analysis using Quant on the 20 April 2011. All irrigation laterals were set up on the 5 May 2011.

The automated Time-Domain Reflectometers (TDR) were purchased from Campbell Scientific®, model CS 616 and were installed and functioning on battery power on the 25 August 2011. The TDR's were placed at 0-150 mm and 150-300 mm. Readings were taken every hour.

A weather station was installed on the 14 September 2011 which recorded the temperatures from the sensors and the crop canopy. Descriptions of sensors are outlined in Section 3.10.

AgResearch installed irrigation in the experiment paddock on the 29 August 2012. In preparation, all TDR probes and irrigation lines were removed from plots 16 and 32 because the guide wire was to run through these plots, 800 mm below the surface. The top of the neutron probe tube was removed in plot 32 on the 29 August 2012 to avoid it being damaged. The bulldozer ripped a 200-250 mm strip, 3-4 rows east of the middle of the plot (Plate 1). TDR rods and an extension on the neutron probe tube were reinstalled on the 30 August 2012. There was sufficient undisturbed area in plot 32 to continue measurements on. For plot 16 the side that measurements were taken in was changed to minimise any bias.

3.4 **Crop Agronomy**

The agrichemical, fertiliser and irrigation use for the period from post emergence to 30 June 2013 is outlined below.

3.4.1 Agrichemical Use

Diazinon (2.4 kg/ha and 2.2 kg/ha) was applied to control grass grub on the 15 April 2011 as there were patches of ryegrass that looked drought stressed and when pulled, plants were removed easily indicating grass grub had chewed the roots. Diazinon (2.4 kg/ha) requires rain after application and there was 25 mm of rain from the 16-17 April 2011. Diflufenican (375 g/ha) was applied to control broadleaf weeds. Chlorpyrifos (500 g/ha) was used to control chewing insects. Methiocarb (7.5 kg/ha) is a slug and snail bait. Ethofumesate (2 kg/ha) and Haloxyfop (150 g/ha) were used to kill Annual Poa (*Poa annua* L.). Metaldehyde (8 kg/ha) is also slug bait. Dicamba (200 g/ha) and Dimethylamine salt (1.5 kg/ha) were applied to control clover and broadleaf weeds. Full details of the different agrichemicals applied to lucerne and perennial ryegrass plots are shown in Appendix 2. On the 22 June 2012, 3 L/ha Glyphosate (720 g/ha) was applied to all of the lucerne plots. Plate 2 shows the lucerne before glyphosate application and Plate 3 shows damaged dryland lucerne after herbicide application.

Plate 2 Lucerne plots prior to glyphosate application on the 22 May 2012**.**

Plate 3 Lucerne damage and regrowth post glyphosate application in a dryland plot on the 17 September 2012.

3.4.2 Soil fertility

Two 0-150 mm and two 150-300 mm soil cores were taken from each wheat plot on 28 February 2011 for nitrate and ammonia tests. One 0-150 mm core from each plot was also taken and combined for a basic soil test (Table 3.1). On the 11 March 2011 soil core samples were retaken from the experimental area at a depth of 0-150 mm to repeat the pH tests which were a concern at pH 5.4 (Table 3.2). The pH was determined to work out the amount of lime required to be applied to bring the pH up to an optimum of 6.4 for lucerne. Based on results Optima fine grind pelleted lime was applied to all plots at a rate of 2 t/ha on the 21 March. All lucerne plots also had two 150 mm soil core samples taken on the 6 July 2011. These were combined and then passed through a 4 mm sieve before being sent to the lab for pH measurements. This was followed by an application of 200 kg/ha of lime to all plots on the 21 July 2011. Two 150 mm soil cores were taken on the 8 December 2011 from each lucerne plot, combined and then passed through a 2 mm sieve. Twelve grams was weighed into a 50 ml beaker with 25 ml of deionized (DI) water. This was stirred and then left to stand for 2 hours before the pH was tested. Lime was applied to the lucerne plots on the 29 December 2011 at a rate of 200 kg /ha. On the 8 May 2012, two 150 mm soil cores from each of the lucerne plots were taken and bulked for each of the four replicates. On the same day, 200 kg/ha of lime was applied to all lucerne plots. One 0-150 mm core from each plot was also taken and combined for a basic soil test (Table 3.1). On the 9 May 2012, pH was tested by adding 10 grams of field moist soil to a beaker and then 25 ml DI water. The sample was then shaken and left to stand for one hour until measurements were taken when the numbers stabilised for 10 seconds. Lime was applied on the 21 June 2012 and 19 October 2012 at a rate of 200 kg/ha. Table 3.2 shows the average pH readings for the lucerne plots, as the lime was applied. The initial application lifted the pH from 5.4 to 6.0 in July 2011 but fell to 5.8 after this.

Table 3.1 Basic soil test results for Olsen P (µg/mL), calcium, magnesium, potassium and sodium from soil cores taken at a depth of 0-150 mm on the 28 February 2011 and 0-75 mm on the 8 May 2012 at AgResearch farm, Canterbury, New Zealand.

	Date	
	28 February 2011	8 May 2012
Olsen P (µg/mL)	29	30
Calcium (QTU)	8	9
Magnesium (QTU)	11	9
Potassium (QTU)	9	5
Sodium (QTU)	11	6

Table 3.2 Results from soil tests for pH from February 2011 to May 2012.

Date	pH (average)
February 2011	5.4
July 2011	6.0
December 2011	5.9
May 2012	5.8

All plots had two soil core samples taken at two depths of 0-150 and 150-300 mm on the 5 September 2011 and 27 August 2012 which were combined to determine the soil mineral nitrogen levels for each of the treatments. On the 5 September 2011 lucerne and perennial ryegrass pastures under all irrigation treatments had ammonium and nitrate levels less than 1 mg/kg. Following the soil test, nitrogen was applied to the plots as urea (46:0:0:0). Urea application rates and the plots it was applied to can be found in Appendix 3. On the 27 August 2012 lucerne and perennial ryegrass pastures under all irrigation treatments had ammonium levels less than 3 mg/kg and nitrate levels less than 4 mg/kg. Following this soil test urea was once again applied (Appendix 3).

For season one from February 2011 to 30 June 2012, the total N applied as urea to the ryegrass plots was dependent on irrigation treatment. Fully irrigated pastures had 834 kg N/ha applied, two weekly irrigation received 757 kg N/ha, three weekly irrigation received 743 kg N/ha while unirrigated pastures received 502 kg N/ha. All lucerne plots had 30 kg N/ha applied as Cropzeal 16N (15.4:8:10:9.6) on the 15 March 2011. In season two from 1 July 2012 to 30 June 2013, there was no nitrogen applied to the lucerne plots. For the ryegrass plots, 649 kg N/ha was applied as urea to the fully irrigated pastures, 591 kg N/ha to the pastures irrigated every two weeks, 512 kg N/ha to the pastures irrigated every three weeks and 347 kg N/ha to the unirrigated pastures. Full fertiliser details are shown in Appendix 3.

3.4.3 Irrigation

During the first season (2011-2012) the amount of drip irrigation applied was determined by daily Penman PET and rainfall data which were collected from Broadfields meteorological station (Section 3.7). The PET values were summed for the period from the previous irrigation to the day before the next irrigation. The total rainfall for that period was subtracted from the total PET amount which gave the amount of water required to be applied as drip irrigation (Equation 2).

Equation 2 $$Irrigation = Periodical\ PET - Periodical\ rainfall$$

During the second season (2012-2013) the TDR readings were collected from the experimental site and used to calculate the amount of irrigation required. The soil profile from 0-300 mm was determined to be at field capacity at 32.5% which was calculated from the highest TDR reading in the first season of 97.5 mm. To avoid any leaching the target capacity for irrigation was 27% or 81 mm. Average TDR readings were calculated for each irrigation treatment which combined species, depths and replicates and then this was used to determine the amount of irrigation required (Equation 3).

Equation 3 $$\boldsymbol{Irrigation = (TC - TDR_a) \times ID}$$

Where, TC is the target capacity (0.27 or 27%), TDR_a is the TDR average for three irrigation treatments and ID is the irrigation depth (300 mm).

Irrigation began on the 1 November 2012 and ended on the 18 April 2013. Total irrigation applied to the fully irrigated and two and three weekly irrigated pastures for the 2012/2013 season was 490 mm, 353 mm and 318 mm (Table 3.3).

Table 3.3 Amount of irrigation water (mm) applied per month under three irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks and Irr 3 is irrigated every three weeks for the 2012/2013 irrigation season at AgResearch farm, Canterbury.

Month	Irrigation treatment		
	Irr 1	Irr 2	Irr 3
November 2012	66.0	54.0	30.0
December 2012	95.8	54.0	27.0
January 2013	129	81.0	87.0
February 2013	133	92.0	111
March 2013	48.0	30.0	48.0
April 2013	18.0	42.0	15.0
Total	490	353	318

Sideroll irrigation was also used occasionally to ensure that dryland treatments were kept alive so that they could be measured in future years of the experiment (Table 3.4). On the 28 February this was also used to wash in the Diazinon insecticide applied.

Table 3.4 Irrigation water (mm) applied using the sideroll irrigator over the two seasons from 2011 to 2013.

Date	Irrigation treatment	Amount (mm)
7 November 2011	1, 2, 3	30
26 December 2011	1	24
30 January 2012	1	8
1 November 2012	All	18
28 February 2013	All	20

3.5 Crop Measurements

Measurements that are analysed in this report will be for the second year of the experiment from the 1 July 2012 to 30 June 2013.

3.5.1 Dry matter measurements

The first biomass harvest on all pasture plots on the 1 June 2011 was completed to determine if there were any differences caused by the previous wheat treatments. A 0.5 m^2 quadrat was cut to above crown level in the lucerne plots and 30 mm above ground level in the ryegrass plots. This was weighed and then dried at 90 ˚C overnight and reweighed to determine the percent dry matter. All plots were then mown to 50 mm in height and a 0.1 m^2 quadrat cut to determine the residual biomass after mowing.

Main biomass harvests involved using the push mower to remove plant material around the neutron probe, TDR and perimeter of the plot. A Cibus forage harvester was then used to remove the biomass from the remainder of the plot which was an area of 8 rows by 5-6 m, down to 70 mm above ground level. The plot area that was harvested was recorded and the total fresh weight measured and then a grab sample of about 500 g fresh weight was taken to determine the percent dry matter and dry matter yield. Two

0.1 m^2 quadrats were also cut on the harvested area to above crown level in the lucerne plots and 30 mm above ground level in the ryegrass plots to determine the residual left after harvest. All samples were placed in a drier at 60 ˚C for 48 hours. The dry weight was then recorded and all samples were ground and stored. Dates of all main biomass harvests are in Appendix 4.

On the 8 May 2013 a 0.2 m^2 quadrat was harvested from all plots. The sample was then quartered to get a subsample of about 25 g. The number of stems in the subsample were counted and sorted into 'stem' and 'other' piles. All samples were then dried at 60 ˚C for 48 hours and weighed. There was no difference in stem population between irrigation treatments which averaged 856 stems/m^2 (Table 3.5).

Table 3.5 The number of lucerne stems/m^2 under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated on the 8/05/2013 at AgResearch farm, Canterbury.

Irrigation treatment	Stems/m^2
Irr 1	818
Irr 2	785
Irr 3	889
Dry	932
Mean	856

Annual dry matter yield was determined by accumulating the dry matter yield from each individual harvest over the 2012/2013 season. This was then plotted against harvest date for the season. The mean daily growth rate for the 2012/2013 season was calculated by dividing total dry matter yield for each harvest period by the number of days in that measurement period.

3.6 Quality and botanical composition

Plant material for quality and botanical composition was supplied by Plant and Food Research. Nutritive quality analysis was completed on samples taken on the 27 March

2013 (harvest one) and 8 May 2013 (harvest two) across all plots and irrigation treatments. A representative sample of both lucerne and perennial ryegrass was ground with a centrifugal grinder (Retsch ZM 200) through a 1 mm sieve and collected in small 30 mm vials. Nitrogen and ME content were determined by near infrared spectroscopy (NIRS) at the Analytical Laboratory Unit at Lincoln University.

Botanical composition of the lucerne plots was determined by separating the entire 100 g fresh weight grab sample into lucerne, dead material and weeds. The 50 g fresh weight grab sample of ryegrass was quartered to approximately 25 g of fresh weight and then separated into ryegrass, dead material and weeds. On the 27/03/2013, eight lucerne plots were also chosen at random from the whole experimental area and five plants were removed and cut into leaf and stem prior to drying. This was to determine if there were any differences in the quality of the leaves and stem across irrigation treatments. All of the unirrigated plots in harvest one on 27/03/2013 were mown and unable to be separated into components therefore botanical composition could not be determined. All of the lucerne plots in harvest two on 8/05/2013 were also mown and unable to be separated into components to determine botanical composition.

3.7 **Meteorological data**

Mean monthly air temperature and total monthly rainfall data were collected from Broadfields meteorological station, situated less than 1 km from the experimental site (43˚62'S, 172˚47'E). The data are shown in Figure 3.1 as well as the long term means for average monthly temperatures and total monthly rainfall for the period 1975-2010 measured at the same location. The temperature data for the experimental period were within the normal range. Rainfall was about average from July to May with a major rainfall event of over 200mm in June. The impact of this rainfall event on dry matter yield was minimal because growth had essentially stopped at this time.

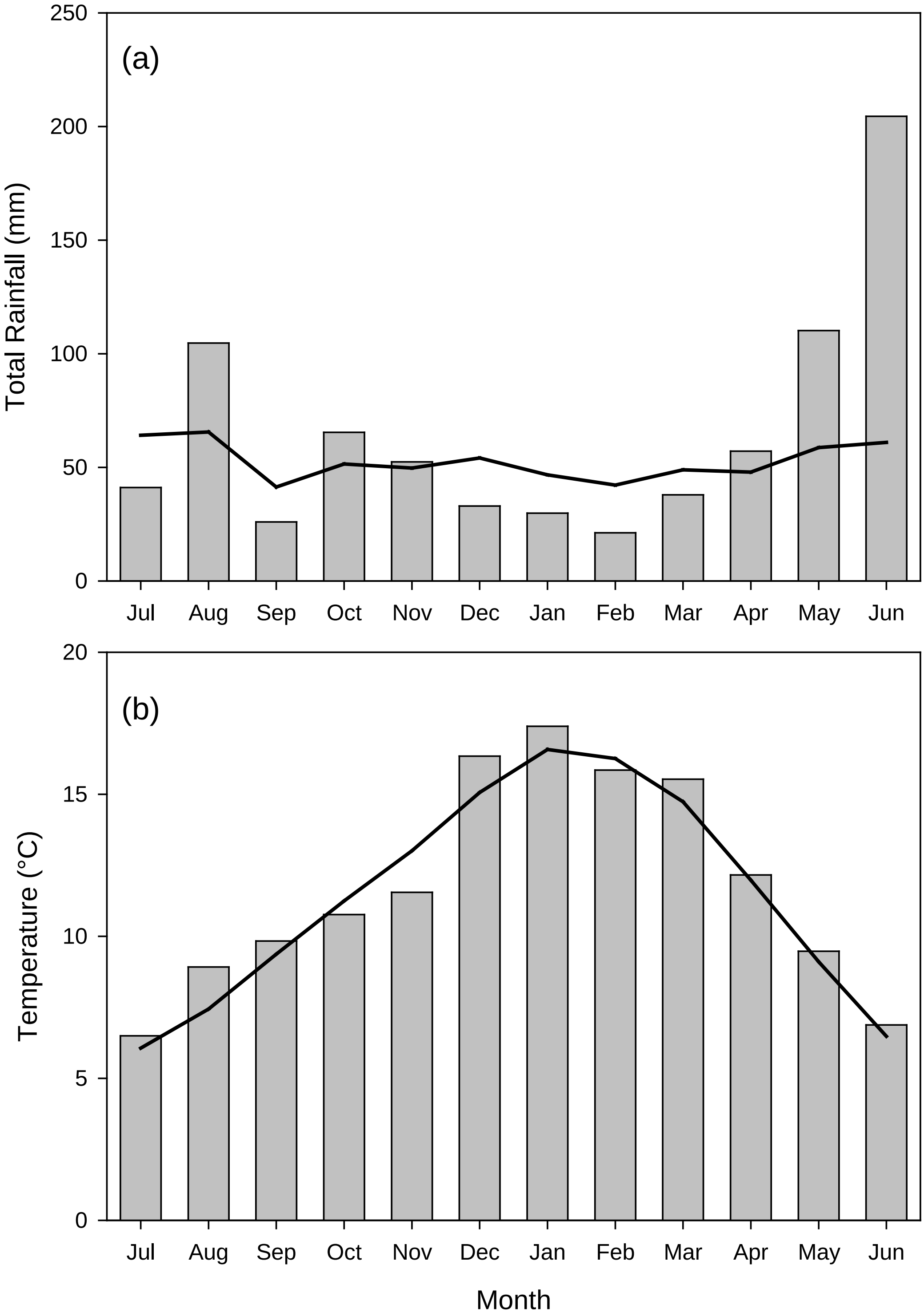

Figure 3.1 The bars are (a) total monthly rainfall (mm) and (b) mean monthly temperature (˚C) at Broadfields meteorological station for the 2012-2013 growth season. The lines are the long term means for the period 1975-2010.

3.8 **Thermal Time**

Two thermal time (Tt, ˚Cd) models were tested to determine the most appropriate method to quantify Tt accumulation for growth of lucerne in a temperate climate (Brown *et al.*, 2005b). The first method, the straight line model, assumed Tt to be zero for mean air temperatures below multiple base temperatures (T_b) of 0-10 ˚C, with a linear increase from the base temperature. The optimum temperature (T_o) was set at 30 ˚C and the maximum (T_m) at 40 ˚C. The second model, termed the broken stick model, assumed a base temperature of 1 ˚C and the same optimum and maximum temperature but Tt was accumulated at 0.71 ˚Cd per ˚C above the T_b of 1 ˚C up to a temperature of 15 ˚C. Above 15 ˚C Tt accumulated at a rate of 1 ˚Cd per ˚C until the optimum temperature (Moot *et al.*, 2001; Brown *et al.*, 2005b). Analysis showed the straight line model with a base temperature of 1 ˚C was the most appropriate as it had the highest coefficient of determination (R^2) of 98.0 (Figure 3.2).

For perennial ryegrass growth the straight line model with multiple base temperatures (0-10 ˚C) was also tested. This had a linear increase from T_b to T_o at 24 ˚C and a linear decrease to T_m at 40 ˚C. A base temperature of 0 ˚C was the most appropriate with the highest coefficient of determination of 98.0 (Figure 3.2). However a base temperature of 1 ˚C (R^2 = 97.9) was chosen to allow direct comparison between lucerne and perennial ryegrass throughout this dissertation.

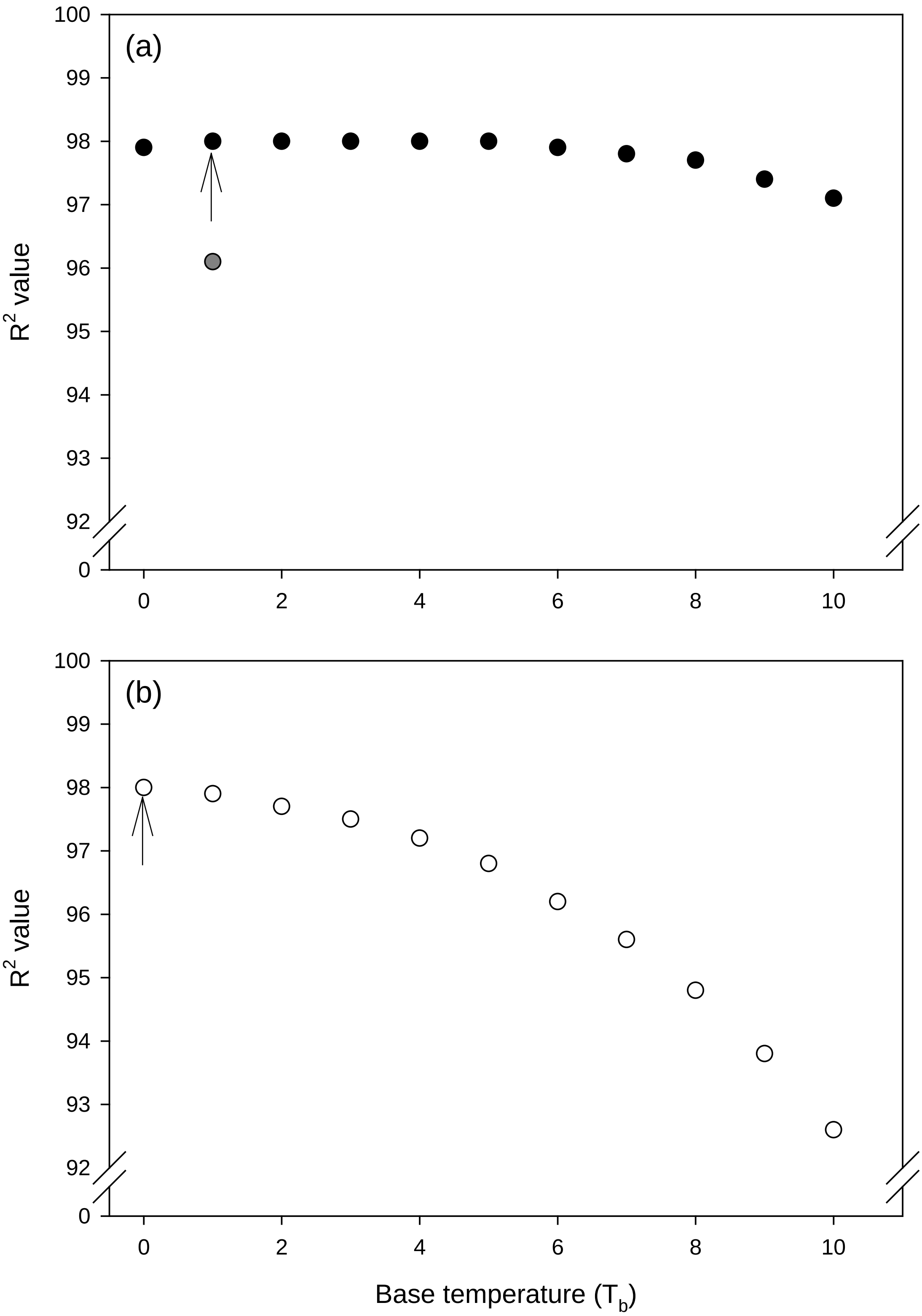

Figure 3.2 Coefficient of determination (R^2) against base temperature (T_b) to determine the base temperature for quantifying thermal time in (a) lucerne and (b) perennial ryegrass for the 2012/ 2013 growth season. Arrows indicate the highest R_2 value. The grey point on the Lucerne graph is the value determined using the three stage model.

The difference in optimum temperatures between lucerne and perennial ryegrass caused a difference in the accumulated thermal units over time once the optimum temperature of 24 °C was reached for perennial ryegrass (Figure 3.3). For example at a mean temperature of 25 °C, lucerne is accumulating 25 thermal units (°Cd) and perennial ryegrass is only accumulating 23 °Cd.

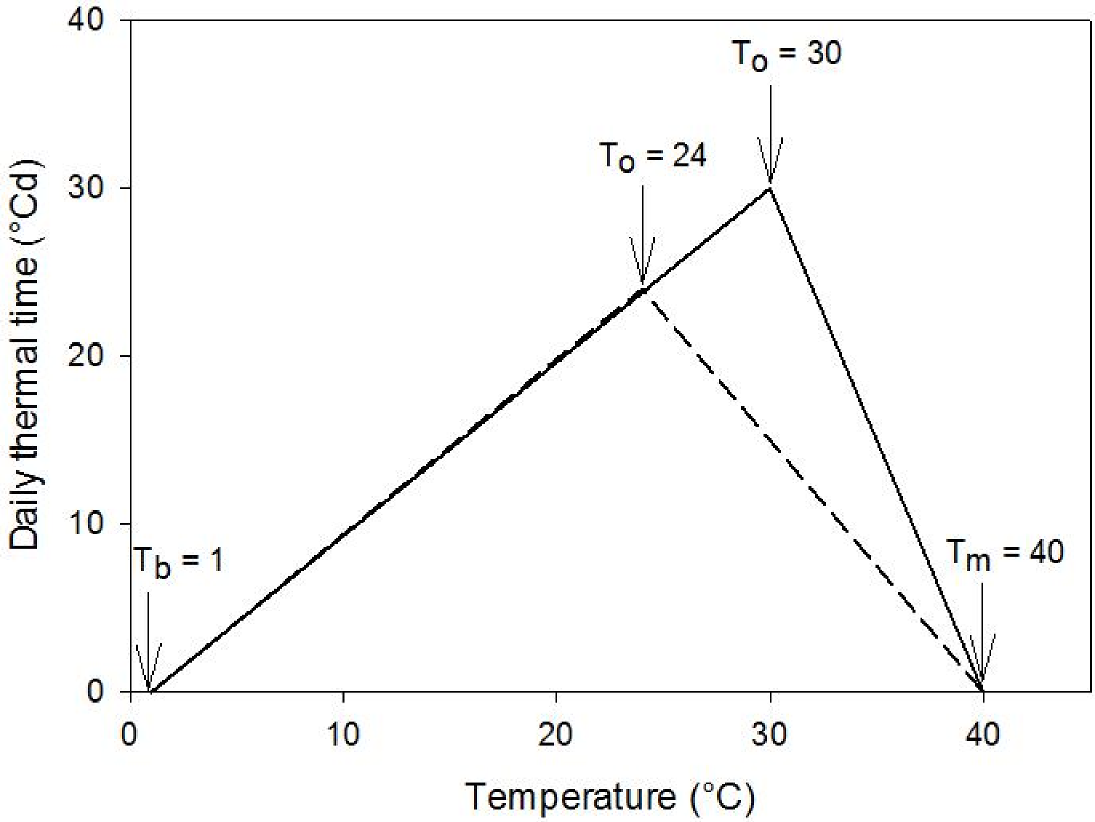

Figure 3.3 Daily thermal time accumulation (°Cd) in relation to temperature for lucerne (solid line) with an optimum temperature (T_O) of 30 C° and perennial ryegrass (broken line) with an optimum temperature of 24 °C. Both had a base temperature (T_b) of 1 °C and a maximum temperature (T_m) of 40 °C.

3.9 **Soil water budget**

3.9.1 Potential soil moisture deficit

The potential soil moisture deficit (PSMD) was determined using data from Broadfields meteorological station. PSMD was calculated using Equation 4 and was not allowed to return a negative value.

Equation 4 $$Todays\ PSMD = Penman\ PET - rainfall + yesterdays\ PSMD$$

PSMD was zeroed on the 1/07/2013 and reached a maximum value of 595 mm on the 15/04/2013 (Figure 3.4).

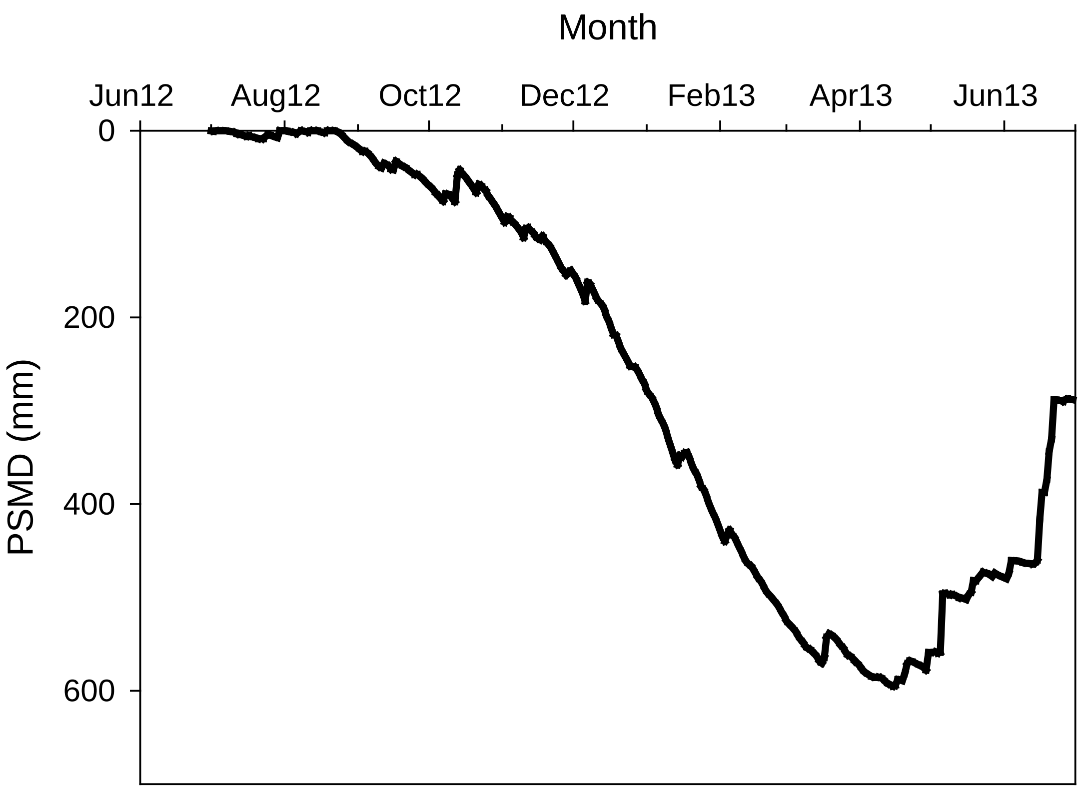

Figure 3.4 Potential soil moisture deficit (PSMD, mm) between the 1/07/2012-30/06/2013 calculated from Broadfields meteorological data.

3.9.2 Soil water content

The volumetric soil water content was measured in each plot for the duration of the experiment. The top two soil layers (0-150 and 150-300 mm) were measured using TDR's.

The neutron probe (CPN 503DR Hydroprobe) was used to take readings of the other seven depths down to 1.5 m, 200 mm apart, starting at 300mm. These measurements determined the total soil water content (SWC), from which plant available water was calculated. Over the experimental period, the upper limit or field capacity where drainage occurred also known as the drained upper limit (DUL) of the SWC was determined as the average of the second and third highest value at a given depth of all plots. The lower limit (LL) or permanent wilting point was determined as the lowest value at each depth for the lucerne and perennial ryegrass unirrigated treatments only. This value was then used as the lower limit for the irrigated lucerne and perennial ryegrass treatments. Total available water for the dryland plots was calculated using Equation 5. The average available water across all dryland plots was then used as the available water for the irrigated treatments. The critical limiting deficit was calculated as 50% of the available water in the dryland plots and used for all irrigation treatments as well (McLaren and Cameron, 1996).

Equation 5

$$\boldsymbol{Available\ water = DUL - LL}$$

3.9.3 Water use

At certain times when inputs from precipitation could not explain the total amount of water gained in the profile to 1.5 m soil depth, likely due to either spatial variability in the receipts or within the margin of error for the non destructive determinations of soil moisture by the monitoring equipment, drainage was not forced down the profile. This allowed water use to be accounted for by changes in soil water status in the top soil layers.

Water use (mm) was calculated for each measurement period (Equation 6) (Sim *et al.*, 2012).

Equation 6

$$\boldsymbol{WU = P_R - (SWC_E - SWC_S)}$$

where, P_R is the sum of rainfall for the experimental period, SWC_E is the soil water content of the profile as measured by the neutron probe at the end of the period and

SWC_S is the soil water content from the previous measurement or start of the period. This represents the change in the SWC of the soil profile.

The daily water use (WU_{daily}) was then calculated based on Penman potential evapotranspiration (P_{ET}) for the experimental period and the daily P_{ET} (Equation 7).

Equation 7

$$\boldsymbol{WU_{daily} = \left(\frac{WU}{P_{ET}}\right) * P_{ET\,daily}}$$

3.10 **Canopy temperature**

The infra-red thermometers were model SI-111 from Apogee® and installed in early February 2012 into plots 3-14 and 19-30. Readings were taken every five minutes from the 20 February 2012 to the 3 December 2012. From then on readings were taken every minute and the data logger calculated the mean for every 15 minutes.

Daily canopy temperatures of lucerne and perennial ryegrass fully irrigated and dryland pastures were calculated by taking the average of the temperatures between 11:00 and 13:00 for all plots under those treatments. Values from plots 3-14 on the 3/11/2012 to 9/11/2012 were unable to be determined as sensors were replaced. Therefore these values were excluded from averages. Daily canopy temperatures for fully irrigated and unirrigated lucerne and perennial ryegrass were then plotted as daily air temperature over time to determine any differences.

3.11 **Statistical Analysis**

All statistical analyses were conducted using Genstat 15 (Version 15, VSN International Ltd, Hemel Hempstead. UK). Yield, mean daily growth rate, plant available water capacity, maximum potential soil moisture deficit, annual water use and quality parameters were analysed by a two-way analysis of variance (ANOVA) with crop type and irrigation treatment as factors and replicate number as block structure. A Fisher's Protected least significant difference (LSD) test was used to compare means between species and irrigation treatments when they were shown as significantly different ($P<0.05$). On the 31 October 2012 the dry matter yield for plot 3 was missing. Therefore the mean for unirrigated lucerne from the other three plots on this date was used to balance the design.

Thermal time and water use efficiency were determined by fitting linear regressions to all treatments. Split-line regressions were then fitted to full irrigation pastures, pastures irrigated every two and three weeks and unirrigated pastures for thermal time. Split-line regressions failed to fit because of insufficient data points in the first phase. Therefore all plots had a zero intercept included in the data series. The regression with the highest coefficient of determination for irrigation treatment two, three and four was chosen for further analysis. The slopes and break point value for thermal time and slope for WUE were analysed using the same method as yield with a two-way ANOVA.

Coefficients of determination for lucerne were analysed by a linear regression of base temperatures (1-10°C for the straight line model and 1°C for the three stage model) against mean accumulated yield for the full irrigation treatment. Coefficients of determination for ryegrass were analysed using the straight line model only.

4 RESULTS

4.1 Dry matter yield

4.1.1 Annual dry matter yield

Annual dry matter yield was affected by the interaction between species and irrigation treatment (Figure 4.1). The interaction was that in all irrigation treatments lucerne yields were above ryegrass yields but the reverse occurred for the unirrigated pastures. Lucerne and perennial ryegrass yields were both highest ($P<0.002$) with full irrigation (18.7±659 t DM/ha). However the lowest yields were 8.29 t DM/ha for perennial ryegrass but only 4.65 t DM/ha for lucerne unirrigated treatments. Yields from the two or three week irrigations were not different across species. Any difference in yield among treatments was unable to be determined up until the 19/12/2012. This was due to lucerne and ryegrass being harvested on different days up until this date. On the 19/12/2012 perennial ryegrass fully irrigated had the highest accumulated yield of 10.3 t DM/ha compared with 4.78 t DM/ha for unirrigated lucerne. On the 23/01/2013 fully irrigated lucerne had the highest yield of 13.5 t DM/ha. Unirrigated lucerne still had the lowest yield of 4.92 t DM/ha. On the 27/02/2013 and 27/03/2013 fully irrigated lucerne maintained the highest accumulated yield and unirrigated lucerne the lowest yield. Yield plateaued for the unirrigated treatments on the 19/11/2012 for perennial ryegrass and one month later on the 19/12/2012 for lucerne. Full details of annual dry matter yields are given in Appendix 5.

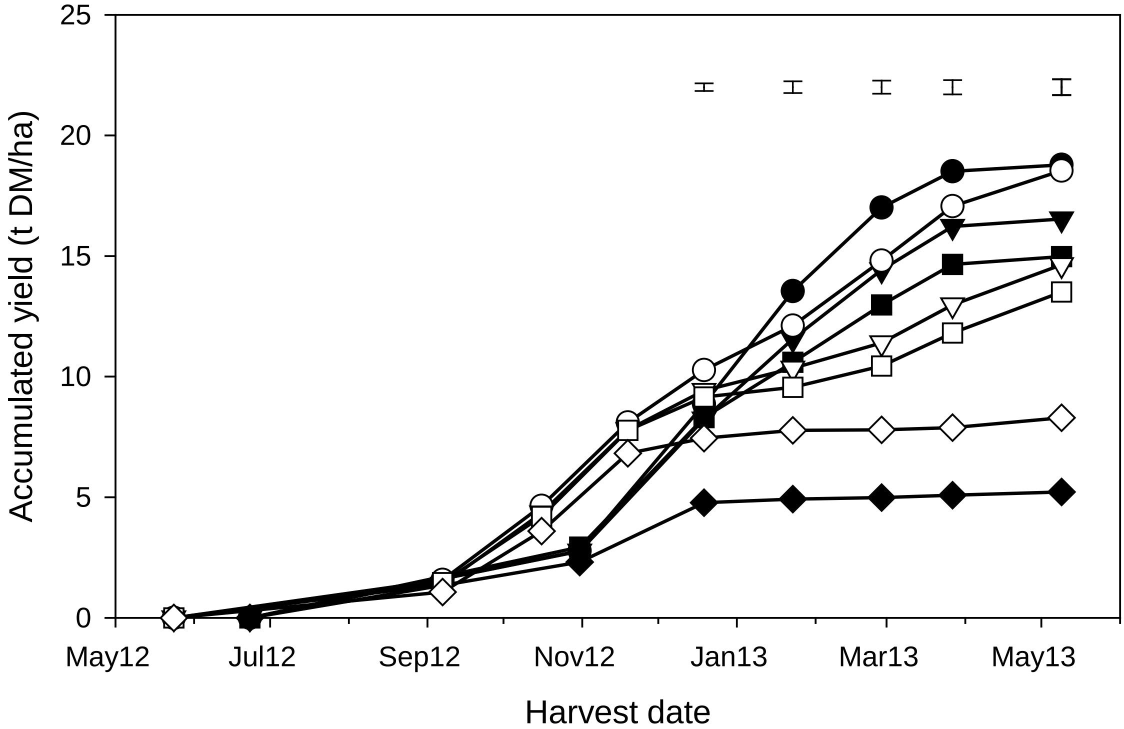

Figure 4.1 Annual dry matter (DM) yield (t DM/ha) of lucerne (closed symbols) and perennial ryegrass (open symbols) under four irrigation treatments: full irrigation (●○), irrigated every two weeks (▼▽), irrigated every three weeks (■□) or unirrigated (◆◇) from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. Error bar is the SEM value for the interaction between species and irrigation treatment.

4.1.2 Mean daily growth rate

It follows that mean daily growth rate was also affected by the interaction between species and irrigation treatment (Figure 4.2). The fully irrigated lucerne and perennial ryegrass had the highest mean daily growth rates of 76.5±2.70 kg DM/ha/day. For unirrigated perennial ryegrass the mean daily growth rate was reduced to 34.0 kg DM/ha/day but for lucerne it was only 19.0 kg DM/ha/day. The initial period of linear growth was longer for lucerne than perennial ryegrass for all irrigated treatments. The growth rate of perennial ryegrass increased on the 7/09/2012 compared with 54 days later on the 31/10/2012 for lucerne. The date of the maximum mean growth rate for lucerne was 25/12/2012 or 36 days later ($P<0.001$) than for perennial ryegrass (19/11/2012). The maximum mean daily growth rate was highest for fully irrigated lucerne at 136±5.15 kg DM/ha/day. The lowest maximum mean daily growth rate was

50.4 kg DM/ha/day for unirrigated lucerne. All irrigated perennial ryegrass pastures had a maximum mean daily growth rate of 103 kg DM/ha/day which was higher (P<0.001) than the unirrigated perennial ryegrass (94.7 kg DM/ha/day). Full details of mean and maximum daily growth rates are given in Appendix 6 and Appendix 7.

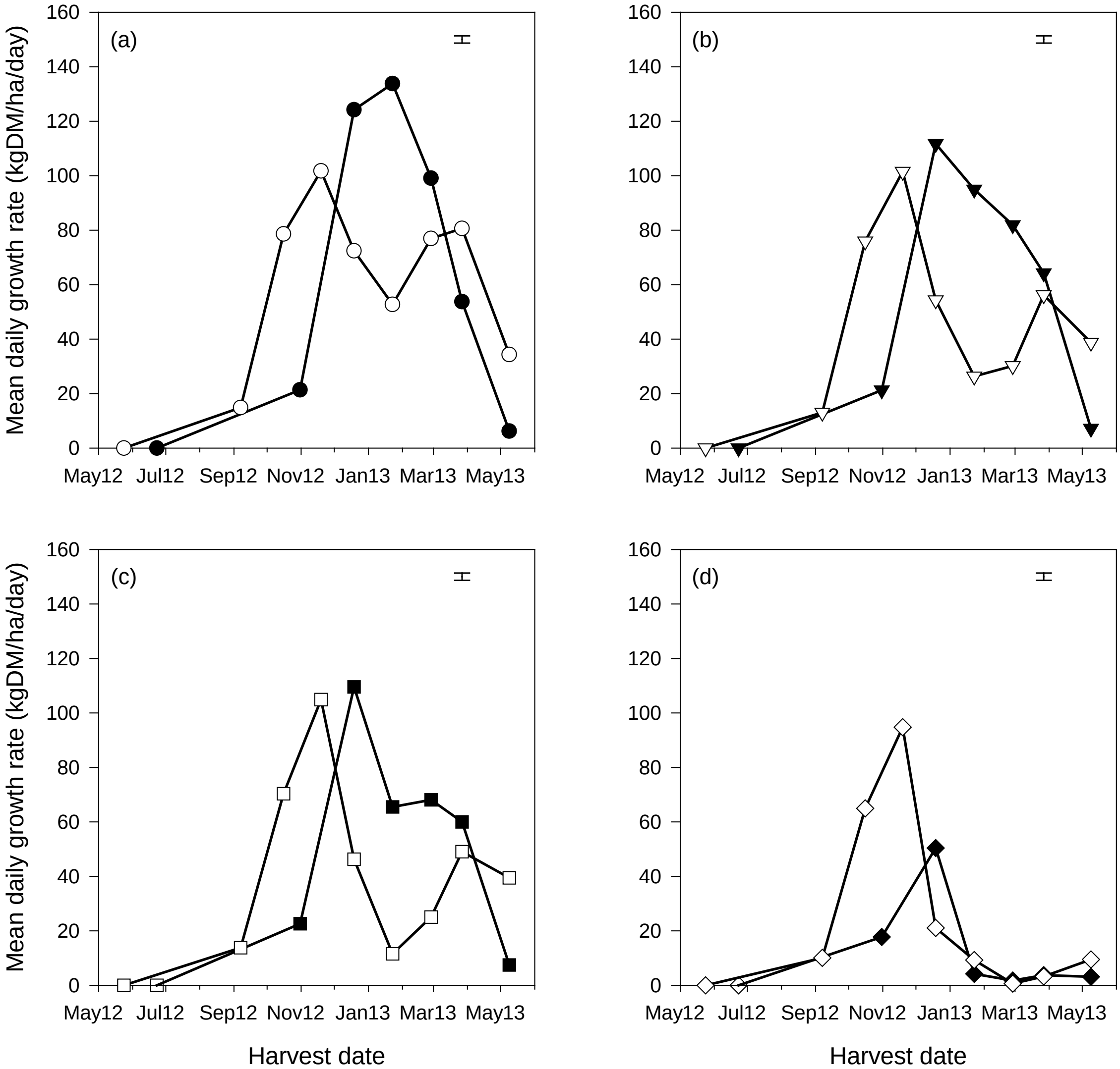

Figure 4.2 Mean daily growth rates (kg DM/ha/day) of lucerne (closed symbols) and perennial ryegrass (open symbols) under four irrigation treatments: (a) full irrigation (●○), (b) irrigated every two weeks (▼▽), (c) irrigated every three weeks (■□) or (d) unirrigated (◆◇) from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. Error bars are the SEM value for the interaction between species and irrigation treatment.

4.2 **Thermal time**

To determine the relationship between temperature and plant growth, thermal time was calculated (Section 2.4). Thermal time was split into two phases to explain the different growth rates across the season. There was an interaction between species and irrigation treatment in the initial linear phase (Figure 4.3). In this phase the fully irrigated lucerne grew at the highest rate of 6.69±0.288 kg DM/ha/°Cd. This was faster ($P<0.001$) than the 3.03 kg DM/ha/°Cd for unirrigated lucerne. All perennial ryegrass pastures grew at similar rates which ranged from 5.79-5.09 kg DM/ha/°Cd. Full details of the phase one interaction are in Appendix 9.

Perennial ryegrass had a breakpoint value at 1575°Cd which corresponded to the 19/11/2012 (Figure 4.3). This was the same day as the breakpoint value for lucerne of 1375°Cd (19/11/2012). The difference in breakpoint value was due to different optimum temperatures of 24°C for perennial ryegrass and 30°C for lucerne. Full details of the breakpoint value are given in Appendix 11.

There was a second linear phase. The fully irrigated lucerne continued to grow at the highest rate of 6.69±0.457 kg DM/ha/°Cd (Figure 4.3). However unirrigated ryegrass and lucerne both grew only 0.39 kg DM/ha/°Cd. The perennial ryegrass pastures irrigated every two and three weeks grew 2.83 kg DM/ha/°Cd. Across the season fully irrigated lucerne grew 1 kg DM/ha/°Cd more than fully irrigated perennial ryegrass. Full details of the phase two interaction are in Appendix 10.

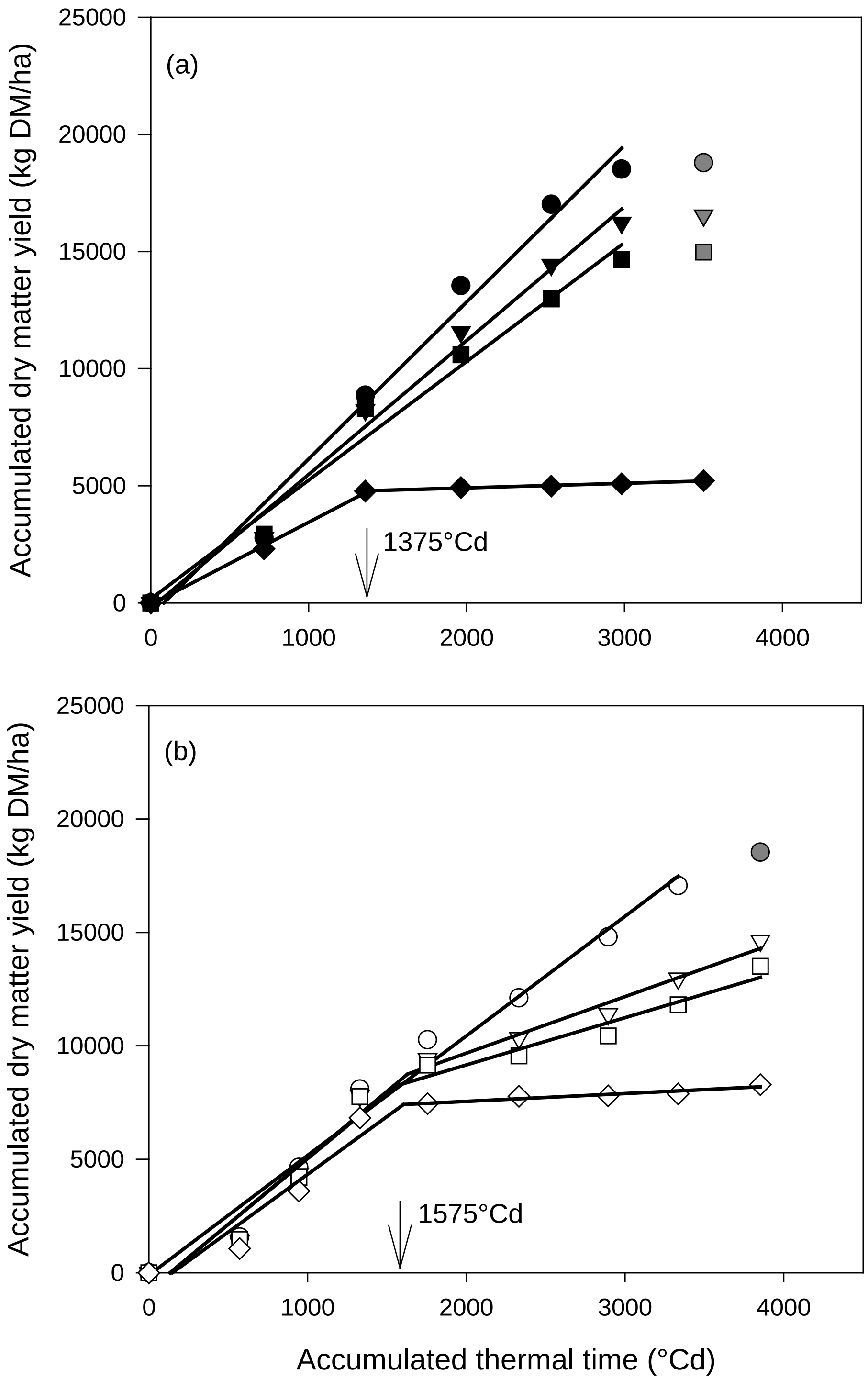

Figure 4.3 Total annual accumulated dry matter yield (kg DM/ha) against accumulated thermal time (˚Cd) for (a) lucerne (T_o 30°C) and (b) perennial ryegrass (T_o 24°C) both with a base temperature of 1°C under four irrigation treatments: fully irrigated (●○), irrigated every two weeks (▼▽), irrigated every three weeks (■□) or unirrigated (◆◇) from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. Breakpoint for main effect of species is shown. Values for the final harvest before winter are shown as the grey points for reference but were excluded from analysis in that treatment as they were taken after linear growth had ceased.

4.3 **Soil water budget**

4.3.1 Available water

The drained upper limit (DUL) and lower limit (LL) of the soil were used to calculate the plant available water in the soil for the 2012/2013 season (Section 3.9.2). The total available water was determined by summing the amount of water available in each 0.2 m soil layer down to a depth of 1.5 m. The lowest volumetric soil water content was 150 mm for plot 2 which was an unirrigated perennial ryegrass pasture (Figure 4.4). The highest volumetric soil water content was 222 mm for plot 22, an unirrigated lucerne pasture. In the top 0.5 m of soil in plot 2 there was a total of 104 mm of water available to the ryegrass. From 1.1 to 1.5 m there was 26 mm of available water. In contrast plot 22 had 145 mm of available water in the top 0.5 m and 55 mm from 1.1 to 1.5 m depth. Despite this variability the plant available water capacity (PAWC) did not differ ($P<0.162$) between unirrigated lucerne or perennial ryegrass pastures, and averaged 171 mm.

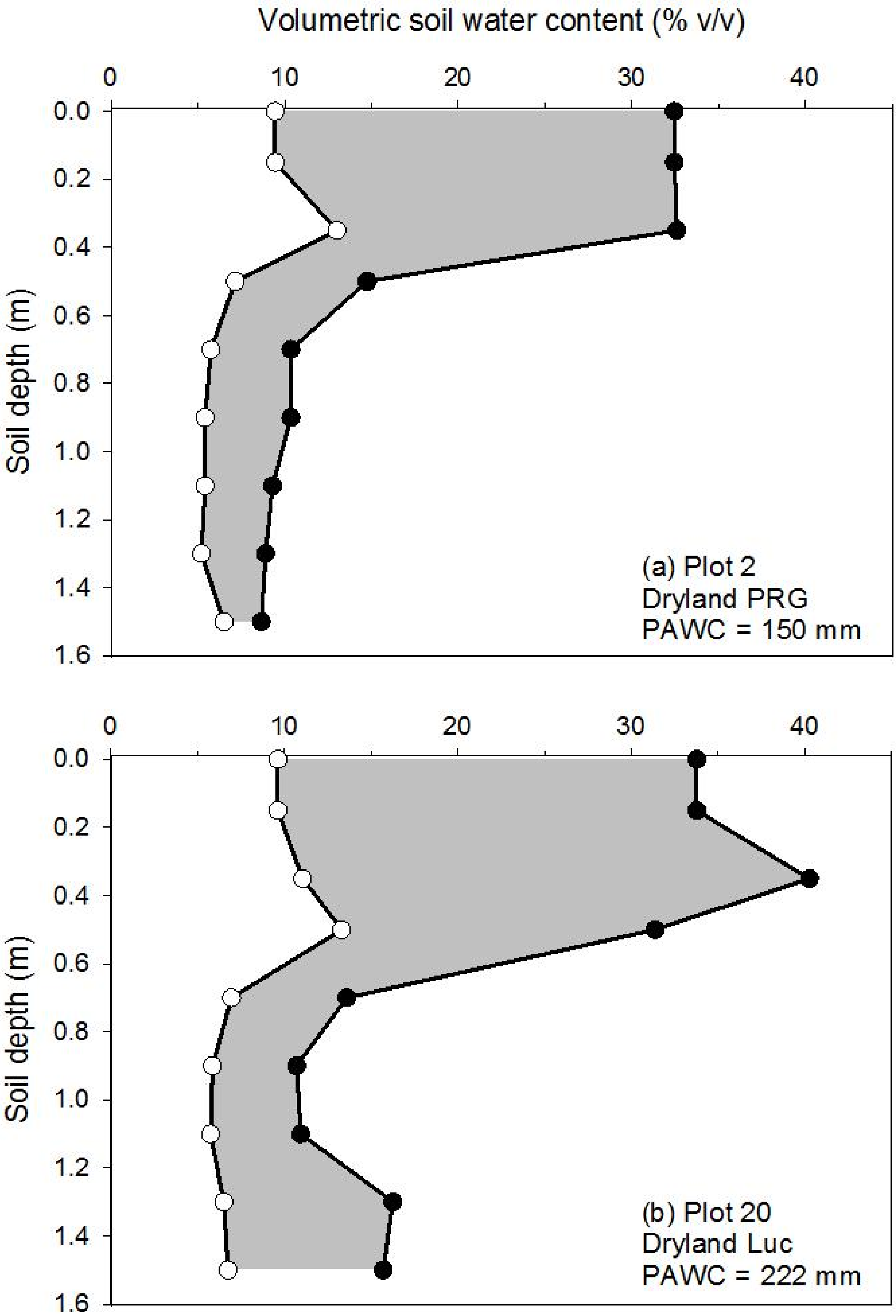

Figure 4.4 Water extraction (mm) from 0-1.5 m depth for (a) dryland perennial ryegrass (Plot 2 PRG) and (b) dryland lucerne (Plot 20 Luc) pasture on a combination of a Templeton silt loam and Eyre silt loam soil from 01/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. ● is the drained upper limit (DUL) and ○ is the lower limit (LL). PAWC is the total plant available water for the profile.

4.3.2 Soil water content

There was an interaction between species and irrigation treatment on maximum soil moisture deficit (MSMD). Unirrigated lucerne had the highest ($P<0.047$) MSMD of 164±5.73 mm. The lowest MSMD of 63.2 mm was for fully irrigated lucerne and perennial ryegrass and ryegrass irrigated every two weeks. Lucerne irrigated every three weeks and unirrigated perennial ryegrass had the a MSMD of 85 mm compared with 104 mm for lucerne irrigated every two weeks and perennial ryegrass irrigated every three weeks. Full details of MSMD are in Appendix 14.

The profile soil water content in the fully irrigated pastures remained relatively stable and between the DUL and estimated critical limiting deficit (Section 3.9.2) of 172 mm over the season (Figure 4.5a and Figure 4.6a). The MSMD occurred on the 10/10/2012 for both pastures. The SWC decreased in September 2012 as rainfall was low and irrigation did not commence until 1 November 2012. Once irrigation began soil water content remained relatively stable.

The SWC remained above the estimated critical limiting deficit for lucerne irrigated every two weeks (Figure 4.5b). In contrast the SWC for perennial ryegrass pastures irrigated every two weeks dropped below the estimated critical limiting deficit on the 4/01/2013 (Figure 4.6b). Lucerne and perennial ryegrass irrigated every two weeks had a MSMD of on the 16/01/2013 and the 4/01/2013, respectively. From December 2012, irrigation plus rainfall (<50 mm per month) were insufficient to maintain the soil at its DUL.

The SWC of lucerne irrigated every three weeks was below the estimated critical limiting deficit from the 5/12/2012 to the 19/12/2012 and from the 16/01/2013 to the 13/02/2013 (Figure 4.5 c). The SWC of perennial ryegrass pastures irrigated every three weeks was below the estimated critical limiting deficit on the 13/02/2013 (Figure 4.6 c). The MSMD for lucerne and perennial ryegrass irrigated every three weeks occurred on the 13/02/2013 for both pastures.

The SWC of unirrigated lucerne was below the estimated critical limiting deficit from the 5/12/2013 to 23/04/2013 (Figure 4.5d). The SWC of unirrigated perennial ryegrass was below the estimated critical limiting deficit from 5/12/2012 to 10/04/2013 which began

13 days earlier than lucerne (Figure 4.6 d). Unirrigated lucerne and perennial ryegrass both had a MSMD on the 27/02/2013.

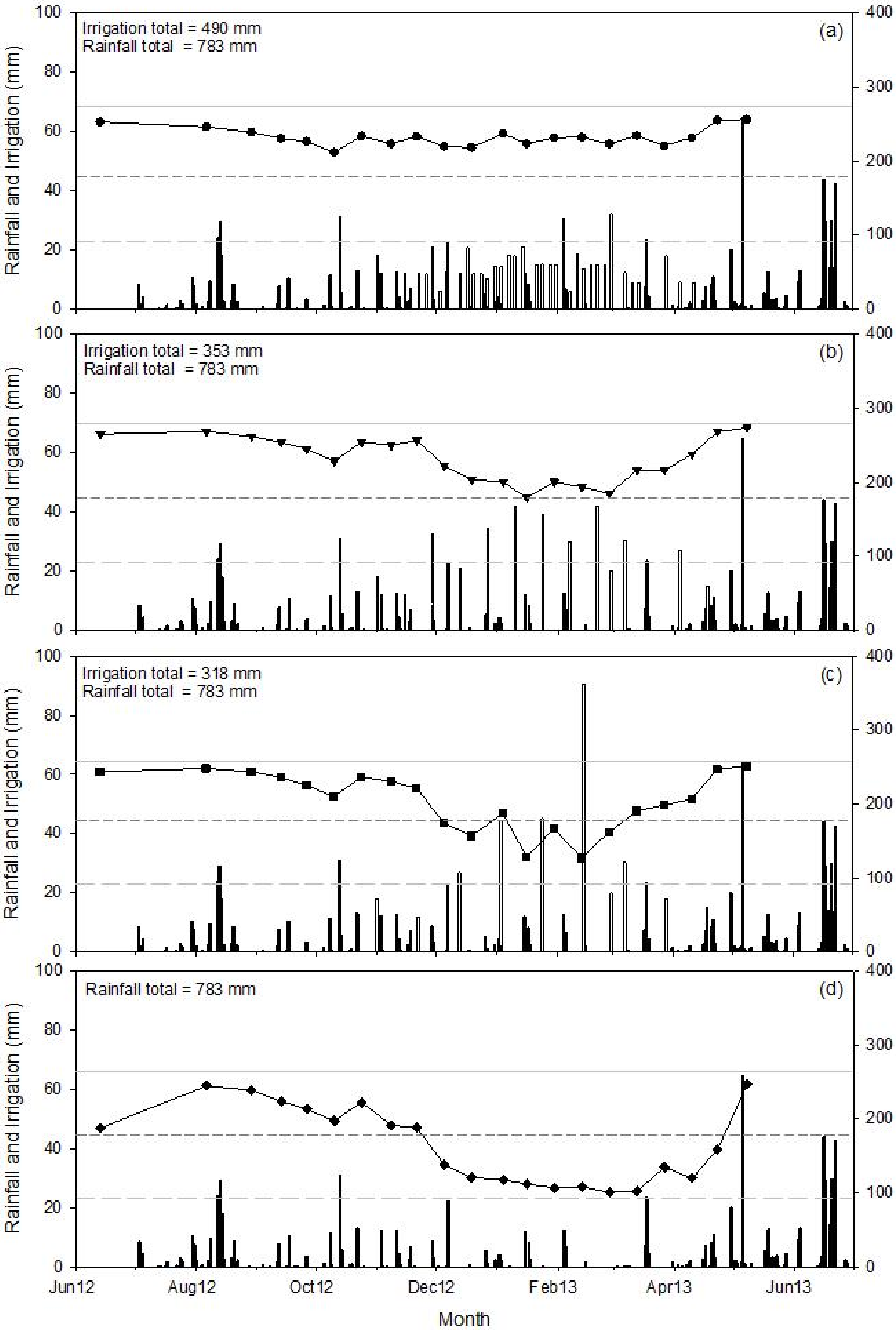

Figure 4.5 The soil water content (mm) in the full profile for lucerne (●) pastures and the accumulated weekly rainfall and irrigation for (a) full irrigation, (b) irrigation every two weeks, (c) irrigation every three weeks or (d) unirrigated from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. The solid grey line is the drained upper limit, the short dash grey line is the estimated critical limiting deficit and the medium dash grey line is the lower limit.

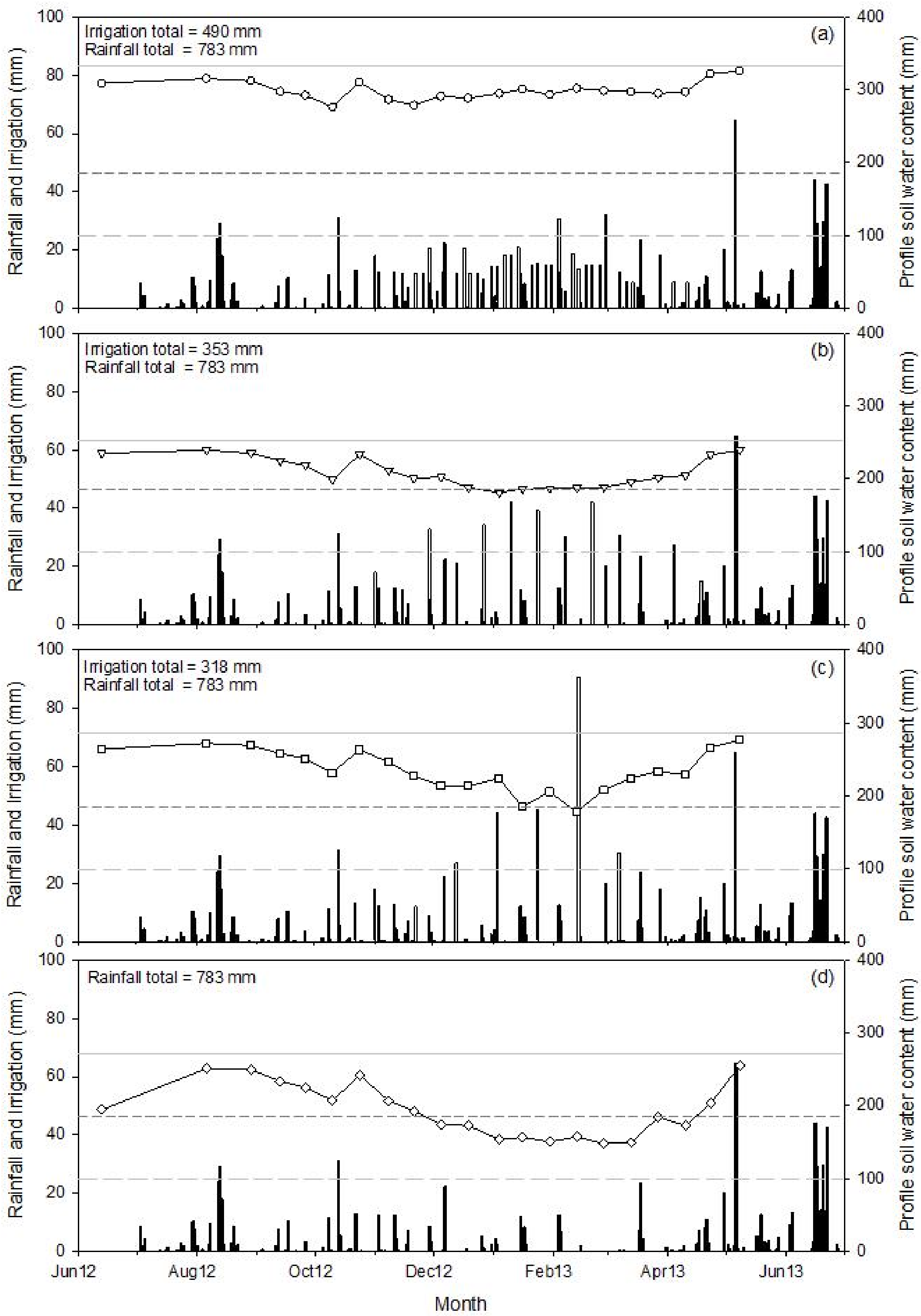

Figure 4.6 The soil water content (mm) in the full profile for perennial ryegrass (○) pastures and the accumulated weekly rainfall and irrigation for (a) full irrigation, (b) irrigation every two weeks, (c) irrigation every three weeks or (d) unirrigated from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. The solid grey line is the drained upper limit, the short dash grey line is the estimated critical limiting deficit and the medium dash grey line is the lower limit.

4.3.3 Annual water use

There was a main effect of irrigation treatment on annual water use. Full irrigation used 692±15.0 mm of water which was 79% more ($P<0.001$) than the 386 mm used by dryland pastures (Table 4.1). Two and three weekly irrigation used 609 and 557 mm of water.

Table 4.1 Annual water use (mm/year) for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated at AgResearch farm, Canterbury. Values with different subscripts are different ($\alpha=0.05$) according to Fisher's LSD test.

Irrigation treatment	Mean	SEM	LSD
Irr 1	692_a	15.0	44.1
Irr 2	609_b		
Irr 3	557_c		
Dry	386_d		

SEM and LSD are for irrigation treatment ($P<0.001$).

4.3.4 Water use efficiency (WUE)

The annual water use efficiency was calculated from the annual accumulated dry matter yield (kg DM/ha) and annual plant water use (mm). Irrigated lucerne had the highest annual WUE ($P<0.001$) of 34.5 kg DM/ha/mm of water used (Figure 4.7). Unirrigated lucerne had the lowest WUE of 11.2 kg DM/ha/mm of water used. Perennial ryegrass had a WUE of 22.5 kg DM/ha/mm of water used. A Fisher's protected LSD on WUE of irrigated lucerne and all perennial ryegrass pastures showed WUE was not significantly different. Therefore a single regression line was fitted to the data. The regression equations, standard errors of coefficients and coefficients of determination for regression of accumulated annual dry matter against accumulated annual water use are given in Appendix 13.

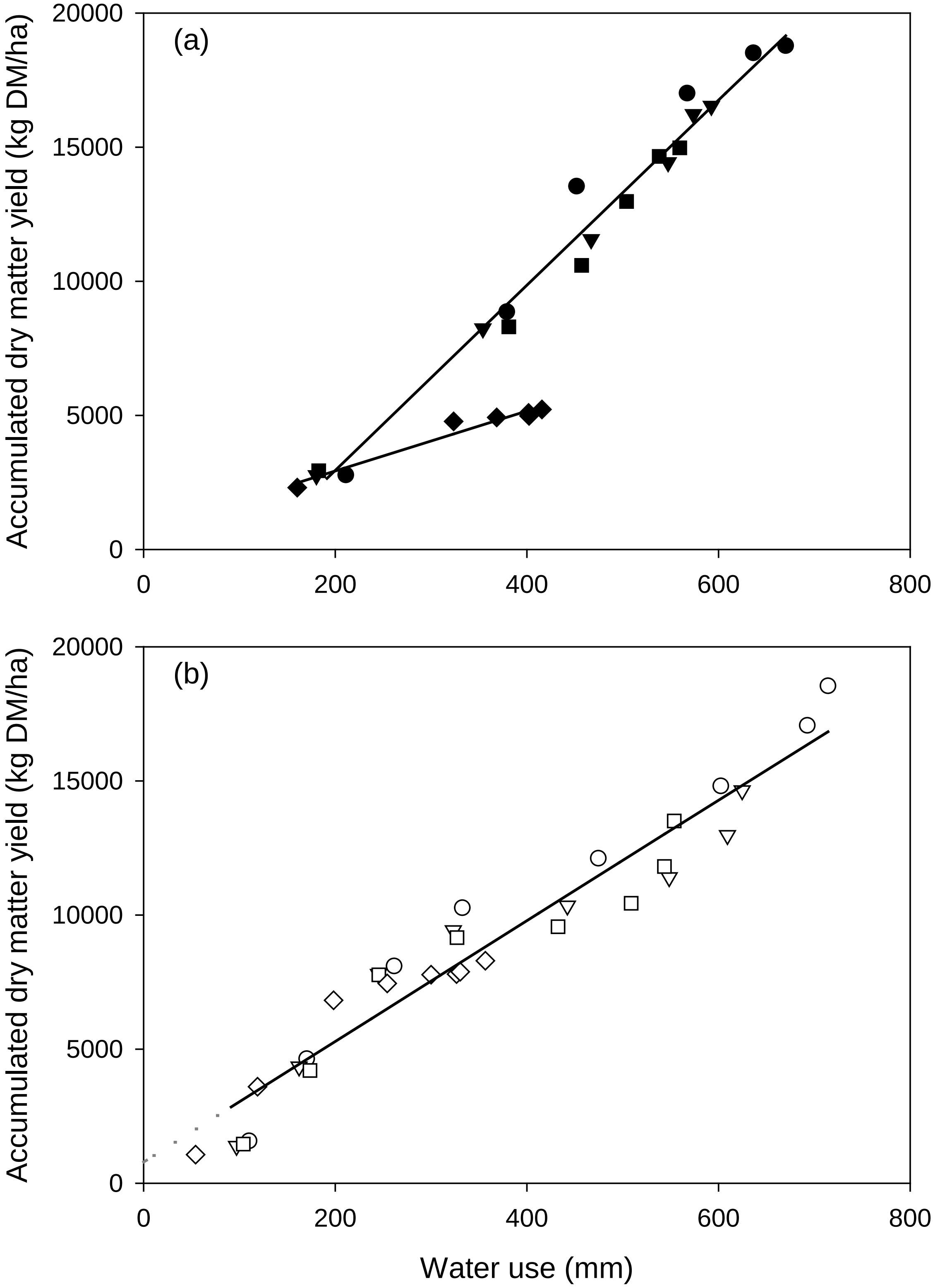

Figure 4.7 Total annual accumulated dry matter yields (kg DM/ha) against annual water use (mm) for irrigated lucerne (●; 34.5 kg DM/ha/mm), unirrigated lucerne (◆; 11.2 kg DM/ha/mm) and perennial ryegrass (○; 22.5 kg DM/ha/mm) from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand. The broken line indicates where PRG would cross the y axis.

4.4 **Canopy temperature**

Canopy temperature rose following the trend of air temperature for lucerne and perennial ryegrass from July 2012 to February 2013 (Figure 4.8). After this date both canopy temperature and air temperature declined. Canopy temperature fluctuated on a daily basis but overall it was higher than the air temperature for both fully irrigated and unirrigated lucerne and perennial ryegrass from September 2012 to April 2013. Canopy temperature of unirrigated lucerne was higher than the fully irrigated pasture from the middle of December 2012 to the middle of March 2013. In contrast, canopy temperature of unirrigated perennial ryegrass increased above canopy temperature for fully irrigated ryegrass from the middle of November 2012 to the middle of March 2013. During this time canopy temperature for dryland lucerne and perennial ryegrass dropped from 47.1 and 45.5 ˚C on the 12/01/2013 to 15.3 and 14.9 ˚C on the 15/01/2013. Temperature remained low on the 17/01/2013 at 11.9 and 13.1 ˚C but rose to 33.6 and 32.3 ˚C on the 19/01/2013. This drop in temperature coincided with two rainfall events of 12.1 mm on the 15/01/2013 and 8.4 mm on the 17/01/2013 and the decrease in temperature from 22.4 ˚C on the 12/01/2013 to 13.6 and 11.2 ˚C. This was determined to be the cause of canopy temperature decline because similar rainfall events and temperature decreases also occurred on the 26/12/2013 and 05/02/2013 which caused a similar trend (Figure 4.8).

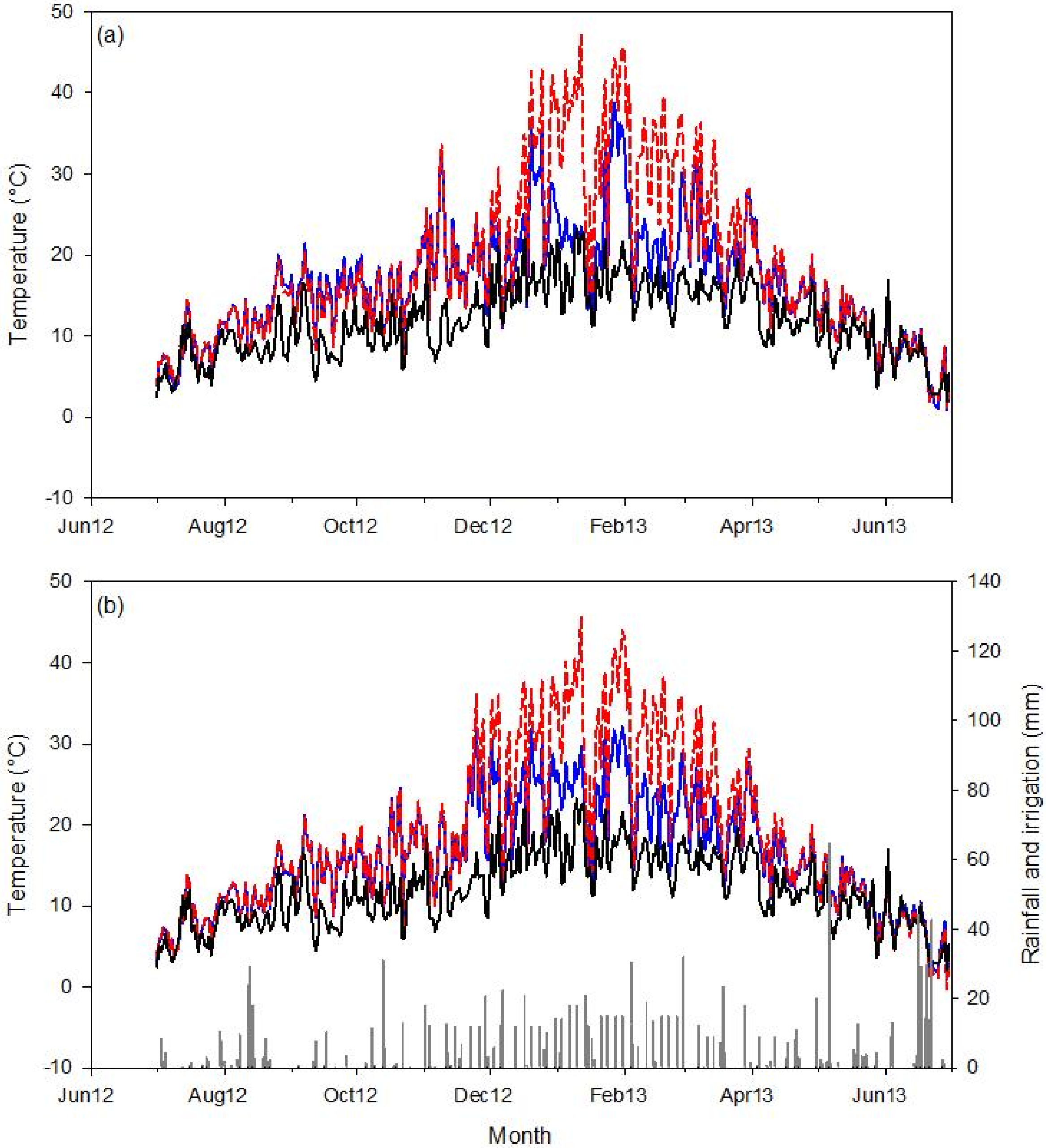

Figure 4.8 Mean daily canopy temperatures (°C) between 11:00 and 13:00 hours of (a) lucerne and (b) perennial ryegrass fully irrigated (■) and unirrigated (■) pastures against air temperature (■) and rainfall and irrigation (mm, ■) from 1/07/2012 to 30/06/2013 at AgResearch farm, Canterbury, New Zealand.

4.5 **Quality and botanical composition**

4.5.1 Harvest one (27/03/2013)

Botanical composition was only collected for the irrigated lucerne and perennial ryegrass treatments from the harvest on 27/03/2013 (Figure 4.9). The two week irrigation of lucerne had the highest proportion of weeds but this was only 1.50%. Effectively all pastures were pure swards with less than 2% weed content. Dead material was highest (5%) in the fully irrigated perennial ryegrass pastures. Thus overall sown components were ~99% for lucerne and at least 95% for perennial ryegrass.

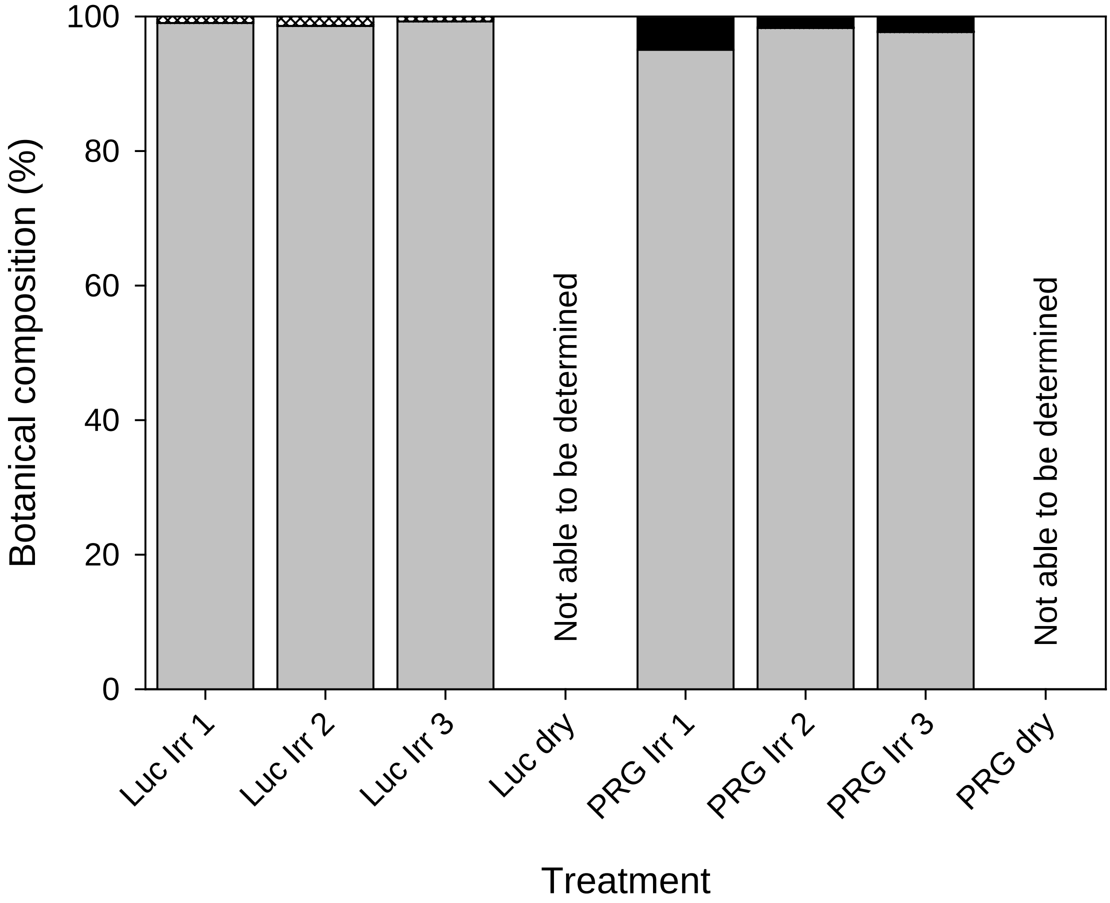

Figure 4.9 Botanical composition (%) of sown species (■), dead (■) and weeds (⊠) for lucerne (Luc) and perennial ryegrass (PRG) under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks and Irr 3 is irrigated every three weeks or dry is unirrigated for harvest one on the 27/03/2013 at AgResearch farm, Canterbury, New Zealand.

The dryland pastures were included in the quality analyses for this harvest to determine any differences. Perennial ryegrass irrigated every two or three weeks or unirrigated had the highest mean metabolisable energy (ME) value of 11.8±0.10 MJ ME/kg DM (Table 4.2). Lucerne irrigated every two or three weeks had the lowest ME value of 10.9 MJ ME/kg DM. Fully irrigated lucerne and perennial ryegrass pastures had the highest ME yield of 23.8±1.75 GJ ME/ha. Unirrigated lucerne and perennial ryegrass pastures had the lowest ME yield of 1.12 GJ ME/ha. Mean nitrogen content of lucerne was 4.32±0.050% and higher ($P<0.001$) than for perennial ryegrass (3.50%). Therefore lucerne also had a higher crude protein (N x 6.25) content of 27% compared with 22% for perennial ryegrass. Unirrigated lucerne and perennial ryegrass pastures had the highest nitrogen content of 4.41±0.071% which converts to a crude protein value of 27.6%. This was 21% higher ($P<0.001$) than the 3.66% (22.9% crude protein) for pastures irrigated every three weeks. Thus lucerne had the highest nitrogen yield of 58.6±4.69 kg N/ha at this harvest. This was 34% higher ($P<0.034$) than the nitrogen yield of perennial ryegrass at 43.6 kg N/ha. Fully irrigated lucerne and perennial ryegrass pastures had the highest ($P<0.001$) nitrogen yield of 81.0±6.63 kg N/ha compared with 4.27 kg N/ha for unirrigated pastures.

Lucerne had no nitrogen applied over the 2012/2013 season. Therefore all nitrogen recovered (N yield Table 4.2) was from nitrogen fixation or mineralisation from soil organic matter. The fully irrigated perennial ryegrass had 93 kg N/ha applied from the 27/02/2013 to 27/03/2013 and 87% of this value was recovered in the herbage (Table 4.2). Perennial ryegrass irrigated every two weeks had 51 kg N/ha applied over this period and 62.8 kg N/ha recovered. Perennial ryegrass irrigated every three weeks had 43 kg N/ha applied and 56.3 kg N/ha was recovered. In both of these treatments soil N or N from previous fertiliser applications must have contributed to the N yield.

Table 4.2 Metabolisable energy (MJ ME/ kg DM), metabolisable energy yield (MJ ME/ha), nitrogen content (N%), nitrogen yield (kg N/ha) and the nitrogen applied between the 27/02/2013 to 27/03/2013 for lucerne and perennial ryegrass under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated, harvested on 27/03/2013 at AgResearch farm, Canterbury, New Zealand. Values are based on the botanical composition of the sown components (Figure 4.9).

Treatment	Metabolisable energy (MJ ME/ kg DM)	ME yield (GJ ME/ha)	Nitrogen content (N%)	Nitrogen yield (kg N/ha)	Nitrogen applied (kg N/ha)
Lucerne					
Irr 1	11.3_{b}	23.8_{a}	3.87_{b}	81.0_{a}	0
Irr 2	10.9_{c}	19.0_{ab}	3.71_{bc}	62.8_{ab}	0
Irr 3	10.9_{c}	17.2_{b}	3.66_{c}	56.3_{b}	0
Dry	11.1_{bc}	1.12_{c}	4.41_{a}	4.27_{c}	0
Mean	11.0	15.3	4.32	58.6	-
Perennial ryegrass					
Irr 1	11.4_{b}	23.8_{a}	3.87_{b}	81.0_{a}	93
Irr 2	11.7_{a}	19.0_{ab}	3.71_{bc}	62.8_{ab}	51
Irr 3	11.8_{a}	17.2_{b}	3.66_{c}	56.3_{b}	43
Dry	11.8_{a}	1.12_{c}	4.41_{a}	4.27_{c}	0
Mean	11.6	15.3	3.50	43.6	-
SEM	0.10	1.75	0.071	6.63	-
LSD	0.29	5.15	0.208	19.5	-
Significance					
Species	<0.001	NS	<0.001	<0.034	-
Irrigation	NS	<0.001	<0.001	<0.001	-
Species*irrigation	<0.006	NS	NS	NS	-

NS not significant. SEM and LSD values are for the significant factor, when there are multiple significant factors then SEM is for the interaction between species and irrigation treatment or the main effect of treatment.

Quality analysis of lucerne stems and leaves on the 27/03/2013 are shown for reference as they were unable to be fully analysed due to missing values for the unirrigated treatment (Table 4.3). Leaves had a higher ME of 11.4 MJME/kg DM compared with 7-9 MJME/kg DM for the stem. Therefore the ME yield for leaves was also higher. Leaves had a higher N content of ～4.7-4.8% compared with 1.5-2.5% for stems. This resulted in a higher N yield for leaves than stem.

Table 4.3 Metabolisable energy (MJ ME/ kg DM), metabolisable energy yield (MJ ME/ha), nitrogen content (N%) and nitrogen yield (kg N/ha) for lucerne leaves and stems under three irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks or Irr 3 is irrigated every three weeks harvested on 27/03/2013 at AgResearch farm, Canterbury, New Zealand.

Treatment	Metabolisable energy (MJ ME/ kg DM)	ME yield (MJ ME/ha)	Nitrogen content (N%)	Nitrogen yield (kg N/ha)
Leaves				
Irr 1	11.4	1230	4.69	5.07
Irr 2	11.4	1085	4.83	4.57
Irr 3	11.4	1215	4.80	5.11
Stem				
Irr 1	9.00	180	2.45	0.47
Irr 2	7.47	168	1.54	0.35
Irr 3	7.55	162	1.82	0.39

4.5.2 Harvest two (8/05/2013)

Botanical composition was only collected from the perennial ryegrass treatments for the harvest on 9/05/2013 (Figure 4.10). The fully irrigated ryegrass had the highest dead content of 10% but no weeds were found in any samples.

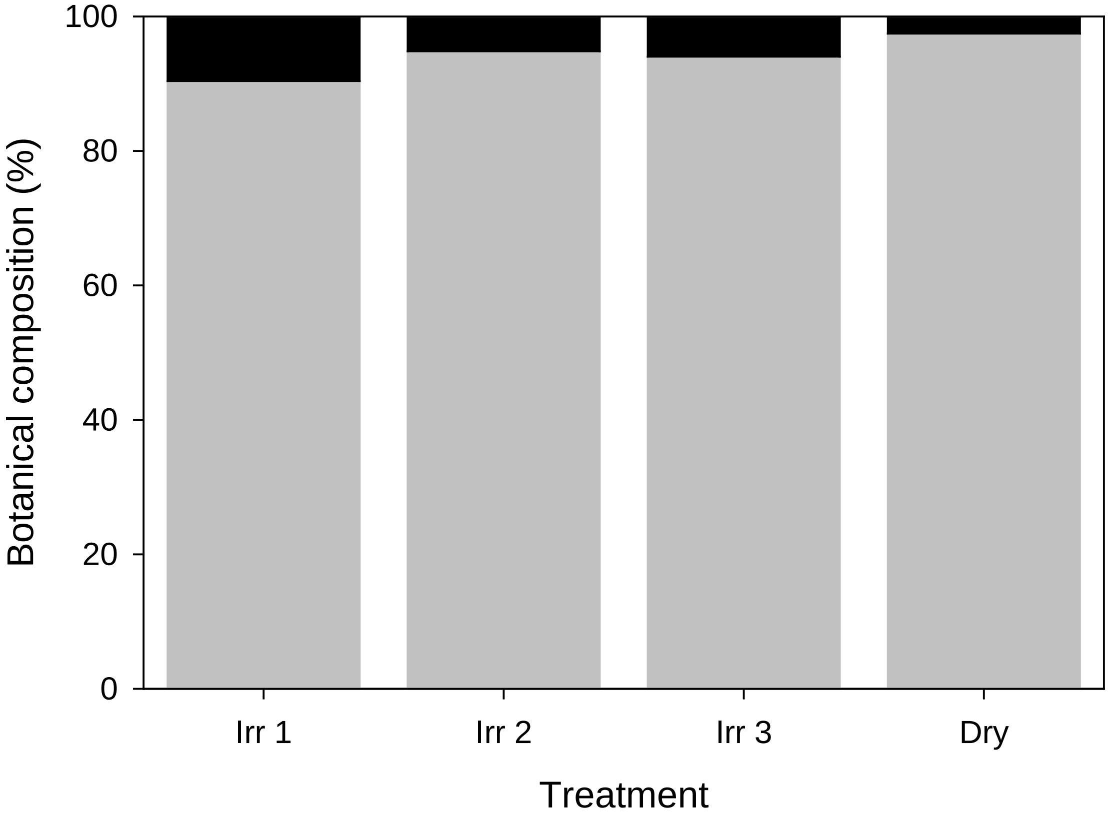

Figure 4.10 Botanical composition (%) of sown ryegrass (■) and dead (■) components under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated for harvest two on the 9/05/2013 at AgResearch farm, Canterbury, New Zealand.

Lucerne was included in the quality analyses for this harvest (9/05/2013) to determine any differences. Unirrigated perennial ryegrass had the highest ($P<0.001$) metabolisable energy value of 12.4±0.07 MJ ME/kg DM (Table 4.4). Fully irrigated lucerne and lucerne irrigated every two weeks had the lowest ME value of 11.5 MJ ME/kg DM. Perennial ryegrass irrigated every two or three weeks had the highest ME yield of 20.0±9.17 GJ ME/ha. Unirrigated lucerne pastures had the lowest ME yield of 1.52 GJ ME/ha. Lucerne irrigated every three weeks had the highest nitrogen content of 4.52±0.072% (28% crude protein). The lowest N content of 3.51% (22% crude protein) was for irrigated perennial ryegrass pastures but they had the highest N yield of 56.4±2.33 kg N/ha. The lowest N yield was 5.75 kg N/ha for unirrigated lucerne.

Lucerne had no nitrogen applied. Therefore all N recovered (N yield Table 4.4) was from N fixation or mineralisation from the soil organic matter. Fully irrigated perennial ryegrass had 84 kg N/ha applied from the 27/03/2013 to 9/05/2013 of which 62% of this value was recovered in N yield (Table 4.4). Perennial ryegrass irrigated every two and three weeks both had 66 kg N/ha applied and 89% of that value was recovered in herbage.

Table 4.4 Metabolisable energy (MJ ME/ kg DM), metabolisable energy yield (MJ ME/ha), nitrogen content (N%), nitrogen yield (kg N/ha) and the nitrogen applied between the 27/03/2013 to 9/05/2013 for lucerne and perennial ryegrass under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated, harvested on 9/05/2013 at AgResearch farm, Canterbury, New Zealand. Values are based on the botanical composition of the sown components for ryegrass (Figure 4.10) and the whole sample for lucerne as components were unable to be separated.

Treatment	Metabolisable energy (MJ ME/ kg DM)	ME yield (GJ ME/ha)	Nitrogen content (N%)	Nitrogen yield (kg N/ha)	Nitrogen applied (kg N/ha)
Lucerne					
Irr 1	11.5_{d}	3.10_{cd}	4.45_{ab}	11.9_{bc}	0
Irr 2	11.5_{d}	3.54_{cd}	4.43_{ab}	13.7_{b}	0
Irr 3	11.6_{cd}	3.73_{cd}	4.52_{a}	14.5_{b}	0
Dry	11.2_{e}	1.52_{d}	4.24_{bc}	5.75_{c}	0
Perennial ryegrass					
Irr 1	11.8_{bc}	17.3_{b}	3.52_{d}	52.0_{a}	84
Irr 2	11.9_{b}	19.9_{ab}	3.56_{d}	58.7_{a}	66
Irr 3	11.8_{bc}	20.1_{a}	3.45_{d}	58.5_{a}	66
Dry	12.4_{a}	5.03_{c}	4.18_{c}	16.9_{b}	0
SEM	0.07	9.17	0.072	2.33	-
LSD	0.20	2697.50	0.210	6.85	-
Significance	<0.01	<0.01	<0.01	<0.01	-

SEM and LSD values are for the interaction between species and irrigation treatment.

5 DISCUSSION

The objectives of this study were to compare the yield and water use of lucerne and perennial ryegrass under dryland and irrigated conditions. To do this dry matter yield, temperature, water use efficiency, canopy temperatures and herbage quality were compared. This chapter discusses results in relation to previous experiments and quantifies the environmental factors affecting pasture growth. Where data for perennial ryegrass monocultures is unavailable, ryegrass has been compared with ryegrass/white clover pastures as it was not N deficient due to consistent applications of nitrogen over the season. Full details of the dates and rates of nitrogen applications are in Appendix 3.

5.1 Dry matter yield

5.1.1 Annual dry matter yield

Lucerne had annual dry matter yields above perennial ryegrass at all three irrigation levels (Figure 4.1). The lucerne production occurred later in the season and was due to growth rates above perennial ryegrass from December to March (Figure 4.2). This result is similar to that from Brown *et al*. (2005a) who found irrigated lucerne yields of 16.2-28.0 t DM/ha also at Lincoln. Hayman (1985) found that with full irrigation on an Eyre soil, lucerne had a yield of 12.2 t DM/ha compared with 11.9 t DM/ha for pasture. Based on these results it seems that if irrigation is available then lucerne will yield more than perennial ryegrass on a Eyre and Templeton soil.

Unexpectedly, dryland lucerne produced a lower annual yield (4.65 t DM/ha) than unirrigated perennial ryegrass (8.29 t DM/ha) (Figure 4.1). Previous results (Section 2.3.2) highlight the superiority of lucerne in dryland environments on free draining soils. For example, Douglas (1986) summarized pasture results and concluded that lucerne yields of at least 40% more than perennial ryegrass could be expected on dryland, Canterbury soils at Lincoln. Given water (Table 4.1), nitrogen (Section 3.4.2) and temperature (Figure 3.1) were not different between dryland lucerne and perennial ryegrass, this reduced lucerne yield must have been due to other factors

Results suggest that the herbicide application of glyphosate on 22 June 2012 to control dandelion (*Taraxacum officinale* F.H. Wigg.) damaged developing lucerne buds and was responsible for this anomalous result (Moot *et al.*, 2003). The glyphosate appears to have negatively impacted the main spring production period as it took longer for dryland lucerne to reach linear growth rates than all other pastures (Figure 4.1). The need to regrow a new cohort of shoots appears to have delayed the lucerne growth (Plate 3). Furthermore, once lucerne growth commenced it was at a slower rate of 3.03 kg DM/ha/˚Cd compared with 6.69 kg DM/ha/˚Cd for irrigated lucerne (Figure 4.3). In an experiment by Arregui *et al*. (2001) dry matter yield on 20 December was significantly lower (19.9 g/m^2) when treated with glyphosate (480 g/ha) on 2 December than with other herbicides such as 2,4-DB (24.7 g/m^2). Yield loss was attributed to phytotoxicity because glyphosate injures actively growing lucerne and reduces yield. No recovery was seen 70 days after herbicide application. Moyer and Acharya (2006) also found that applications of 750 or 1500 g a.i. of glyphosate caused severe injury to lucerne. In most years visual injury ranged from 50-90%. Therefore glyphosate at this rate should not be applied on dryland lucerne to control weeds.

Unirrigated lucerne and perennial ryegrass produced lower yields than irrigated lucerne and perennial ryegrass (Figure 4.1). Lower yields for unirrigated swards are expected in summer dry environments. Unirrigated lucerne and perennial ryegrass would have taken longer to reach canopy closure after defoliation which would reduce the amount of incident solar radiation intercepted and decrease growth compared with irrigated pastures (Section 2.3.2). Douglas (1986) reported dryland lucerne production, in the 600-800 mm rainfall zone, of 5.9-12.0 t DM/ha which is higher than for the current experiment.

5.1.2 Mean daily growth rate

The pattern of dry matter production was quantified through differences in mean daily growth rates (Figure 4.2). Irrigated lucerne had a higher and later maximum mean daily growth rate than irrigated perennial ryegrass pastures (Figure 4.2). The difference was due to lucerne having a higher optimum temperature for growth of 30 ˚C compared with 24 ˚C for perennial ryegrass (Figure 3.3). Therefore when ryegrass growth had decreased due to temperatures above 24 ˚C, lucerne was still growing at an optimum until 30 ˚C (Figure 3.3). Fully irrigated lucerne had a maximum mean daily growth rate of 136 kg DM/ha/day and all irrigated lucerne reached a maximum mean daily growth rate in late December/early January. This was later than mid-November for irrigated perennial ryegrass. Previous results also show that lucerne had superior growth rates in the summer/autumn period (Section 2.3.2). Therefore to maximise production in spring when animal demand is high, lucerne should be grown over perennial ryegrass under irrigated conditions.

Unirrigated lucerne had a lower maximum and mean daily growth rate compared with unirrigated perennial ryegrass and irrigated lucerne (Figure 4.2). This was unexpected as lucerne has a reputation for higher growth rates in late spring and summer compared with perennial ryegrass (Section 2.3.1 and 2.3.2). Also at the beginning of the season swards are unlikely to be water stressed due to winter rainfall refilling the soil profile therefore irrigated and dryland lucerne yields should not be different (Section 2.3.2). Based on these results the reduction in growth rate of unirrigated lucerne was probably due to the application of glyphosate on 22 June 2012.

The maximum mean daily growth rate of perennial ryegrass was followed by a slump in mean daily growth rate over summer (Figure 4.2). The increase up to the maximum mean daily growth rate in spring could be due to the ryegrass turning reproductive and therefore putting energy into growing seed heads increasing the amount of dry matter produced per day. Over late spring, early summer Baars and Waller (1979) found that dry matter yield declined in ryegrass due to a change from vegetative to reproductive stage. Post this reproductive phase, perennial ryegrass may be reallocating assimilates to recharge roots in a similar way to lucerne in autumn (Moot, 2012). This could warrant lucerne being used in a farm system with perennial ryegrass as it could cover the feed deficit caused by the seed heads.

5.2 **Irrigated pastures**

5.2.1 Thermal time

Thermal time was quantified to take account of fluctuations in mean daily growth rate caused by variations in temperature. The base temperature for lucerne and perennial ryegrass was 1 ˚C with an optimum temperature of 24 ˚C for ryegrass and 30 ˚C for lucerne (Section 3.8). A base temperature of 0-4 ˚C is considered appropriate for temperate grass and legume species (Moot *et al.*, 2000). Black *et al*. (2006) also found a base temperature of <4 ˚C for development in perennial ryegrass. Brown *et al*. (2005b) used an optimum temperature of 30 ˚C for lucerne and a base temperature of 5 ˚C. However Moot *et al*. (2001) presented results from cool climates that suggest that a base temperature of 5 ˚C for lucerne is too high for lucerne growth and development. Therefore, from these results, a base temperature of 1 ˚C is more likely to be representative for lucerne. This also allowed comparison of the rate of thermal time accumulation between lucerne and perennial ryegrass.

The difference in dry matter production between fully irrigated lucerne and perennial ryegrass can be quantified by differences in thermal time accumulation. Thermal time was split into two phases. Fully irrigated lucerne grew 6.69 kg DM/ha/˚Cd compared with 5.27 kg DM/ha/˚Cd for fully irrigated perennial ryegrass across the entire season (Figure 4.3). This was due to differences in optimum temperatures. Therefore when temperatures where greater than 24 ˚C, the accumulated thermal time of perennial ryegrass declined but lucerne still accumulated thermal time up to 30 ˚C. These results suggest lucerne should be sown in areas with hot summers as it is still able to grow at an optimum up to a temperature of 30 ˚C. This is probably why it has been so successful in Central Otago and the Mackenzie Basin (Moot, 2012).

In the first phase, lucerne and perennial ryegrass pastures irrigated every two or three weeks grew at a similar rate of 5.40 kg DM/ha/˚Cd (Figure 4.3). This is surprising that lucerne grew at the same rate as ryegrass because lucerne has a reputation for slow early spring growth (Mills *et al.*, 2008). However it did begin growth later at the beginning of the season compared to perennial ryegrass (Figure 4.1). These results show that lucerne irrigated every two or three weeks can match growth rates of perennial ryegrass in late winter to early spring.

In phase two, lucerne pastures irrigated every two or three weeks continued to grow at the same rate as in phase one (Figure 4.3). The rate that perennial ryegrass pastures irrigated every two and three weeks grew at slowed to 2.83 kg DM/ha/˚Cd. This change in growth rate occurred on the 19/11/2012. The decrease in growth rate of the ryegrass pastures was caused by moisture stress. This shows that the amount of irrigation supplied to ryegrass pastures was insufficient to maintain initial growth rates. Therefore if pastures are irrigated infrequently lucerne has been shown to be a better option on this shallow soil.

5.2.2 Soil water budget

5.2.2.1 Soil water content

The profile soil water content of fully irrigated lucerne and perennial ryegrass pastures remained above the estimated critical limiting deficit for the entire season (Figure 4.5a) and Figure 4.6a). This shows that these pastures were never water stressed over the 2012/2013 season (Section 2.5.1). Therefore, this supports that the differences in dry matter production between fully irrigated lucerne and perennial ryegrass was a result of differing optimum temperatures and water use efficiency.

The profile soil water content in lucerne pastures irrigated every two weeks remained above the critical limiting deficit for the 2012/2013 season (Figure 4.5b). In contrast the profile soil water content of perennial ryegrass pastures irrigated every two weeks dropped below the critical limiting deficit on the 4/01/2013 (Figure 4.6b). Lucerne had a higher dry matter production compared with perennial ryegrass as it never reached the critical limiting deficit therefore grew at a higher rate (Figure 4.2). This also shows that lucerne used the water it had access to more efficiently.

The profile soil water content in lucerne pastures irrigated every three weeks dropped below the critical limiting deficit from the 5/12/2012 to 19/12/2012 and from the 16/01/2013 to 13/02/2012 (Figure 4.5c). The profile soil water content in perennial ryegrass pastures irrigated every three weeks was below the estimated critical limiting deficit on the 13/02/2013 (Figure 4.6c). This shows that lucerne was water stressed for a longer period than perennial ryegrass pastures. Therefore the higher yield of lucerne was due to its ability to withstand a lower profile soil water content and use the available soil water more efficiently. Therefore the critical limiting deficit may have been too low for lucerne as it did not seem to show signs of water stress by decreasing growth to levels lower than perennial ryegrass.

5.2.2.2 Annual water use

Annual water use differed between irrigation treatments (Table 4.1). Fully irrigated pastures had the highest WU of 692 mm. These pastures did not reach the estimated critical limiting deficit therefore they always had readily available water. This resulted in the highest ($P<0.002$) dry matter production across irrigation treatments (Figure 4.1). The difference in dry matter production between fully irrigated lucerne and perennial ryegrass was therefore due to the efficiency with which these pastures used water. The WU in this experiment was lower than the WU for irrigated pastures of 900 mm reported by Brown *et al*. (2005a). The difference in WU could be due to the different soil type (Wakanui silt loam) in this experiment. A Wakanui silt loam is a deeper soil than an Eyre or Templeton soil in the current experiment. Therefore there would be more readily available water that a plant could easily access and use. The higher amount of summer rainfall would have also maintained the pasture at a level close to or above the critical limiting deficit therefore the plants were able to access and use more water, before any plant stress occurred.

Pastures irrigated every two and three weeks had an annual WU of 609 and 557 mm (Table 4.1). The lower WU in pastures irrigated less frequently was due to a longer period spent below the estimated critical limiting deficit. Below the estimated critical limiting deficit water is still available but it is harder for plants to extract. Therefore less is used over that period than if water was used from above the estimated critical limiting deficit.

Once again there was no difference in water use between species therefore the difference in dry matter production between species (Figure 4.1) was due to the efficiency with which each pasture used water.

5.2.2.3 Water use efficiency

Irrigated lucerne had a WUE of 34.5 kg DM/ha/mm compared with 22.5 kg DM/ha/mm for irrigated perennial ryegrass (Figure 4.7). This shows that despite lucerne and perennial ryegrass having the same WU under the same irrigation treatment, lucerne used the water more efficiently under all irrigation treatments to produce a higher yield (Figure 4.1). Based on these results lucerne could be grown under irrigation in this environment because it can produce a higher dry matter yield with the same amount or less water than perennial ryegrass.

5.3 **Unirrigated pastures**

5.3.1 Thermal time

In the first linear phase, unirrigated perennial ryegrass grew 5.09 kg DM/ha/˚Cd compared with 3.03 kg DM/ha/˚Cd for unirrigated lucerne (Figure 4.3). This is not what would be expected as usually lucerne has higher growth rates than ryegrass in a dryland environment (Section 2.4). However, it does quantify the differences in annual dry matter yield (Figure 4.1). It also supports the contention that there were issues with the unirrigated lucerne as it had significantly lower growth rates than unirrigated perennial ryegrass prior to the onset of water stress.

In the slower phase two, both unirrigated lucerne and perennial ryegrass had a decrease in growth rate to 0.43 and 0.35 kg DM/ha/˚Cd (Figure 4.3). This decrease in growth rate was caused by moisture stress and it occurred from the 19/11/2012 onwards. This was one month prior to the when soil water content was below the critical limiting deficit. Therefore the estimated critical limiting deficit may need to be above the current value for dryland lucerne and perennial ryegrass on this soil type.

5.3.2 Soil water budget

5.3.2.1 Available water

The differences in PAWC showed the variability in soil type over a short distance (Figure 4.4). Dryland perennial ryegrass in plot 2 had the lowest annual PAWC of 150 mm and dryland lucerne in plot 22 had the highest of 222 mm. Figure 4.4 shows that in the top 0.3 m of the top soil there was a drained upper limit of over 30% and lower limit of 9%. Below depths of 0.7 m the drained upper limits were between 10 and 17% indicating the presence of stones and a lot less silt at depth. This lowered the plant available water in each layer. Tonmukayakul *et al*. (2009) mentioned a feature of soils in Canterbury is their variability in depth to gravel which affects soil water holding capacity. In that experiment a cocksfoot/sub clover pasture had 223 mm of available water compared with 340 mm for a lucerne pasture in the same replicate (Section 2.5). Despite the variability in soil type there was no difference in PAWC between dryland lucerne and perennial ryegrass plots in the current experiment. Therefore the PAWC would have no effect on differences in dry matter yield.

5.3.2.2 Soil water content

The profile soil water content for unirrigated lucerne was below the estimated critical limiting deficit from the 5/12/2013 to 8/05/2013 (Figure 4.5d). The profile soil water content of unirrigated perennial ryegrass was below the estimated critical limiting deficit from the 21/11/2012 to the 23/04/2013 (Figure 4.6d). The dates that lucerne and perennial ryegrass reached the critical limiting deficit correspond to the dates when accumulated dry matter yield flattened off (Figure 4.1). This shows that lower accumulated dry matter yield of dryland pastures compared with irrigated pastures was due to moisture stress. This date is also around the time when the breakpoint occurred in accumulated thermal time against accumulated dry matter yield relationships. Together these results show that growth in the second phase was affected by water stress.

Unirrigated lucerne had the highest ($P<0.047$) MSMD of 164 mm compared with 63.2 mm for fully irrigated lucerne and perennial ryegrass and ryegrass irrigated every two weeks (Figure 4.5 and Figure 4.6). This was due to unirrigated lucerne being reliant on rainfall to supply water compared with the irrigated treatments having a consistent supply of water through irrigation. Therefore if rainfall was infrequent, unirrigated lucerne would continue to use water and accumulate a higher MSMD as the water was not being replenished. This is similar to what Martin (1990) found as pasture production began to decline below a critical limiting deficit of 90 mm on a similar soil type (Section 2.5.1).

5.3.2.3 Annual water use

Unirrigated pastures used 386 mm of water annually (Table 4.1) and had a longer period of time below the critical limiting deficit compared with irrigated pastures (Figure 4.5 and Figure 4.6). The water below this level is harder to access which would have reduced the water use compared with irrigated pastures. There was no difference in water use between lucerne and perennial ryegrass therefore the difference in dry matter production (Figure 4.1) was due to the efficiency with which the water was used. The water use for dryland pastures was lower in this experiment than in Brown *et al*. (2005a) who reported WU values of 650-750 mm for dryland lucerne on a Wakanui silt loam soil.

5.3.2.4 Water use efficiency

Unirrigated lucerne had a WUE of 11.2 kg DM/ha/mm compared with 22.5 kg DM/ha/mm for unirrigated perennial ryegrass (Figure 4.7). The same amount of water was used by dryland lucerne and perennial ryegrass. Therefore this shows that perennial ryegrass had a higher dry matter yield (Figure 4.1) because it used the water more efficiently. This is not what would be expected as usually lucerne has a higher WUE than ryegrass in a dryland environment. Tonmukayakul *et al*. (2009) reported spring water use efficiencies of 30 kg DM/ha/mm for lucerne and 18 kg DM/ha/mm for a ryegrass/white clover pasture. WUE on a Templeton soil was 24 kg DM/ha/mm for lucerne and 13 kg DM/ha/mm for ryegrass under dryland conditions (Moot *et al.*, 2008). Therefore, this is further evidence of the negative impact of the glyphosate application.

5.4 **Canopy temperature**

Dryland lucerne and perennial ryegrass had the highest canopy temperatures from December 2012 to April 2013 (Figure 4.8). Canopy temperatures can be an indication of water stress. When plants are under water stress they close their stomata to minimise water loss by evaporation. Therefore the leaf surface heats up to a temperature greater than air temperature due to reduced transpiration (Moot *et al.*, 2003). Dryland pastures had higher canopy temperatures as they were under water stress when rainfall was low from December to April. This correlates to the period when profile soil water content was below the critical limiting deficit for both pastures (Figure 4.5d and Figure 4.6 d). This was also consistent with the decrease in mean daily growth rate of dryland lucerne and ryegrass from December to April.

Fully irrigated pastures did not reach the same canopy temperatures as dryland lucerne and perennial ryegrass over this period as plants were able to keep their stomata open due to the consistent supply of water through irrigation. Both pastures never reached the estimated critical limiting deficit therefore were not water stressed (Figure 4.5a and Figure 4.6a). However there are periods when the irrigated canopy temperatures are above the air temperature. The measurements for daily canopy temperature were averaged over the temperatures between 11:00 and 13:00 hours (Section 3.10). Over this time radiation is at its highest level for the day and plants cannot absorb enough water to maintain a temperature. Therefore, canopy temperature increases and stomata partially close decreasing photosynthetic rate.

5.5 **Botanical composition**

All pastures were basically pure swards in both harvests showing that the herbicide application of glyphosate controlled weeds in lucerne pastures. Lucerne had less than 2% weeds in harvest one (27/03/2013) due to the application of glyphosate in June 2012. Perennial ryegrass had less than 5% dead material in harvest one (Figure 4.9). Perennial ryegrass in harvest two (9/05/2013) had less than 10% dead material (Figure 4.10). This was due to consistent biomass harvests to low residuals which encouraged dead matter stubble (Plate 1) or it could be due to the production of seed heads which is shown by the decrease in mean daily growth rate over this time (Figure 4.2). Mills *et al*. (2008) also found a dead matter content of 5% in a dryland ryegrass/white clover pasture.

5.6 **Quality**

5.6.1 Metabolisable energy

In harvest one (27/03/2013) perennial ryegrass pastures irrigated every two or three weeks or unirrigated had a higher ME content (11.8 MJ ME/kg DM) than lucerne pastures (11.0 MJ ME/kg DM) under the same irrigation treatments (Table 4.2). In harvest two (9/05/2013) dryland perennial ryegrass also had the highest ME content of 12.4 MJ ME/ kg DM (Table 4.4). Unirrigated lucerne had the lowest ME content of 11.2 MJ ME/kg DM. In an experiment by Mills and Moot (2010) the average ME content of dryland ryegrass was ～11.7 MJ/kg DM which is similar to the ME content at harvest one but lower than the ME content for harvest two. Dryland lucerne had an average ME content of 11.0 MJ/kg DM which is similar to both harvests. Brown *et al*. (2005a) found that there were no differences in ME or CP between irrigated and dryland pastures. ME for irrigated and unirrigated lucerne was 11 MJ/kg DM which is similar to the ME for lucerne on both harvest dates. Based on these results lucerne and perennial ryegrass were high quality swards at both harvests.

As expected ME yield was highest in full irrigation pastures (23.8 GJ ME/kg DM) compared with the lowest ME in dryland pastures (1.12 GJ ME/kg DM) in harvest one (Table 4.2). This was due to the differences in dry matter yield because ME yield is ME multiplied by yield. At harvest two ME yields were highest ($P<0.01$) for irrigated perennial ryegrass (Table 4.4). This was due to lucerne growth slowing as temperatures were reduced heading into winter. Figure 4.2 shows lucerne growth rates below perennial ryegrass growth rates on 9/05/2013. Brown *et al*. (2005a) reported growth rates for dryland and irrigated lucerne of 20 kg DM/ha/day in May and <5 kg DM/ha/day from June to August.

5.6.2 Nitrogen

In contrast to ME, nitrogen and therefore CP content were highest in lucerne pastures in harvest one (Table 4.2). Dryland pastures also had a higher N and CP content than irrigated pastures. All perennial ryegrass irrigation treatments had relatively high N content due to the consistent application of N fertilisers, which is not always viable in a dryland system (Fasi *et al.*, 2008). Lucerne was able to maintain a high N content without any application of N fertilisers. In harvest one, all values remained above 3.66% which is similar to other experiments and above the N content of 2.6% that indicated a severely compromised photosynthetic rate (Section 2.7) (Peri *et al.*, 2002). Therefore soil water is limiting dry matter production.

In harvest two, N and CP content were higher in lucerne than perennial ryegrass pastures (Table 4.4). Therefore, in this experiment, all lucerne pastures and unirrigated ryegrass had adequate N content for maximum photosynthetic efficiency. In the lucerne pastures the photosynthetic efficiency per unit leaf area appears to have been maximised and higher rates of photosynthesis were obtained per unit of water used (Moot *et al.*, 2008). This appears to have led to higher dry matter yields (Figure 4.1) on the 9/05/2013 for irrigated lucerne pastures.

Nitrogen yield was highest in lucerne pastures compared with ryegrass pastures in harvest one. Fully irrigated pastures also had the highest N yield despite having a moderate N content. This was due to N yield being determined by multiplying N content by yield and lucerne and fully irrigated pastures had the highest yield (Figure 4.1). In harvest two irrigated perennial ryegrass pastures had the highest N content. This was due to lucerne growth slowing as temperatures were decreasing closer to winter (Figure 4.2). However, once the beginning of winter was reached, effects of irrigation treatments were minimal as irrigation had ceased on the 18/04/2013. This was shown by a similar yield across all irrigated treatments in individual species as it was controlled by temperature rather than other factors at this time. Therefore, lower annual yields of N for lucerne would be predicted at this time as it has lower cool season activity and partitions more nitrogen to roots rather than shoots.

Importantly, lucerne had no nitrogen applied in the period leading up to harvest one or two therefore all nitrogen recovered was from nitrogen fixation or soil mineralisation. Biological nitrogen fixation rates can range between 100-300 kg N/ha/yr for grass/clover pastures in New Zealand (Sun *et al.*, 2008). In the second year of a study by Gault *et al.* (1995) lucerne fixed 275 kg of N when seeds were inoculated and superphosphate was applied annually. In future studies, analysis of the ratio of N14:N15 could be used to determine exactly how much nitrogen has been supplied by both of these processes.

Fully irrigated perennial ryegrass had high nitrogen recovery of 87% in herbage compared with 23% more N recovered than applied in the two and 31% more in the three weekly irrigated pastures in harvest one (Table 4.2). The irrigated pastures had a high N recovery as they had adequate water over the whole season. Therefore, it was able to utilise N for growth as the pasture was not water stressed. When soil moisture is not limiting pasture production, nitrogen is the main determinant of growth (Mills *et al.*, 2006). In the fully irrigated pastures some nitrogen may have been leached if rainfall occurred after irrigation. This could have caused the lower N recovery in fully irrigated pastures compared with pastures irrigated every two or three weeks. Mineralisation of nitrogen occurred in ryegrass pastures irrigated every two or three weeks to increase the N yield above N applied. The increase in N yield could also be due to N leftover in the soil from previous N applications. Mineralisation also occurred in dryland pastures or N was still available in the soil from previous applications as no N was applied.

At harvest two, fully irrigated ryegrass had the lowest N recovery of 62% compared with 89% for two and three weekly irrigations (Table 4.4). N recovery was lower at the second harvest than the first. This could be due to growth slowing as temperatures decreased into winter. Therefore, less N is required for growth. This would mean that some of the applied N may be available to be leached. When urea is applied there is free ammonia present at the soil surface that is available to be volatilized (McLaren and Cameron, 1996). The pH of the soil around a fertiliser granule can increase sharply following application which also promotes ammonia volatilization. If the plant was not using N for growth then more could be available and lost to the atmosphere through volatilization. Mineralisation appears to have occurred in unirrigated ryegrass as no N was applied over this period otherwise N was still available from previous applications.

6 GENERAL DISCUSSION AND CONCLUSIONS

6.1 General discussion

6.1.1 Herbicide application

The results from this experiment suggest 3 L/ha Glyphosate (720 g/L a.i) should not be applied to dryland lucerne in mid-winter as it negatively impacts yield and WUE over the following season. However, application of glyphosate to irrigated lucerne pastures gave complete weed control and it has the ability to still produce a higher annual dry matter yield than perennial ryegrass. The use of glyphosate for lucerne is off label, but its effectiveness for weed control means many farmers use it (D. Moot, 2013, Pers. Comm.). In the US, genetically modified lucerne does allow the use of Round-up but this option is unlikely to be available to New Zealand farmers. Therefore, future work could look at the impact of rate and timing of Round-up applications on lucerne stands. This would allow the determination of a rate that provides cost efficient broad spectrum control but avoids crop damage as the current recommendation of Atrazine and Paraquat do not control dandelions which are a major weed of lucerne (Moot *et al.*, 2003).

6.1.2 Integration into farm systems

This study has shown lucerne had the ability to produce high yields under irrigation. Therefore lucerne could be grown on irrigated Canterbury dairy farms to fill the summer feed deficit that occurs when perennial ryegrass turns reproductive, and has a decrease in growth rates from December to March. Under well watered conditions lucerne is capable of high summer production with an advantage of 40 kg DM/ha/day over perennial ryegrass/white clover pastures (Brown *et al.*, 2005a). The superior spring and autumn yield of lucerne with its greater persistence suggest it is also the most appropriate pasture to include in an irrigated farm system. Lucerne could be planted on the whole farm if cows were wintered off. This would overcome its negligible winter growth. The higher growth rates at other times of the year compared with perennial ryegrass would then more than compensate with higher quality feed. The consensus of results over the last 30 years is that irrigated lucerne will out-yield pasture for at least five years on most soil types (Hayman, 1985). Based on these results it seems likely that more farms will convert to lucerne as a major component of their farm system under irrigated conditions.

The high yield and quality of lucerne means it could also be used as the primary feed source in an indoor dairy farming system. Lucerne could be grown on dryland or irrigated land and utilised in a cut and carry system with a high energy supplement such as maize. This would remove any issues of having to destock over winter due to the low growth of lucerne at this time. It would also minimise nitrogen leaching losses associated with grazed pastures and urine patches. This is because the majority of nitrogen would be removed when the herbage is harvested. The capture of effluent from a housed system would also allow the nutrients to be returned to the lucerne stand in a controlled manner at a time that minimises the risk of nitrate leaching.

In this experiment perennial ryegrass yield was higher than lucerne so it would appear to be advantageous for a dryland farm. However the yield of dryland lucerne in this experiment was not representative of common dryland lucerne yield due to the effect of the glyphosate application. Therefore, the best choice would still be to plant lucerne on a dryland property. It usually has the highest production in spring when dryland farming systems have their highest feed demand (Brown *et al.*, 2005a). In addition, over time, the persistence of ryegrass within a dryland sward would become compromised by low summer rainfall (Mills *et al.*, 2008). On dryland sheep farms the recommendation is to plant 40-60% of the farm in lucerne to maximise lamb liveweight gains (Moot *et al.*, 2003). Finishing stock need to be grazed solely on lucerne for six to eight weeks at an allowance of 2.5-4.0 kg DM/hd/d.

6.1.3 Soil type

On a soil type that is a mixture of a Templeton silt loam and Eyre soil, lucerne was shown to be the most appropriate forage to grow. It is able to access water further down the soil profile than perennial ryegrass. This would become more important if the soil has a high proportion of Eyre soil due to its shallow top soil above gravel which lucerne can still penetrate. Brown *et al*. (2003) recommended that lucerne should be planted on the deepest soils available, because it is able to utilise water stored at depth compared with a shallow rooting species such as perennial ryegrass. An issue with this soil in this experiment was the sub optimal pH of less than 6.0 (Table 3.2). This can have negative effects on dry matter production (Section 2.2).

There are many regions throughout New Zealand that are limited by water availability due to a lack of rainfall in summer or soils with low water holding capacity and a low amount of available water. Such regions include Northland, Taupo, Bay of Plenty, Central Otago and the east coast of both the North and South Island. Therefore lucerne could be used more extensively to increase dry matter yield in these regions, and has been in the past (Douglas, 1986).

6.1.4 Irrigation

When lucerne is grown under irrigation the optimum timing and frequency of water application will be dependent on the available water holding capacity of the soil (Hayman, 1985; Moot *et al.*, 2003). However, irrigation encourages weed seed germination. Therefore, lucerne should be irrigated in 30-50 mm instalments every 3-4 weeks, 7-10 days after grazing. This amount could potentially need to be increased to 80 - 100 mm in January and February depending on rainfall. This amount is similar to what was applied to the irrigated lucerne in this trial. Irrigated treatments produced high yields and did not show signs of water stress. The benefit of these irrigation treatments over full irrigation was that it had the potential to decrease weed seed germination. The infrequent irrigation applications also gave basal buds the chance to expand so that when water is applied lucerne has already begun to grow and can outcompete weeds. Large amounts of irrigation irregularly would also mean that less water is lost through soil evaporation compared with the drip irrigation used in this experiment which can maximise WUE (Section 2.6.2). Flood irrigation would also be inefficient as water is lost due to drainage and run off which could potentially remove essential nutrients as well. Therefore the best application method is through a system that is similar to a pivot that can apply an even distribution of a large amount of water. Perennial ryegrass would require more regular applications of water than lucerne, which can be an issue when water is low in summer and restrictions to irrigation schemes may be applied. In recent years there has been growing awareness that water resources in Canterbury are finite and that there are multiple demands on this water resource (Martin *et al.*, 2006). A ryegrass/white clover pasture would be expected to extract minimal water over 1 m depth so it would not have access to water stored lower in the soil profile and will therefore have a lower yield or higher irrigation requirement than lucerne (Brown *et al.*, 2005a).

6.1.5 Nitrogen

Lucerne produced high yields without any applied nitrogen. Over the 2012/2013 season, perennial ryegrass had 649 kg N/ha applied to the fully irrigated pastures, 591 kg N/ha to the pastures irrigated every two weeks, 512 kg N/ha to the pastures irrigated every three weeks and 347 kg N/ha to the unirrigated pastures. The affordability of this amount of fertiliser for dryland farmers may be limited especially due to the cost of CAN and urea doubling since 2001 (Fasi *et al.*, 2008). Currently CAN and urea cost $690 and $641/tonne (Ravensdown Ltd, 2013). For urea, this works out to be $0.29/kg N. Therefore the cost of N application was $188 in the fully irrigated ryegrass, $171 for ryegrass irrigated every two weeks, $148 for ryegrass irrigated every three weeks and $100 for unirrigated ryegrass. The differences in N applied and yield between fully irrigated ryegrass and ryegrass irrigated every two weeks was 58 kg N/ha/yr and 3900 kg DM/ha/yr. This is a N response of 67 kg DM/kg N. The differences between ryegrass irrigated every two and three weeks was 79 kg N/ha and 1130 kg DM/ha. This resulted in 14 kg DM/kg N. The differences between ryegrass irrigated every three weeks and dryland ryegrass was 165 kg N/ha and 5220 kg DM/ha. This resulted in 32 kg DM/kg N. The differences between fully irrigated and dryland ryegrass was 302 kg N/ha and 10250 kg DM/ha, resulting in 34 kg DM/kg N when irrigation was applied. The highest response was between full irrigation and irrigation every two weeks. The response of dry matter to N was high compared to ～20 kg DM/kg N reported by Fasi *et al*. (2008) This could be due to irrigation. Therefore by planting lucerne the same N content is able to be maintained without the additional cost of applying N fertilisers. This means that leaf expansion and photosynthesis rates will not be compromised ensuring maximum light interception and growth (Mills and Moot, 2010).

6.1.6 Future research

Future research could compare lucerne and perennial ryegrass under more natural conditions to determine any differences in dry matter yield as the weed and dead content was highly controlled in this experiment. Further research could also look at the same experiment but without the herbicide application to determine whether dryland lucerne would have higher growth than dryland perennial ryegrass and if WUE would be comparable to that of irrigated lucerne. The outcome of this experiment in the 2013/2014 season will be interesting to determine if the dryland lucerne was able to recover and increase yields to match dryland perennial ryegrass and increase WUE.

6.2 **Conclusions**

- Lucerne had annual dry matter yields above perennial ryegrass at all three irrigation levels. Based on these results if irrigation is available then lucerne should be sown on a Eyre or Templeton soil.
- Unexpectedly dryland lucerne had a lower annual dry matter yield (4.65 t DM/ha) than dryland perennial ryegrass (8.29 t DM/ha). Results suggest that the herbicide application of glyphosate on the 22 June 2012 was responsible for this result.
- Differences in dry matter production were due to WUE. Irrigated lucerne had a WUE of 34.5 kg DM/ha/˚Cd compared with 11.2 kg DM/ha/˚Cd for unirrigated lucerne and 22.5 kg DM/ha/˚Cd for all perennial ryegrass pastures.
- All pastures had an ME content above 11.0 MJ ME/kg DM and nitrogen content above 3.5%. Therefore the lucerne and perennial ryegrass were high quality pastures and the proportion of N was above the threshold of 2.6% that indicates a severely compromised photosynthetic rate.
- Glyphosate is not a recommended herbicide for weed control in lucerne. However, this experiment shows that it has potential to be applied to irrigated stands for complete weed control and the lucerne will still be able to maintain a yield above irrigated perennial ryegrass. Future research could look at the impact of rate and timing of glyphosate applications on lucerne stands.

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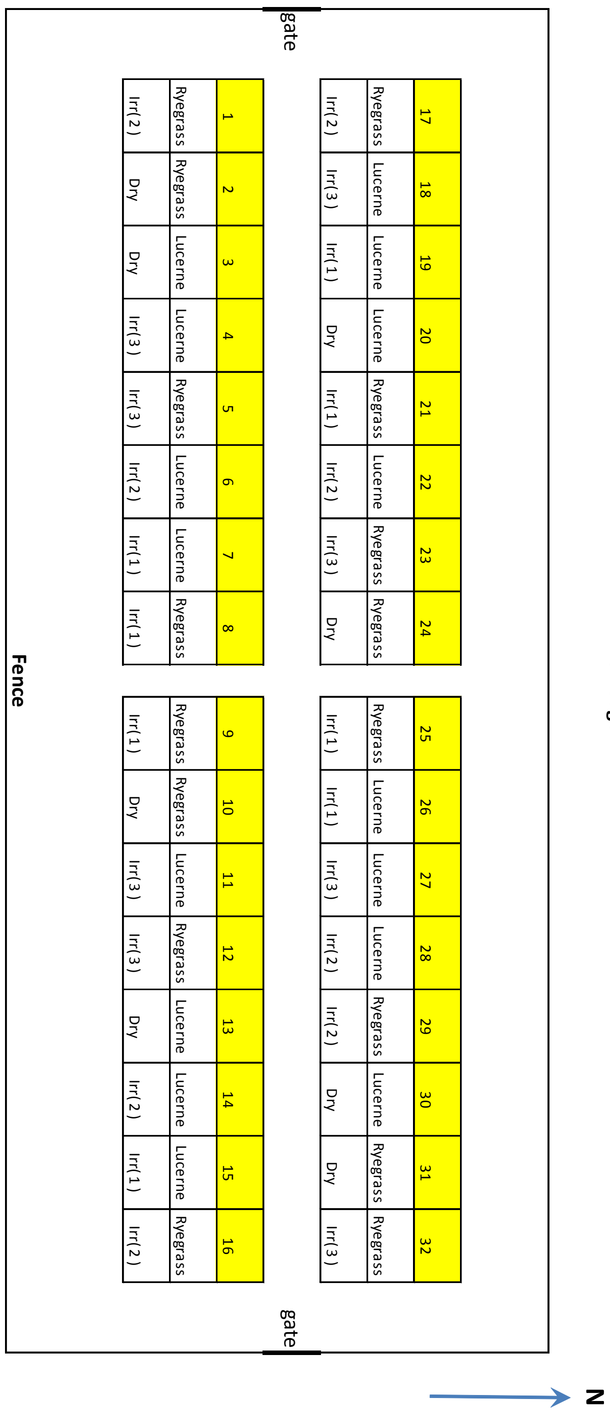
APPENDICES

Appendix 1 Experimental plan for Lucerne and Pasture Trial, AgResearch Farm, Canterbury. The irrigation treatments are: irr (1) which is irrigated weekly, irr (2) is irrigated fortnightly, irr (3) is irrigated every three weeks and dry has no irrigation. The numbers represent the plot numbers.



Appendix 2 The agrichemical applied, application rate, active ingredient and the plots which it was applied to for the period from establishment to 30 June 2013.

Date	Agrichemical applied	Application Rate	Active Ingredient	Plots applied to
18 March 2011	Chlorpyrifos (Lorsban)	1 L/ha in 200 L/ha water	500 g /ha	Lucerne
4 April 2011	Haloxyfop (Gallant)	1 L/ha with uptake oil at 500 ml per 100 L water	150 g/ha	Lucerne
15 April 2011	Diazinon (Digrub)	3 L/ha in 200 L/ha water	2.4 kg/ha	All
29 April 2011	Imazethapyr (Spinnaker)	400 ml/ha in 200 L/ha water	280 g/ha	Lucerne
5 May 2011	Diflufenican (Jaguar)	1.5 L/ha in 200 L/ha water	375 g/ha	Ryegrass
16 May 2011	Glyphosate (Roundup)	2 L/ha	720 g/ha	End of ryegrass plots
20 May 2011	Chlorpyrifos (Lorsban)	1 L/ha	500 g/ha	Lucerne
30 May 2011	Methiocarb (Mesurol)	8 kg/ha	6 kg/ha	Lucerne
2 June 2011	Ethofumesate (Nortron)	4 L/ha in 200 L/ha water	2 kg/ha	Ryegrass
22 December 2011	Chlorpyrifos (Lorsban)	1 L/ha in 200 L/ha water	500 g/ha	Lucerne
1 March 2012	Metaldehyde (Metarex)	8 kg/ha	400 g/ha	All
16 March 2012	Diazinon (Gesapon)	11 kg/ha	2.2 kg/ha	All
2 April 2012	Copper sulphate pentahydrate	800 ml/ha and a sticking agent at 20 ml per 100 L water	784 ml/ha	Lucerne
22 June 2012	Glyphosate (Roundup)	3 L/ha	720 g/ha	Lucerne
4 September 2012	Chlorpyrifos (Lorsban)	1 L/ha in 200 L/ha water	500 g/ha	Lucerne
7 November 2012	Haloxyfop (Gallant)	1 L/ha with 1 L/ha uptake oil	150 g/ha	Lucerne
7 November 2012	Chlorpyrifos (Lorsban)	1 L/ha in 200 L/ha water	500 g/ha	Lucerne

29 November 2012	Diazinon (Gesapon)	11 kg/ha	2.2 kg/ha	All
21 February 2013	Diazinon (Gesapon)	11 kg/ha	2.2 kg/ha	Ryegrass
28 February 2013	Diazinon (Gesapon)	11 kg/ha	2.2 kg/ha	All
4 March 2013	Dicamba (Banvel)	1 L/ha in 200 L/ha water	200 g/ha	Pasture treatments 1, 2 and 3
	Dimethylamine salt (MCPA)	2 L/ha in 200 L/ha water	1.5 kg/ha	Pasture treatments 1, 2 and 3
5 March 2013	Metaldehyde (Slugout)	15 kg/ha	750 g/ha	All
19 April 2013	Haloxyfop (Gallant Ultra)	500 ml/ha with 1 L/ha uptake oil in 200 L/ha water	260 g/ha	Lucerne

Appendix 3 Details of fertiliser product used, application rate and plots applied to for the period from emergence to the 30 June 2013.

Date	Fertiliser Product	Application Rate	N:P:K:S (kg ha^{-1})	Plots applied to
15 March 2011	Cropzeal 16N	200 kg/ha	(15.4:8:10:9.6)	Lucerne
21 March 2011	Optima fine grind pelleted lime	2 t/ha		All
25 March 2011	Cropzeal 20N	200 kg/ha	(19.2:10:0:12)	Ryegrass
	KCl	40 kg/ha	(0:0:50:0)	Ryegrass
21 July 2011	Optima fine grind pelleted lime	200 kg/ha (23 kg/plot)		All
12 August 2011	Urea	100 kg N/ha irr 1 40 kg N/ha irr 2 and 3.	(46:0:0:0) (46:0:0:0)	Ryegrass
6 September 2011	Granulated boron	5 kg/ha	14% B	Lucerne
	Granulated Molybdenum	200 kg/ha	10% Mo	Lucerne

1 October 2011	Urea	100 kg N/ha	(46:0:0:0)	Ryegrass
2 November 2011	Urea	122 kg N/ha	(46:0:0:0)	Ryegrass
4 November 2011	30% Potash super	300 kg/ha	(0:6.3:15:7.7)	All
5 December 2011	Urea	76 kg N/ha irr 1, 79 kg N/ha irr 2, 76 kg N/ha irr 3, 66 kg N/ha irr 4.	(46:0:0:0)	Ryegrass
22 December 2011	30% Potash super	300 kg/ha	(0:6.3:15:7.7)	Lucerne
29 December 2011	Urea	81 kg N/ha irr 1, 76 kg N/ha irr 2, 76 kg N/ha irr 3, 57 kg N/ha irr 4	(46:0:0:0)	Ryegrass
	Optima fine grind pelleted lime	200 kg/ha		Lucerne
1 February 2012	Urea	100 kg N/ha irr 1, 91 kg N/ha irr 2, 84 kg N/ha irr 3, 24 kg N/ha irr 4	(46:0:0:0)	Ryegrass
2 March 2012	Urea	115 kg N/ha irr 1, 109 kg N/ha irr 2, 109 kg N/ha irr 3, 24 kg N/ha irr 4	(46:0:0:0)	Ryegrass
7 March 2012	30% Potash super	300 kg/ha irr 1,2 & 3 30 kg/ha irr 4	(0:6.3:15:7.7)	All
10 April 2012	Urea	102 kg N/ha irr 1 & 2 98 kg N/ha irr 3, 71 kg N/ha irr 4	(46:0:0:0)	Ryegrass
10 April 2012	Molybdenum	2 L/ha and a sticking agent at 20 ml per 100 L water		Lucerne
8 May 2012	Optima fine grind pelleted lime	200 kg/ha (640 g per plot)		Lucerne
21 June 2012	Optima fine grind pelleted	200 kg/ha (640 g per plot)		Lucerne

	lime			
31 August 2012	30% Potash super	300 kg/ha	(0:6.3:15:7.7)	All
11 September 2012	Urea	100 kg N/ha	(46:0:0:0)	Ryegrass
18 October 2012	Urea	102 kg N/ha irr 1, 100 kg N/ha irr 2, 93 kg N/ha irr 3, 89 kg N/ha irr 4	(46:0:0:0)	Ryegrass
19 October 2012	Optima fine grind pelleted lime	200 kg/ha (640 g per plot)		Lucerne
29 November 2012	Urea	115 kg N/ha	(46:0:0:0)	Ryegrass
14 January 2013	Urea	81 kg N/ha irr 1, 66 kg N/ha irr 2, 60 kg N/h irr 3, 29 kg N/ha irr 4	(46:0:0:0)	Ryegrass
2 February 2013	30% Potash super	200 kg/ha	(0:6.3:15:7.7)	All
	Urea	74 kg N/ha irr 1, 93 kg N/ha irr 2, 41 kg N/ha irr 3, 14 kg N/ha irr 4	(46:0:0:0)	Ryegrass
28 February 2013	Urea	93 kg N/ha irr 1, 51 kg N/ha irr 2, 43 kg N/ha irr 3	(46:0:0:0)	Ryegrass
2 April 2013	Urea	84 kg N/ha irr 1, 66 kg N/ha irr 2, 60 kg N/ha irr 3	(46:0:0:0)	Ryegrass

Appendix 4 Dates and plots for main biomass harvests for the period from 1 June 2011 to 30 June 2013.

Harvest type	Date	Plots
Main biomass harvest	1 June 2011	Ryegrass
	29 September 2011	Ryegrass
	1 November 2011	All
	30 November 2011	Ryegrass
	20 December 2011	All
	26 January 2012	All
	29 February 2012	All
	3 April 2012	Ryegrass
	23 May 2012 (final harvest before winter)	All
	7 September 2012	Ryegrass
	16 October 2012	Ryegrass
	31 October 2012	Lucerne
	19 November 2012	Ryegrass
	19 December 2012	All
	23 January 2013	All
	27 February 2013	All
	27 March 2013	All
	9 May 2013 (final harvest before winter)	All

Appendix 5 Accumulated yield (kg DM/ha) for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	18780_{a}	18540_{a}
Irr 2	16535_{b}	14640_{bc}
Irr 3	14975_{bc}	13510_{c}
Dry	4645_{e}	8290_{d}
SEM	659	
LSD	1938.2	

SEM and LSD values are for the interaction between species and irrigation treatment (P<0.002).

Appendix 6 Mean daily growth rate (kg DM/ha/day) for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	77.0_{a}	76.0_{a}
Irr 2	67.8_{b}	60.0_{bc}
Irr 3	61.4_{bc}	55.4_{c}
Dry	19.0_{e}	34.0_{d}
SEM	2.70	
LSD	7.94	

SEM and LSD values are for the interaction between irrigation treatment and species (P<0.002).

Appendix 7 Maximum mean daily growth rates (kg DM/ha/day) for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	136_{a}	102_{bc}
Irr 2	112_{b}	102_{bc}
Irr 3	112_{b}	105_{bc}
Dry	50.4_{d}	94.7_{c}
SEM	5.15	
LSD	15.15	

SEM and LSD values are for the interaction between irrigation treatment and species (P<0.001).

Appendix 8 The regression equations, standard errors of the coefficients and the coefficients of determination for the regression of accumulated dry matter yield (kg DM/ha) against accumulated thermal time (˚Cd) in phase one and two for lucerne and perennial ryegrass under four irrigation treatments for the 2012/2013 season at the AgResearch farm, Canterbury, New Zealand. Full details of the treatments are given in Section **0**.

	Lucerne			
Irrigation treatment	Equation (slope 1)	R^2	Equation (slope 2)	R^2
Irr 1	y = 6.69±0.428x - 548±811	98.0	-	
Irr 2	y = 5.71±0.312x - 234±591	98.5	-	
Irr 3	y = 5.07±0.342x + 168±647	97.8	-	
Dry	y = 3.51±0.108x - 67.0	99.7	y = 0.197±0.0914x - 67.0	99.7

	Perennial ryegrass			
Irrigation treatment	Equation (slope 1)	R^2	Equation (slope 2)	R^2
Irr 1	y = 5.27±0.293x - 109±577	97.9	-	
Irr 2	y = 5.85±0.833x - 789±046	97.4	y = 2.50±0.497x + 4686±754	97.4
Irr 3	y = 5.79±0.872x - 768±1030	96.6	y = 2.08±0.521x + 4991±994	96.6
Dry	y = 5.09±0.745x - 757±1010	94.8	y= 0.345±0.444x + 6862±211	94.8

Appendix 9 Comparison of thermal time phase one for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated at the AgResearch farm, Canterbury, New Zealand. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	6.69_{a}	5.27_{b}
Irr 2	5.71_{b}	5.43_{b}
Irr 3	5.07_{b}	5.79_{b}
Dry	3.03_{c}	5.09_{b}
SEM	0.288	
LSD	0.848	

SEM and LSD values are for the interaction between irrigation treatment and species (P<0.001).

Appendix 10 Comparison of thermal time phase two for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated at the AgResearch farm, Canterbury, New Zealand. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	6.69_{a}	5.27_{b}
Irr 2	5.71_{ab}	2.82_{c}
Irr 3	5.07_{b}	2.83_{c}
Dry	0.43_{d}	0.35_{d}
SEM	0.457	
LSD	1.343	

SEM and LSD values are for the interaction between irrigation treatment and species (P<0.033).

Appendix 11 Comparison of thermal time breakpoint x for lucerne and perennial ryegrass plots for the 2012/2013 season at the AgResearch farm, Canterbury, New Zealand.

Species	Mean	SEM	LSD
Lucerne	1375	17.5	58.6
Perennial ryegrass	1575		

SEM and LSD values are for species (P<0.001).

Appendix 12 Comparison of water use slope for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated at the AgResearch farm, Canterbury, New Zealand. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	37.0_a	24.9_b
Irr 2	34.1_a	20.7_b
Irr 3	32.3_a	21.7_b
Dry	11.2_c	22.4_b
SEM	2.46	
LSD	7.22	

SEM and LSD values are for the interaction between irrigation treatment and species (P<0.001).

Appendix 13 The regression equations, standard errors of the coefficients and the coefficients of determination for the regression of accumulated dry matter yield (kg DM/ha) against annual water use (mm) for lucerne irrigated and unirrigated and perennial ryegrass at all irrigation levels for the 2012/2013 season at the AgResearch farm, Canterbury, New Zealand.

	Lucerne	
Irrigation treatment	Equation	R^2
Irrigated	y = 34.5±0.858x - 3964±412	99.7
Unirrigated	y = 11.2±1.33x + 693±472	93.3
	Perennial ryegrass	
Irrigation treatment	Equation	R^2
All irrigation treatments	y = 22.5±2.32x + 787±904	93.0

Appendix 14 Maximum soil moisture deficit (mm) for lucerne and perennial ryegrass plots for the 2012/2013 season under four irrigation treatments: Irr 1 is full irrigation, Irr 2 is irrigated every two weeks, Irr 3 is irrigated every three weeks or dry is unirrigated. Values with different subscripts are different (α=0.05) according to Fisher's LSD test.

Irrigation treatment	Lucerne	Perennial ryegrass
Irr 1	61.3_{d}	56.7_{d}
Irr 2	101_{c}	71.5_{d}
Irr 3	131_{b}	108_{c}
Dry	164_{a}	125_{b}
SEM	5.73	
LSD	16.85	

SEM and LSD values are for the interaction between species and irrigation treatment (P<0.047).