Dry matter production and water use of dryland cocksfoot/lupin and lucerne pastures in the third year after establishment

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Brenna Coleman

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Cocksfoot (*Dactylis glomerata*) is a preferred grass option for dryland pastures on high country farms in the South Island of New Zealand. However, increasing the productivity of cocksfoot based pastures with legumes is difficult due to the harsh environment and difficulty to apply fertiliser. Russell lupin, or perennial lupin (*Lupinus polyphyllus*) has been identified as a potential legume option due to its ability to tolerate low fertile and acidic soils, cold winters and hot, dry summers in extensive high country grasslands. However, the productivity and water use of cocksfoot/lupin pastures is not well understood. The aim of this study was to compare the dry matter (DM) production and water use of cocksfoot/lupin pastures compared with a standard pure lucerne (*Medicago sativa*) pasture under dryland conditions. The two pasture types were sown in December 2013 at Lincoln University and in this study they were compared during their third year after establishment. During the first and second years after establishment, lucerne produced more DM than cocksfoot/lupin, and the lupin content halved each year such that the cocksfoot dominated the cocksfoot/lupin pasture after 2.5 years. In attempt to increase the legume content of cocksfoot/lupin pasture, a mixture of two cultivars of subterranean clover (*Trifolium subterraneum*) (Denmark and Narrikup) were oversown in autumn 2017. Six 0.13 ha paddocks of each pasture type were rotationally grazed by young sheep and not irrigated.

In the third year after establishment (11 July 2016 to 29 June 2017), lucerne produced 10,617 kg DM/ha compared with 6,433 kg DM/ha for cocksfoot/lupin. The lucerne yield contained 97% lucerne, 0.2% voluntary white clover and 3.2% weed, whereas the cocksfoot/lupin yield contained 86% cocksfoot, 12% lupin, 0.05% sub clover, 1.2% voluntary white clover and 0.8% weed. Sub clover content averaged 2% in the cocksfoot/lupin pasture during the first grazing rotation in the following spring (3 August to 14 September 2017), with 28% of this Denmark and 72% Narrikp. Nitrogen yield in the herbage was 223 kg N/ha for lucerne compared with 87 kg N/ha for cocksfoot/lupin. Pasture growth rates for lucerne and cocksfoot/lupin were 2.06 and 1.21 kg DM/°Cd from 11 July to 17 August, then 6.36 and 3.94 kg DM/°Cd to 13 December and then 1.75 and 0.88 kg DM/°Cd to 29 June. Water use was 503 mm for lucerne and 498 mm for cocksfoot/lupin. Water use efficiency for lucerne and cocksfoot/lupin was 6.35 and 3.40 kg DM/ha/mm from 11 July to 17 August, then 23.33 and 16.30 kg DM/ha/mm to 13 December and then 16.46 and 7.50 kg DM/ha/mm to 29 June. Leaf area index, which was quantified pre-grazing in each paddock from 2 March to 22 May, was 2.0 for lucerne, 2.8 for cocksfoot and 1.5 for lupin. Overall the results suggest that the lucerne pasture was able to produce more DM than the cocksfoot/lupin pasture due to a faster pasture growth particularly in spring. This faster growth rate which lead to a higher water use efficiency, deeper access to soil moisture during summer, and possibly a higher LAI which could have resulted in increased light interception. These attributes make lucerne an attractive option for dryland pastures in areas of the South Island high country where soil fertility is unsuitable for lucerne. By comparison, lupin did not persist and Denmark and Narrikup were established from oversowing in the cocksfoot-dominant pasture.

Keywords: alfalfa, *Dactylis glomerata*, leaf area index, *Lupinus polyphyllus*, *Medicago sativa*, nitrogen, soil moisture, South Island high country, *Trifolium subterraneum*, water use

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Chapter 1

Introduction

White clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*) are the most common forage species grown in pasture mixes for grazing animals (Charlton & Stewart, 1999). However these species struggle in low rainfall and low fertility environments (Ates *et al*., 2010). This means alternative species are required (Brown *et al.,* 2006; Mills *et al.,* 2008) for dryland pastures, especially for improving spring production, when soil moisture is more available. Cocksfoot (*Dactylis glomerata*) is the most popular dryland grass species (Charlton & Stewart, 1999; Moloney, 1993) and is commonly grown in these low rainfall environments. However, cocksfoot is very competitive and dominates white clover when grown together. An alternative legume is required for this environment in spring to provide masses of high energy pasture for ewes and their lambs during late pregnancy, lactation and lamb liveweight gains, the main profit driver on New Zealand sheep and beef farms (Mathias-Davis *et al.,* 2013).

Lucerne (*Medicago sativa*) has been identified as a high performing pasture legume, with high summer dry growth and the ability to meet both ewe and lamb demands throughout summer (Brown *et al.,* 2005; Moot *et al.,* 2003). It is widely grown as a monoculture and used on an annual basis from October to April (Brown *et al.,* 2005). However, for best management, lucerne should not be grazed from July to at least mid-September (Moot *et al.,* 2003). In autumn, lucerne assimilation changes from above ground to below ground to replenish root reserves it used over summer (Teixeira, 2006). Therefore, for longer persistence and better spring and summer growth, lucerne should be spelled over winter, which creates a feed deficit over this period for dryland farms, that needs to be filled.

Much of the New Zealand South Island high country has been identified as poor producing, unprofitable grassland because pasture growth is low and therefore limits animal production. This is an environment too cold and dry to support many shrub or grass species, with tussock grasslands typically dominating the area (Ledgard, 1988). Due to this, and the difficulty to increase soil fertility in the high country, grazed areas have a low fertility and low productivity, with very few solutions to increase both (Scott et al., 1985). Soils are typically low in fertility including pH, and potentially contain high levels of exchangeable aluminium (Al), which limits the establishment and productivity of legumes (Moir & Moot, 2014). Applications of fertiliser and lime can be used to increase soil fertility and pH, which in turn keep exchangeable Al concentrations at an acceptable level (Moir & Moot, 2014). Soil moisture deficit and low fertility are physically and economically challenging on high country farm systems. Legumes, especially lucerne are very susceptible to Al toxicity, causing significant production and persistence disadvantages, as large amounts of Al in soils reduces legume nodulation, limiting nitrogen (N) fixation (Edmeades *et al.,* 1991). This therefore reduces legume production, decreasing the legume content in pastures and reducing N supply to other plants, which limits the total dry matter (DM) production of pastures. Legumes are essential for the persistence and survival of grazed pastures. In harsher environments where low soil moisture and soil fertility are an issue, legumes have struggled to remain in pastures for a significant length of time (Scott, 2014).

Previously, perennial lupins (*Lupinus polyphyllus*) have been trialled in attempt increase the total legume content in high country pastures in South Island New Zealand, with many trials conducted around Lake Tekapo, Canterbury, New Zealand (Black *et al.,* 2014; Scott, 2014). Another trial (Black & Ryan-Salter, 2016) was set up in December 2013 at Lincoln University, Canterbury, New Zealand, where a cocksfoot/lupin pasture mix was compared with a lucerne monoculture. Over the last 3 years (December 2013 - June 2016) this experiment has been regularly monitored and sheep liveweight gain and DM production of these two pastures have been measured, in an attempt to determine if lupin can survive in a more intensive, dryland grazing system. This dissertation reports on the third year (2016/2017) after establishment of this experiment and, due to the frequent differences in sheep liveweight gains and herbage yield, an attempt was made to explain the significant differences in DM production between the two pasture types. It was also observed that lupin content of the cocksfoot pasture has decreased from 40% to 10% over the first 2.5 years (Black & Ryan-Salter, 2016), and that this pasture was potentially N deficient. Therefore, annual subterranean clover (*Trifolium subterraneum*), identified as a productive dryland legume for summer dry lowland and hill country pastures in New Zealand (Chapman *et al.,* 1986), was oversown into the cocksfoot/lupin pasture in autumn 2017 in an attempt to increase the overall legume content. Two different sub clover cultivars were used in this trial: Denmark and Narrikup. Denmark is an older cultivar, with proven performance in long term trials at Lincoln University (Black & Moir, 2015; Mills et al., 2015). It has a high seed yield and flowers late in the season. Denmark was well adapted to New Zealand farms, especially for set stocking in spring (Nichols *et al*., 2013). Narrikup is a more recent cultivar, introduced to New Zealand in 2014 (Nichols *et al*., 2013). It has outstanding burial ability and a mid-season flowering, ideal for dryland environments. Although having no large field trials carried out with Narrikup, small plot trials at Lincoln University have been very successful (Wright, 2015).

The objectives of this study were to:

- Identify any differences in dry matter production of a cocksfoot/lupin/clover pasture mix compared to a lucerne monoculture during the third production year (2016/2017) after establishment of a dryland pasture experiment described by Black and Ryan-Salter (2016).
- Attempt to quantify any herbage yield differences in terms of botanical composition, N content, water use, thermal time and leaf area index (LAI).
- Quantify the germination rate of Denmark and Narrikup sub clover cultivars, and their impact on improving the legume content of the cocksfoot/lupin pasture.

Chapter 2

Literature Review

The objectives of this review were to outline the issues relating to legumes in the South Island high country of New Zealand and discuss the ability of lupin to survive in this environment. The performance of lupin in cocksfoot dominant pastures was also discussed, with reference to the past 3 years of the "lupin grazing trial "at Lincoln University. The ability of sub clover as an alternative legume for the South Island high country was also discussed. And finally, this review outlined the main drivers of pasture production and their importance in lucerne and cocksfoot dominant pastures.

2.1 Legmes in the South Island high country, New Zealand

The presence of legumes and their ability to fix atmospheric Nin pastures is essential for many farming systems (Lucas *et al.,* 2010). This N is transferred to the grasses by excretions from the grazing animals after consuming the legumes, or as mineral N in the soil, therefore increasing DM production, and in turn increasing animal liveweight gain, especially in lambs (Ates *et al.,* 2013). Legume N fixation ranges from 0-350 kg N/ha/year, depending on the legume content and its growth rate of the legume species in response to abiotic temperature, moisture, soil fertility and biotic (grazing, pests and diseases) factors (Figure 2.1).

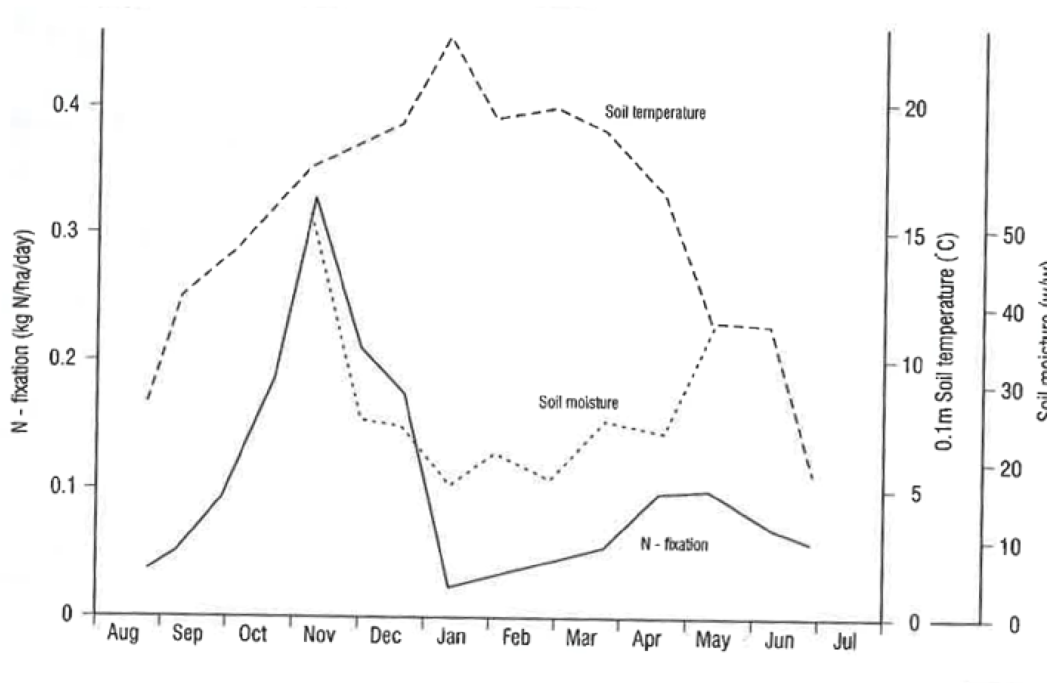

Figure 2.1 Influence of soil temperature (°C) and moisture (mm) on the rate of nitrogen fixation (kg N/ha/day) by white clover over a year (Kemp *et al.*, 1999b).

Perennial ryegrass and white clover have been the main pasture options for grazing livestock for both breeding and finishing systems in New Zealand (Kemp *et al*., 1999a) since the 1930s (Charlton & Stewart, 1999). Although able to produce at least 6 t DM/ha and support hoggets growing an average 200 g/day (Ryan & Widdup, 1997) this pasture mix has poor tolerance in dry environments due to shallow roots (Fraser, 1994; Mills *et al.,* 2015). Therefore, it does not suit some regions of New Zealand, in particular the South Island high country. In this environment rainfall averages 550-600 mm/year (NIWA, 2016b), limiting what species can be grown. Maximum and minimum temperatures for this environment are 14.3°C and 3.1°C respectively, also creating challenges for plant survival.

Alternative pasture species have been suggested to improve dryland pasture production (Brown *et al.,* 2003; McGowan *et al.,* 2003), and lucerne has been highlighted to be a dryland pasture species (Brown *et al*., 2005). Lucerne is a widely known dryland pasture option for its ability to grow in dry (annual rainfall <800 mm/year) conditions due to its long deep tap roots (Brown *et al.,* 2005). Lucerne thrives in cool to moderate temperatures (8 – 25 °C) and high to moderate altitudes (>600 m above sea level). It is highly suitable to dry environments that typically have prolonged water stress periods, and it has a high feeding value (Charlton & Stewart, 1999; Scott *et al.,* 1985). Lucerne can grow in moderate fertility soils, but does not survive in acidic soils (<0.3 me/100 g soil (Moir & Moot, 2010)). The grazing tolerance of lucerne is high, but lucerne is dormant over winter (White *et al.,* 1999) to allow root replenishment to occur (Scott *et al.,* 1985). Therefore, lucerne is unable to provide winter feed to livestock (Charlton & Stewart, 1999). After defoliation, lucerne partitions N and carbohydrate reserves from roots to shoots until photosynthesis is great enough to maintain reserves itself, reducing the lull growth period immediately after grazing. During late autumn and winter lucerne replenishes these reserves, partitioning N and carbohydrates from the shoots to the roots, reducing dry matter production (Varella, 2002).

Many South Island high country soils have low pH and possible high exchangeable Al concentrations (Moir & Moot, 2014). Moir and Moot (2010) found that soil pH was strongly related to levels of soil plant-available aluminium, with Al levels increasing rapidly below a pH 5.8 (Figure 2.2).

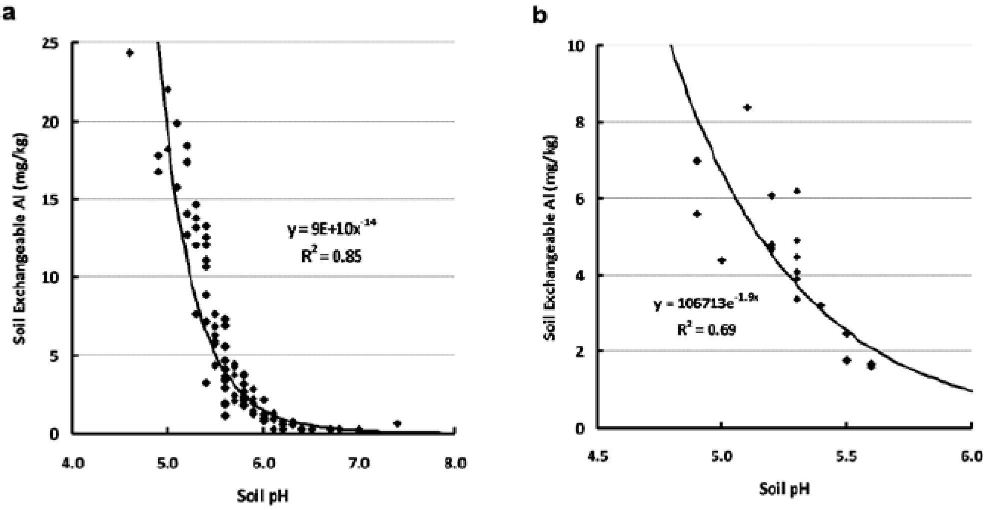

Figure 2.2 Relationship between the soil pH and soil exchangeable Al on a (a) lucerne pasture at Mt Pember Station, North Canterbury, New Zealand, and a (b) cocksfoot/lupin mix at Glenmore Station, Lake Tekapo, Canterbury, New Zealand (Moir & Moot, 2014).

Most legumes, especially lucerne, cannot thrive in soils with traces of Al as their roots avoid the Al layer by growing horizontally (Moir & Moot, 2014). The root growth is reduced by the presence of Al in the soil, with horizontal and restricted root growth (Moir & Moot, 2010) and therefore legume dry matter production (Moot & Pollock, 2014).

Lucerne has been found as a valuable tool for dryland farmers (Brown *et al.,* 2006) as the plants deep roots can extract water to at least 2.3 m, holding on longer in dry conditions than a typical perennial ryegrass/white clover pasture. Andrew (1976) determined that growth and nodulation of legumes was severely limited at a pH below 5.0. With high Al concentrations at this point nodule mass decreased more severely with the presence of Al in the soil, showing a higher pH is needed before expecting high legume yields. The easiest way to neutralise this issue is to lime soils to increase the pH. However, this may not be economical in some soils. Therefore, the soils are too acidic for legumes and potential productivity declines rapidly (Edmeades *et al.,* 1991). Applying lime only effects the top 0-7.5 cm when oversown (Moir & Moot, 2010). Therefore, any low pH and high exchangeable Al levels below 7.5 cm in the soil profile will not be improved unless the lime was incorporated into the soil. This is difficult to do in high country soils. This means that lucerne may not the best legume for areas of the New Zealand South Island high country, where maintaining an optimum soil pH is difficult. Due to the poor response from lucerne in low fertile, low pH soils of the New Zealand High Country other species have been researched and trialled for their performance in the environment, including perennial (or Russell) lupin.

2.1.1 Lupins as a legume option

The perennial forage, Russell lupin was derived from western North America (California and Washington) where seeds were collected from and introduced to Britain as a potential garden flower in 1826. Many hybrids were then created with tree lupin (*Lupinus arboreus*) with many different flower colours being created, before it was released commercially in the 1930s. It is assumed it was introduced to New Zealand shortly after this as a garden flower (Scott, 1989). Lupin seed was broadcasted along roadsides south of Lake Tekapo in 1952, which was the first large area sowing in New Zealand (Scott, 1989). Due to the ability to survive and dominate unmanaged roadsides, lupin was identified as a potential pasture legume. Early use of lupin on farmland in New Zealand was for revegetation of alpine areas in the South Island high country (Nordmeyer & Davis, 1978). These trials showed the high performance of lupins in the dry, acidic, low P and high Al soils (Scott, 2014). Lupin was also found to accumulate Al in the foliage, shifting the Al contamination from the soil into the organic matter in the top soil layer, where it could be overcome with lime applications. Lupins were first researched for their potential as a grazing legume in 1982, (Scott, 1989) at Lake Tekapo, with experiments comparing a total 25 species for their production and sheep production. Over 6 years of the experiment, lupin was found to germinate the fastest in cold spring conditions and have similar growth to more common legumes (white clover and red clover) in the first year after establishment. In low fertiliser trials, lupin remained the dominant and highest yielding species (Scott, 1989), suggesting better performance than other legumes and grasses in low fertile soils.

2.2 Feeding lupins for sheep production

Lupins have been successful in summer dry, moderately fertile soils in the South Island high country, but there have been few commercial plantings of lupins in the New Zealand high country (Scott, 1989). Over recent years, grazing experiments involving perennial lupins have been conducted, typically at Lake Tekapo. A 3-year experiment (Black *et al.,* 2014) investigated the performance of Merino ewes on perennial lupin compared with lucerne at Sawdon station, which is a commercial farm near Lake Tekapo (Table 2.1).

Table 2.1 Sheep live weight (LW), liveweight gain (LWG) and lambing percentage (%) over 3 years on a lupin pasture, compared with lucerne at Sawdon Station, Lake Tekapo, Canterbury, New Zealand (Black *et al.,* 2014).

	Year 1 (2011-2012)		Year 2 (2012-2013)		Year 3 (2013-2014)	
	Lupin	Lucerne	Lupin	Lucerne	Lupin	Lucerne
Lambing %	-	-	103	93	120	117
Lamb LW[1] at docking (kg)	-	-	20	21	19	17
Ewe LW[1] loss over lambing (kg)	-	-	8	2	4.3	4
Lamb LW[1] at weaning (kg)	28	31	28	31	30	30
Lamb LWG[2] docking-weaning (g/d)	150	217	121	152	166	194
Ewe LWG[2] docking-weaning (kg)	-3	5	0	3	1.3	-3.6
Ewe LWG[2] weaning-mating (g/d)	125	161	64	120	63	96

[1]LW = live weight
[2]LWG = liveweight gain

On the lupin pasture at Sawdon Station, lamb liveweight gain from docking to weaning was only 69%, 80% and 86% of that received in lucerne, for years one, two and three respectively (Table 2.1). Lambing percentage remained slightly higher on lupins than on lucerne as did the ewe liveweight loss over lambing, which was likely influenced by the higher lambing percentage and greater stress on the ewes. Ewe liveweight gain over autumn (weaning to mating) varied significantly throughout the years. However, lucerne ewes continually gained more (2.0, 2.6 and 0.9 kg for each year respectively) weight over this period, with growth rates averaging 34% greater on lucerne than lupins (Black *et al.,* 2014).

In late spring (October), lupin yielded at 2.7 t DM/ha, increased to a peak of 7.2 t DM/ha in December, before decreasing to 5.8 t DM/ha in February. By May lupin herbage had decreased further to 4.1 t DM/ha. The most palatable component of the lupin, the leaf (Moot & Pollock, 2014), fluctuated significantly over the year, contributing 41%, 42% (including petiole) and 24% to the average herbage mass in the first year. Herbage mass in year two fluctuated from 1.7 t DM/ha in September to 8.3 t DM/ha in December, 2.9 t DM/ha in March, 3.2 t DM/ha in April and 2.9 t DM/ha in May. The leaf and petiole contributed 40%, 37% and 22% in September, December, April and May respectively. Sheep prefer high N herbage (Edwards *et al.,* 1993) and therefore typically selectively graze legumes from a pasture, with greater consumption of leaves and flowers of legumes as they have higher N concentrations compared to the stem (Brown *et al.,* 2006; Moot & Pollock, 2014). High N content was found in the leaves and flowers of legumes, with lower levels in the petioles, stems and dead material, and fluctuated over the season. N content peaked at 5.4%, 3.1% and 4.3% in lupin leaf, petiole and stem before decreasing to 3.8%, 1.5% and 0.7% at their lowest points respectively (Black *et al.,* 2014).

Another Lake Tekapo experiment (Scott, 2014) investigated the persistence and interaction of 25 different pasture species over three decades under different fertiliser and sheep management regimes in that trial. Lupin contributed 60% of the 1.5 x 50 m subplot it was sown into, with a 2% yield decrease annually, significantly less than most of the other sown legumes (clover and lucerne). The mean relative yield (119 kg DM/ha) was highest when sown with lupin and cocksfoot or brome (*Bromus inermis*). In both cases, when either cultivated then sown with lupins, or oversown lupins into different swards, the lupin content persisted and increased by spreading seed well over two decades, remaining the dominant legume species. When grazed it was found to have only moderate sheep acceptability due to its high alkaloid content (Scott, 1989). However, stock adapted to this over time. These two experiments demonstrate using perennial lupins may be a suitable legume for areas of the South Island high country, although not as productive as lucerne, they may be an option where growing lucerne is not possible.

2.3 Lupins in a grazing pasture mix

Perennial lupins have been investigated to determine if they have the potential to become a dominant high-country pasture legume. Lupins are suited to environments with moderate temperatures and altitudes and medium to low fertility (Scott, 1989). They have a moderate tolerance for prolonged water stress, have a medium feeding value and high stock acceptance (Scott *et al.,* 1985). With their ability to fit N and survive in dry climates, lupins may be a productive option in locations lucerne cannot thrive, even with the presence of Al in the soil.

Cocksfoot is the second most common grass species in New Zealand (Moloney, 1993), following perennial ryegrass (Charlton & Stewart, 1999). However, it is the most common dryland species due to its ability to persist in low rainfall climates. Cocksfoot is a perennial grass well adapted to dry environments, therefore having the ability to survive a soil moisture deficit longer than most other perennial grass species (Volaire & Thomas, 1995). Under dryland conditions cocksfoot produced 55% and 32% more dry matter than perennial ryegrass on flat and hill country trials, respectively in New Zealand (Lancashire & Brock, 1983; Stevens *et al.,* 1992).

Growing cocksfoot with the most common pasture legume white clover (Charlton & Stewart, 1999) is challenging due to the strong competition between the two species in summer (Moloney, 1993), reducing the productivity of the pasture during this period. Lupins, with the ability to persist in low rainfall environments (Scott, 1989), have been found to complement cocksfoot dominant pastures, providing N through N fixation and extracting water down to at least 190 cm into the profile, where after this soil moisture remained constant (Hamblin & Hamblin, 1985).

A 3 year experiment (Black & Ryan-Salter, 2016) was set up at Lincoln University, (Canterbury, New Zealand), to directly compare the dry matter productivity of a cocksfoot/lupin pasture to lucerne under dryland, unfertilised conditions. Young sheep (ewe lambs and hoggets) liveweight yield was consistently greater for the lucerne monoculture compared with the cocksfoot/lupin mix; 54%, 68% and 50% in years one, two and three respectively. Liveweight gain varied throughout the trial depending on herbage intake, botanical composition and nutritional value. In year one liveweight gain (g/head/day) of sheep grazing the cocksfoot/lupin mix averaged 48% of the 60 g/head/day by the sheep grazing the lucerne. This increased in year two to 73% of the 251 g/head/day from the lucerne, before decreasing slightly in year 3 (66% of 264 g/head/day). Lucerne remained the most productive pasture species, although the difference between the lucerne and the lupin/cocksfoot pasture varied (Black & Ryan-Salter, 2016). The cocksfoot/lupin pasture yielded an average 50-68% of the yield produced by the lucerne in the first 3 years of a trial (Black & Ryan-Salter, 2016).

In the first year of the experiment the cocksfoot/lupin pasture mix contained 18% more herbage mass when compared with the lucerne pasture (3520 kg DM/ha) sown at the same time. However, the lucerne yielded 64% more than the 6570 kg DM/ha produced by the cocksfoot/lupin in year two after both pasture types were well established and were grazed for a full year. In year three the yield difference was smaller, although lucerne still produced a 41% greater yield than the 4000 kg DM/ha produced by the cocksfoot/lupin pasture (Black & Ryan-Salter, 2016). Overtime the cocksfoot dominated the pasture, with lupin contributing to 40%, 20% and 10% of the total green material in the pasture in years one, two and three respectively. By comparison, the lucerne contributed 80%, 95% and 98% to the total green material in the pasture over years one, two and three respectively (Black & Ryan-Salter, 2016).

2.4 Other legume options

Another possible pasture legume option for low soil fertile and dry areas of the South Island high country is subterranean clover (sub clover). Sub clover is an autumn germinating, winter active clover with the ability to avoid drought by setting seed in late spring and germinating some of that seed in the following autumn (Widdup & Pennell, 2000).

Sub clover has good winter and spring dry matter production, and can be grazed continuously over this period. In mixed pastures in dry environments, sub clover can contribute to 20% of total herbage (Charlton & Stewart, 1999). During flowering in late spring, lax grazing (low stocking rate to maintain full ground cover) is required to maximise seed production before the seed heads bend over and bury their seeds into the soil surface. These remain dormant over summer until rainfall resumes to initiate germination. The later the flowering date the more herbage mass produced over spring, provided drought doesn't begin before November (Nichols *et al.,* 2013). Denmark and Antas are late flowering cultivars and Narrikup and Woogenellup flower slightly earlier (mid-season flowering) (Nichols *et al.,* 2013).

Compared with lucerne, grass dominant pastures cannot produce the same dry matter (DM) or sheep live weight yield year after year. For example lucerne produced 33-42% more liveweight gain than perennial ryegrass/white clover and cocksfoot/sub clover pasture mixes (Mills *et al.,* 2008). Although having fewer grazing days, lucerne yielded the greatest liveweight yield, with hoggets growing 260 g/day over spring. This was significantly greater than the 195 g/day and 180 g/day averages from perennial ryegrass/white clover and cocksfoot/sub clover respectively. Lucerne also yielded more DM, with annual yield ranging from 10.0-18.5 t DM/ha/year. In all pastures, spring alone contributed to 64% of liveweight gains and 40-63% of DM yields. The legume content in these grass pastures varied (3-52%) with the content of sub clover greater than all other mixes. Summer live weight production was highly variable due to the variability of rainfall over these months, with these affecting autumn growth rates also. Dry summers contributed to 15-18% of annual live weight production over both summer and autumn; whereas moist summers contributed to >30% and 2-3% of total live weight yield over summer and autumn respectively (Mills *et al.,* 2008). Overall it was found that a lucerne pasture produced the greatest live weight and dry matter production, especially during spring. Complementing this pasture with a cocksfoot/sub clover mix for good summer production and late autumn/winter feed is recommended for summer dry environments. Adding white clover to this mix increases the legume content over moist summers while the sub clover is dormant. Being an annual clover species, the persistence of sub clover is likely better to that of lupin or other clover species as it has the ability to survive both moist and dry summers. Sub clover has a good tolerance, withstanding temperatures as low as -7°C (Caradus, 1995). This is essential as it needs to germinate and grow during the cold winter months. Frost tolerance is less studied, especially in new, Australian bred cultivars (Nichols *et al*., 2013).

Peoples and Baldock (2001) found estimates of legume N fixation should be based around 20-25 kg N/ha fixed per t legume DM/ha. In dryland cocksfoot-based pasture mixes at Lincoln University, sub clover fixed an average 42% more kg N/ha than white clover, due to an increased winter and early spring growth and avoiding the highly competitive summer dry months (Lucas *et al.,* 2010). This would increase cocksfoot DM production, thus increasing animal liveweight gains.

2.5 Environmental drivers of pasture production

Plants require a specific balance of environmental resources for plant growth and development. The most important environmental factors influencing the profitability of farming businesses and the choice of what pasture species to grow are: soil moisture, temperature, solar radiation and mineral nutrients (Chapin *et al.,* 1987; Scott *et al.,* 1985). Each species has slightly different optimal, minimum and maximum levels of each of these factors; at which the plant can function and survive. If any of these resources are below or above the range at which the plant requires them, neither growth nor development will occur. In areas where both the soil moisture and temperature rapidly decline (South Island high country) the decision on what pasture species to use is extremely important to maintain production in challenging environments.

2.5.1 Radiation use efficiency

The seasonal input of solar energy as photosynthetically active radiation (PAR) is the main driver of pasture growth when other essential factors; temperature, water and nutrients are non-limiting (Peri, 2002). PAR is the amount of light available for photosynthesis, with wavelengths between 400 and 700 nm. The conversion of production is called radiation use efficiency (RUE). The RUE of C_3 plants approximately 2.5 g/DM/MJ of PAR (McKenzie *et al.,* 1999). The RUE of cocksfoot also showed seasonal variation, with an irrigated and N fertilised cocksfoot pasture averaging 1.16, 1.00, 0.80 and 0.89 g DM/MJ PAR over spring, summer, autumn and winter, respectively. Autumn was constantly found to have the lowest RUE (Figure 2.3) with dry unfertilised cocksfoot having a RUE 0.26 g DM/MJ PAR (Mills *et al.,* 2009).

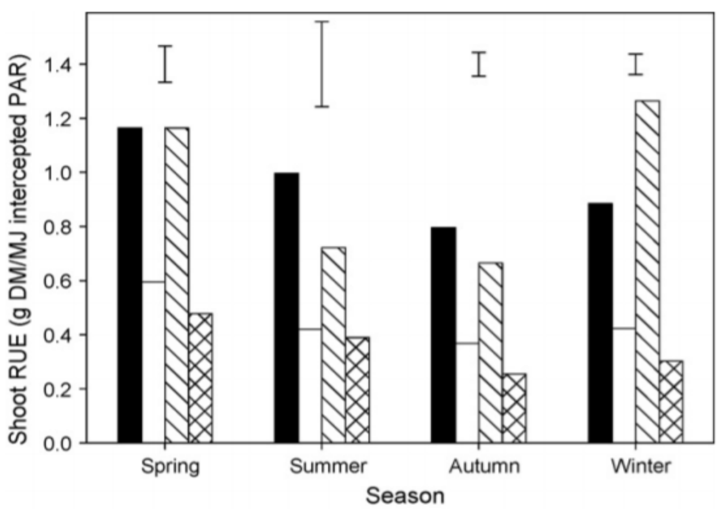

Figure 2.3 Seasonal patterns of shoot radiation use efficiency (RUE) of irrigated and fertilised (solid), irrigated unfertilised (white), dryland and fertilised (stripe) and dryland unfertilised (crisscross) cocksfoot pastures averaged over two growing seasons (2004-2005) at Lincoln University, Canterbury, New Zealand (Mills *et al.,* 2009).

These RUE values from cocksfoot are all lower than those estimated by Loomis and Connor (1992) and Khaiti and Lemaire (1992) for lucerne. In full sunlight conditions, due to the vertical growth, ability to fix its own atmospheric N and the high photosynthetic effect lucerne has, the RUE is much higher of that of cocksfoot (Varella, 2002). These values (2.8 g of total DM/MJ PAR (Loomis & Connor, 1992) and 2.4 g of total DM/MJ PAR (Khaiti & Lemaire, 1992)) appear to remain constant over the year when including both shoot and root dry matter. When estimating from shoot dry matter alone, a difference between summer (1.8 g of total DM/MJ PAR) and autumn (1.1 g of total DM/MJ PAR) were found, suggesting lucerne RUE did not react to differences in temperature and photoperiod factors; just by the partitioning of assimilation between the shoots and roots (Varella, 2002).

Leaves are the functional units of pasture photosynthesis and their efficiency in capturing and utilizing solar energy determines productivity (Peri, 2002). Leaf photosynthesis (maximum saturate leaf photosynthetic rate, photosynthetic efficiency and degree of curvature) is one way to predict pasture growth. Another is by estimating canopy photosynthesis, using the leaf area index (LAI) and the arrangement of foliage (Peri, 2002). LAI is dependent on leaf appearance, growth and development of tillers and leaves, and their morphological changes; and are dependent on temperature, N supply and water status (Davies, 1988). One of the main factors affecting leaf area is the leaf angle in the canopy. This may be affected by the environment (N, water stress and light), regrowth duration or the variation within layers in the pasture canopy (Peri, 2002).

Loomis and Connor (1992) stated that grasses with horizontal leaves and a LAI below 2 were the most productive. Above a LAI of 4 the leaves were more erect and available radiation was spread more evenly over a greater leaf area, leading to greater RUE. Average canopy leaf angle for cocksfoot grown in open, irrigated and N fertilised pastures was 68° (Peri, 2002). The greatest LAI for cocksfoot pastures occurred in late spring (October and November) with a mean LAI of 4.1 in open pastures, before a rapid decrease occurred in late summer till winter, with the minimum LAI (0.5) in April (Figure 2.4) (Peri, 2002). Cocksfoot LAI was also affected by the N treatment of the pasture, with added N having a positive effect on LAI.

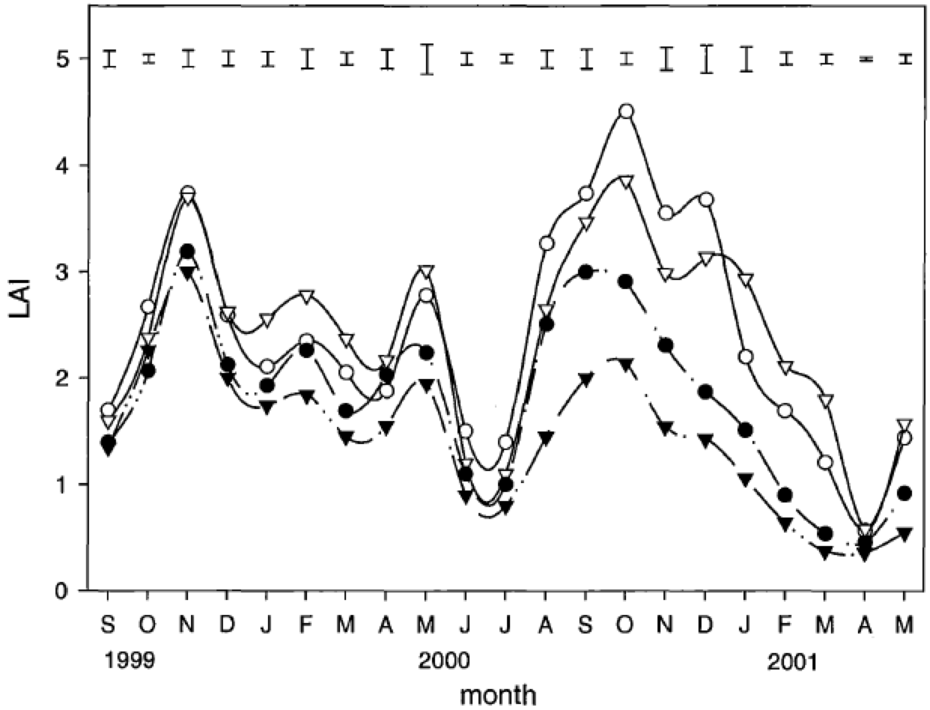

Figure 2.4 Cocksfoot leaf area index (LAI) over different shade treatments, open (○), open + slats (△), under trees (●) and under trees + slats (▲), established in 1990 at Lincoln University, Canterbury, New Zealand. Bars indicate standard error of the mean (Peri, 2002).

Woodward and Sheehy (1979) found that lucerne reached a LAI of 6 after 56 days of regrowth, with 50% of this leaf area in the top 0.5-0.6m of the canopy. Critical LAI occurred between 0.3 and 0.4 m canopy height at an LAI of 4. It appeared the canopy architecture expanded leaf area in the most efficient position for PAR interception, with Wilson (1965) determining each leaf remained at or close to a 50° from the stem, allowing strong light interception throughout the canopy.

Accumulated dry matter yield (kg DM/ha) was found to have a positive correlation with increasing LAI in cocksfoot pastures (Figure 2.5). This was analysed using a non-linear regression analysis and produced the following equation (R^2= 0.92): $DM = -960 + 916e^{(0.25*LAI)}$ (Peri, 2002).

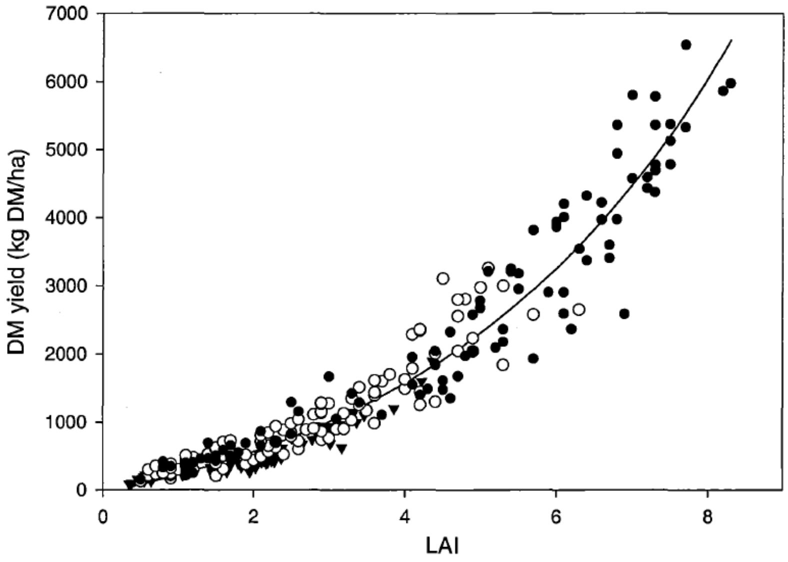

Figure 2.5 Accumulated dry matter yield (kg DM/ha) against leaf area index (LAI) of cocksfoot, under shade (▲), open with no fertiliser (○) and open with 300 kg N/ha fertiliser (●), established 1990, at Lincoln University, New Zealand (Peri, 2002).

The relationship in Figure 2.5 also demonstrates an increase in N increases the LAI, with herbage yield per LAI with no N over 3000 kg DM/ha less than with N (Peri, 2002).

2.5.2 Temperature

Temperature is a fundamental factor when choosing pasture species and estimating potential pasture production (Peri, 2002). Temperature affects the rate of plant growth and development, determining the length of time in each stage of development. It varies depending on the season, altitude, latitude, aspect and slope of an environment, with the mean monthly temperature varying an average 10 °C (Scott *et al.,* 1985). The New Zealand high country is classified as having the lowest mean temperatures and greatest range of extremes in New Zealand (NIWA, 2016a). Pasture species for this environment should be able to grow in low temperatures. In general grasses (especially cocksfoot) can withstand colder temperatures than legumes (for example sub clover), however to maintain and/or improve pasture production legumes are essential for a system (Brown *et al*., 2006). Most pasture plants have an optimum temperature between 20-25 °C, with a growth ceasing below 5-10 °C (McKenzie *et al.,* 1999). Cocksfoot growth decreased by 78% when temperatures in a controlled environment were reduced to 7.0 °C (Mitchel & Lucanus, 1960) compared with 15.5 °C, and Knievel and Smith (1973) found cocksfoot growth above 28 °C was severely reduced. Cocksfoot required temperatures between 10°C and 35 °C for photosynthesis, with optimum conditions between 15°C and 22°C (Eagles, 1967; Mitchell, 1956). Above and below the optimum temperatures, the rate of photosynthesis is reduced as enzyme activity decreases (Frank & Barker, 1976). This is slightly higher than the optimal temperature range for lucerne with growth occurring between 8-25 °C (Dolling *et al.,* 2005). Lucerne assimilation of reserves also reacted to changes in temperature and photoperiod, with 22% of assimilation from shoots to roots by the end of summer, and 55% by the end of autumn as temperatures and photoperiod decrease (Varella, 2002). Thermal degree days, or growing degree days (°Cd), is the cumulative temperature above a base that represents the temperature at which growth ceases (Arnold & Monteith, 1974).

2.5.3 Water

Soil moisture is also an essential factor determining pasture production, and in high country environments cannot be altered by irrigation. Many regions in New Zealand, especially eastern and central regions often experience periods of low rainfall, especially during summer (Moot *et al.,* 2008). During each summer rainfall 97% of water taken up by plants is lost to the atmosphere through transpiration and the remaining 3% is used for growth (2%) and photosynthesis (1%) (Taiz & Zeiger, 2010). Without water plants cannot grow, no matter the species. Firstly, water stress reduces growth, reducing canopy expansion and reducing light interception and therefore photosynthesis (Mills *et al.,* 2006). To stay profitable and continue to run stock over dry summers, many farmers need to focus on the water use efficiency (WUE) and the ability for pastures to continue growing long after a rainfall event. Lucerne is classed as a WUE species, due to its deep rooting ability and great water stress tolerance, with an average WUE of 1.2 g DM/kg transpired water. This was better than the WUE of white clover (2.4 g DM/kg transpired water) and cocksfoot (1.5 g DM/kg transpired water) (Singh *et al.,* 2003).

Rooting depth is a potential WUE trait, with a 50 mm increasing (250-300 mm) in rooting depth increasing WUE by 0.5 kg DM/ha/mm water and 2.3% increase in yield in perennial ryegrass treatments (White & Snow, 2012). Rooting depth is affected by water uptake and drainage, and increased rooting depth allows plants to uptake water from layers of the soil profile that would have otherwise drained from the system. Most of the soil extracted from a soil during a dry period after field capacity has been reached is from the top layers of the soil profile due to the greater root density and shorter flow path. After these layers are dry roots must extract from further into the profile (Sheaffer *et al.,* 1988), with maximum water extractions from lucerne occurring at 180-240 cm depth in Canterbury soils (Evans, 1978; MacLaren & Cameron, 1990). Brown (1999) found a 40 cm difference in maximum extraction depth between irrigated (190 cm) and non-irrigated (230 cm) lucerne.

Previous research on the lupin grazing trial (prior to this dissertation) by Williams (2015) found lucerne and cocksfoot dominant pastures had similar accumulated water use values of 526 mm and 473 mm respectively (Figure 2.6). These were similar due to the complete ground cover being a function of water availability and not atmospheric conditions not biological processes (Penman, 1948). Cocksfoot yield declined when soil moisture decreased to 22.9% and lucerne 10 14.1% soil moisture in the top 230 cm of the profile. This difference is likely explained by the extra 0.3 m of root extractions down the soil profile, with the cocksfoot pasture extracting water in the top 1.7 m and lucerne in the top 2 m of soil (Williams, 2015). These are similar to other known dryland pasture species, with red clover and chicory roots extracting water from a maximum of 1.9 m (Brown *et al.,* 2005).

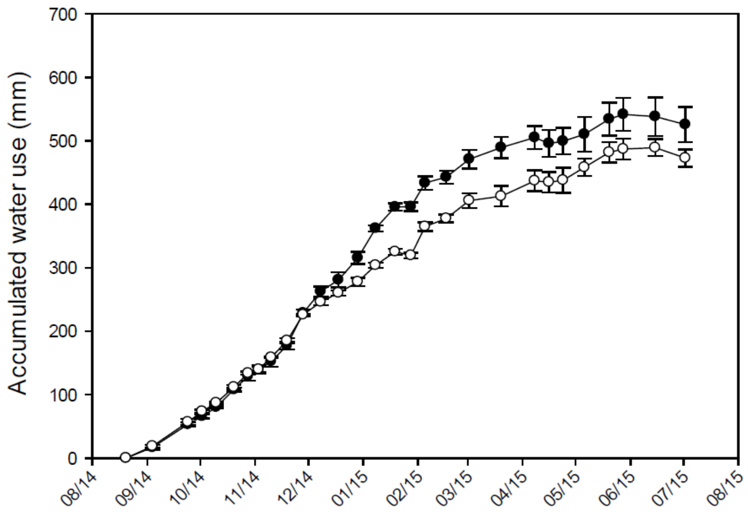

Figure 2.6 Accumulated water use (mm) in a cocksfoot-lupin (●) pasture and lucerne (○) pasture over the 2014/2015 growing season at Lincoln University, Canterbury. Error bars represent the standard error of the mean (Williams, 2015).

2.5.4 Nitrogen

Plants have essential plant nutrients, with the most essential and most commonly restricted nutrient for pasture plants being N (Lambert *et al.,* 1982). N is an essential macro nutrient throughout plant growth and development as it plays a significant role in DNA, RNA, chlorophyll, ATP production and protein/enzymes (Andrews *et al.,* 2013). Plants generally contain 1-6% N, depending on the species and plant N supply (Andrews *et al.,* 2013). Although plants can take up many different forms of organic or inorganic N (such as: ammonium (NH_4^+), urea and amino acids), nitrate (NO_3^-) is the main form taken up by plants and assimilated by most crops in well aerated soils, (Andrews *et al.,* 2013).

Legume species, including lucerne, sub clover and lupin, are unique in the way they fix atmospheric N_2 through a symbiotic relationship with rhizobia in the root nodules, thus legumes do not rely on the amount of available N in the soil as they have their own constant supply of mineral N (Andrews *et al.,* 2011; White & Hodgson, 1999). Grasses and other non-legume pasture species rely on N in the soil, supplied by either the addition of fertiliser (typically urea, 49% N), or by grazing animals urinating and defecating on the pastures, after the consumption of feed N, especially legumes. Pasture growth in urine patches (high concentration of N) fluctuated with maximum growth rates in October and November, three times greater than no-urine patches of cocksfoot (Peri *et al*., 2002). The differences between the urine and non-urine patches decreased in summer and autumn with the growth rates almost the same (Peri *et al*., 2002), due to water stress causing a decrease in growth rates.

Williams (2015) found lucerne had a N content consistently above 4% (4.2-5.5%), greater than the 3.2-3.9% found in cocksfoot leaves. The N content of the cocksfoot/lupin pasture continuously increased as the N application increased (3.1% with 0 kg N/ha compared with 5.5% with 1,000 kg N/ha), demonstrating a significant increase in growth and overall yield when N supply was available for the cocksfoot (Figure 2.7). Analysis of the lupin alone from the cocksfoot/lupin pasture showed lupin N content increased from 3.7% to 4.7% over the growing season under no fertiliser application, compared with a 4.1-5.5% range when 50-600 kg N/ha was applied.

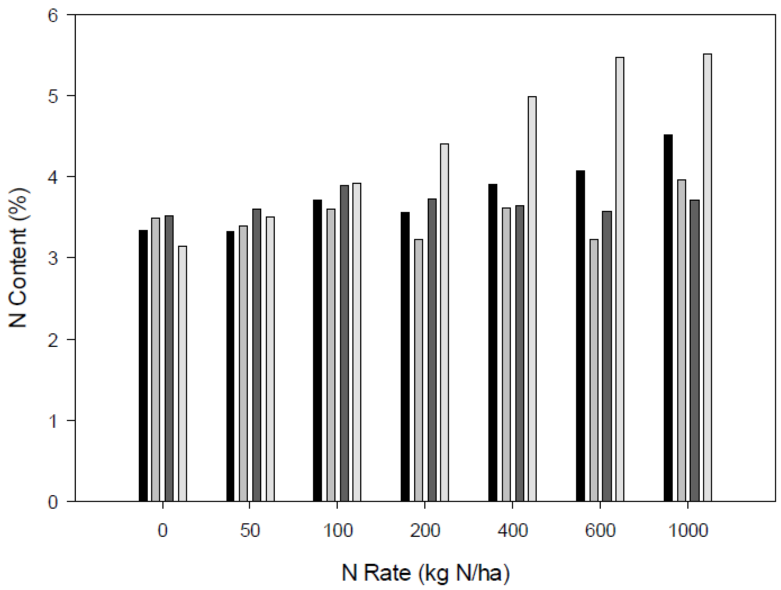

Figure 2.7 Nitrogen content (%) in cocksfoot/lupin pastures with applications of N (kg N/ha) during March and harvested in May (black), applied and harvested in July (medium grey), applied and harvested in September (dark grey) and applied in July and harvested in September (light grey) at Lincoln University (Williams, 2015).

Canopy development also occurs under high N with tiller population and canopy height increasing. Auda *et al*. (1966) found the number of cocksfoot tillers increased three times greater under 224 kg N/ha compared with no N. As a perennial ryegrass/white clover pasture can produce the same level of dry matter as a perennial ryegrass pasture with 200 kg N/ha of fertiliser, and 70% of a pasture with 350-450 kg N/ha, it can be assumed adding legumes to a cocksfoot pasture will also work in the same way as the N fertiliser, increasing tiller production by approximately three times.

2.6 Conclusion

- Lupin can survive in the South Island high country of New Zealand and can be fed to sheep as a forage. It can also be grown in a cocksfoot dominant pasture, but persistence of lupin decreases after 4 years in a grazing rotation.

- Lucerne pastures increase sheep liveweight gain and DM production more, when compared with a cocksfoot/lupin dryland pasture but reasons for this have not been quantified.

- Dry matter production is affected by a combination of soil moisture, solar radiation, mineral nutrients and temperature and production is reduced when one or more of these factors is limited.

- The water use and drought tolerance of lupin has not been quantified and requires further research.

- The sub clover cultivar Denmark has been researched in dryland grass dominant pastures In New Zealand and was found to increase dry matter production in cocksfoot dominant pastures. A newer cultivar, Narrikup, has not been studied in as much detail, but in small field trials has performed better than Denmark, increasing cocksfoot dominant pastures more significantly.

This dissertation attempted to fill some of the gaps in the literature by quantifying reasons for the differences in DM production reported by Black and Ryan-Salter (2016) in the first and second years after establishment under dryland conditions at Lincoln University. Firstly, the annual and seasonal DM production were quantified for the two pasture types in their third year (2016-2017) after establishment. Seasonal and annual botanical composition and N yield differences, annual water-use and average water use efficiency, average dry matter production per degree day and LAI were quantified to help explain the differences in production between the lucerne and cocksfoot/lupin pastures under dryland conditions at Lincoln University, New Zealand.

Chapter 3
Materials and Methods

3.1 Experimental site and preperation

The experiment described in this dissertation was conducted in paddock H12 (1.56 ha) at the Horticulture Research Area, Lincoln University, Canterbury, New Zealand (43°38'53" S, 172°27'24" E; 9 m above sea level). It continues on from three years (December 2013 – July 2016) of previous research by Black and Ryan-Salter (2016). This dissertation covers the 2016/2017 growing season (11 July 2016 to 29 June 2017). The soil type was a Templeton silt loam soil overlying alluvial gravel, with a pH of 6.0, Olsen P of 17 mg/litre and sulphates S of 1 mg/kg in the top 7.5 cm (Black & Ryan-Salter, 2016). Rainfall data over this period are presented in

Figure 3.1 and temperature data in Figure 3.2.

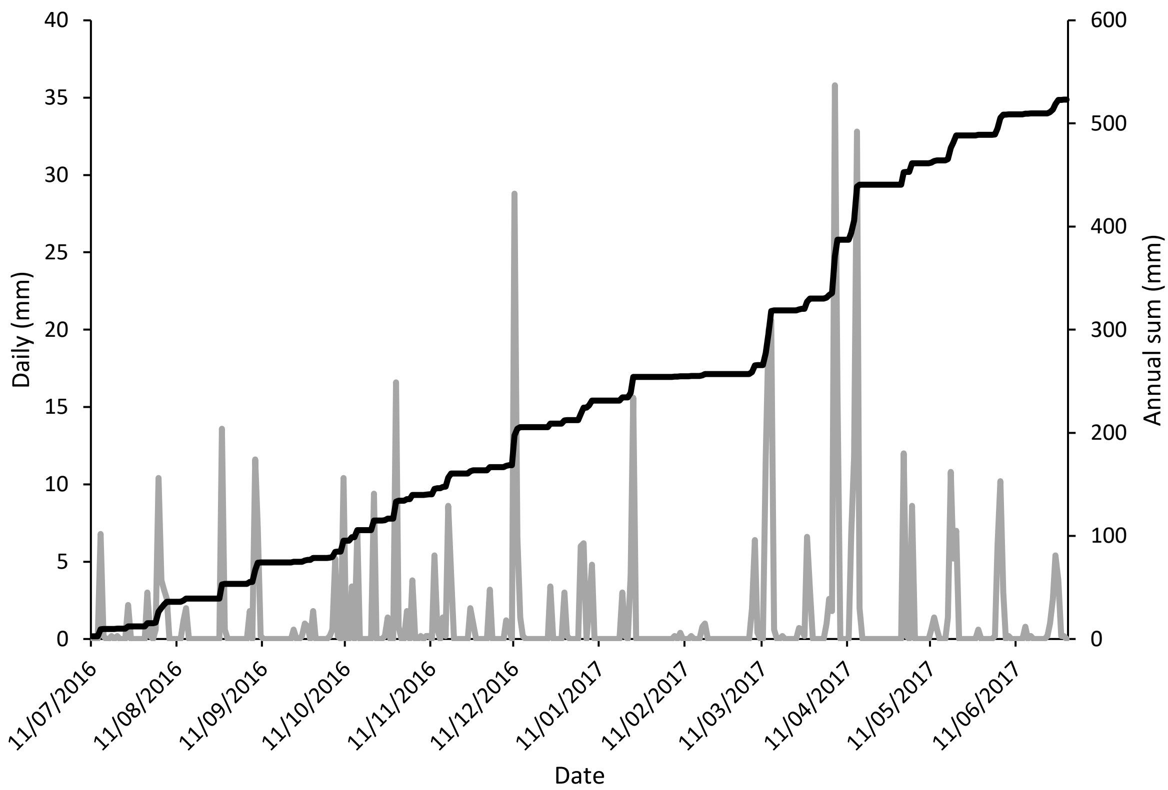

Figure 3.1 Daily (light grey) and accumulated (black) rainfall (mm) over the trial period (11 July 2016 – 29 June 2017) from Broadfields meteorological station (number 17603), located 2 km north of the experimental site at Lincoln University, Canterbury.

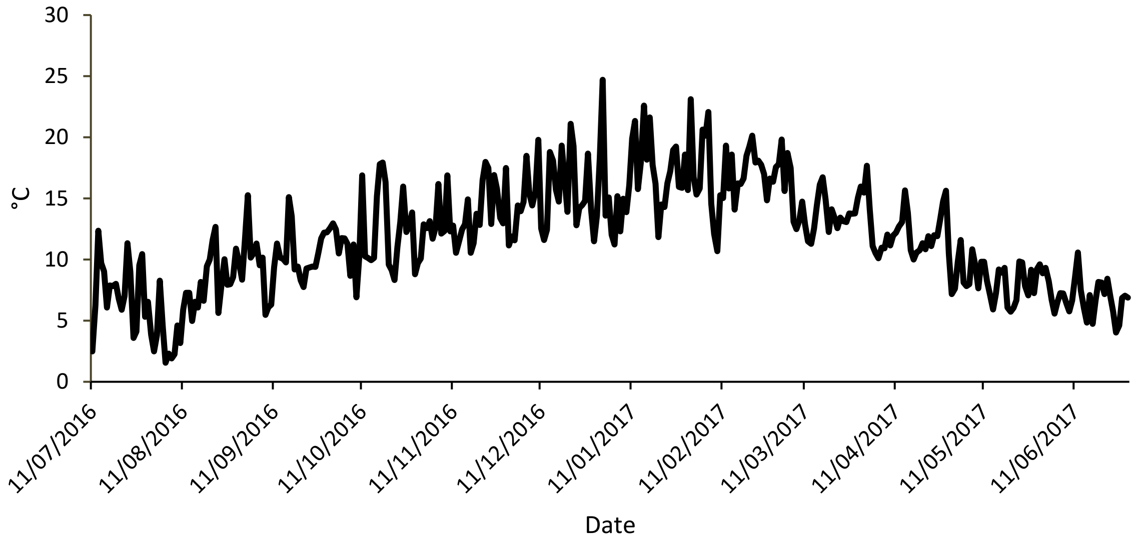

Figure 3.2 Average daily temperature over the trial period (11 July 2016 – 29 June 2017) from Broadfields meteorological station (number 17603), located 2 km north of the experimental site at Lincoln University, Canterbury.

Prior to sowing (5 December 2013), the paddock was under a long-term pasture (dominated by perennial ryegrass and white clover and then one winter crop of forage oats (*Avena sativa*) for baleage, harvested October 2013. The paddock was then irrigated (approximately 50 mm over 2 weeks), ploughed and tilled into a seedbed in November 2013. Before sowing the paddock was divided into three replicates (blocks) of 0.52 ha (59 x 90 m) and then each block was divided into two halves of 0.26 ha (29.5 x 90 m), creating six paddocks (replicas) for each pasture. Two pastures were randomly allocated one plot each, in each of the three blocks and sown into each plot on 5 December 2013 with a precision drill with coulters spaced 0.15 m apart (Flexiseeder, Christchurch, New Zealand). No fertiliser was applied.

3.1.1 Pasture extablishment

Two perennial varieties of lupin seed ('Russell' and 'Blue') were sourced from Rosavear & Co. Ltd. Ashburton, New Zealand from a commercial grower. This seed was scarified and inoculated with Group G *Bradyrhizobium* inoculant (recommended by BASF, Auckland, New Zealand) one day prior to sowing. This Russell and Blue lupin seed was sown in a 50:50 mix, at 30 kg/ha and was mixed with 10 kg/ha of Kara cocksfoot seed (supplied by Agricom, New Zealand). The positive control pasture was a monoculture lucerne pasture sown with 15 kg/ha of SF Force 4 lucerne (Seed Force, New Zealand). All plots were irrigated (50 mm) over 2 weeks in February 2014 to assist with pasture establishment. The six plots were then fenced with permanent wire netting fencing and plumbed with small plastic portable water troughs. Over the past 3 years the two pasture types in this trial have been rotationally grazed with young sheep (lambs and hoggets) with no fertiliser or irrigation use.

In 2017 (3 January 2017 – 22 May 2017) 20 kg/ha of sub clover was broadcasted over the paddock prior to grazing, creating a cocksfoot/lupin/sub clover pasture. The sub clover was sown as a 50:50 mix of 'Denmark' and 'Narrikup' cultivars, obtained from Seed Force, New Zealand.

3.2 Sheep

Two mobs of Coopworth ewe hoggets, (born spring 2015 at Ashley Dene, Lincoln University) were rotationally grazed on the two pasture types (one each) from 17 August 2016 to 13 February 2017, remaining on the one of the two pasture types every day and night, except for shearing (3 November 2016) where the sheep were fasted overnight before shearing in the morning, and were weighed off and back on to the pasture after shearing. These 2015 born hoggets were removed from the experiment on the 13 February 2017 and a group of 2016 born ewe lambs (from Ashley Dene) replaced these on the 14 February 2017, grazing through until the 1 June 2017. The stocking rate and rotation length varied over the grazing period, depending on the herbage mass in each paddock. Sheep numbers ranged from 6 – 36 per group, attempting to maintain a similar herbage allowance (approximately 2.5 kg DM/head/day), and each group grazed each paddock for 7 – 11 days a time, giving a total grazing time per paddock between 42 - 66 days throughout the year. In 2016/2017 the regrowth period (time between one grazing and the next) also varied (average 60 days). For each pasture type a selection of 'core' animals were randomly allocated to each pasture type at the start of spring grazing (17 August 2016) by the 2015 born hoggets (six for the cocksfoot/lupin pasture and eight for the lucerne pasture, which was adjusted to five and five on the cocksfoot/lupin and lucerne pastures, respectively, after shearing), and again on 14 February (four and four on the cocksfoot/lupin and lucerne pastures, respectively, when the 2016 born lambs began grazing. These core sheep stayed on the pastures and allowed an accurate liveweight gain from each pasture type to be determined over the three seasons (spring, summer and autumn).

3.3 Management

The sheep on each pasture type were rotationally grazed in numerical order around the six paddocks (replicates), with each paddock being grazed six times throughout the 2016/2017 grazing period. The sheep on each pasture type were shifted to the next paddock in rotation on the same day; with removal, weighing and shifting occurring at approximately the same time of the day for both pasture types. The stocking rate was adjusted using a 'Put and Take' policy where additional sheep (excluding the core animals) were added or removed at the day of weighing and shifting according to the herbage mass and length of grazing, to maintain a similar herbage allowance of 2.5 kg DM/head/day (2.36 kg DM/day cocksfoot/lupin, 2.46 kg DM/day lucerne, ($P>0.05$)) for each pasture types. All sheep were removed from the trial on 1 June 2017 as pastures were not grazed over winter (before 11 July

2016 and after 1 June 2017) as herbage mass was no longer sufficient to maintain the feeding levels of the core sheep.

When required the pastures were mown to a height of 4-5 cm above ground level after the sheep were removed, to keep both pastures at a similar vegetative growth stage. Paddock one of lucerne was mown at the end of its first grazing (24 August 2016) and all six paddocks of cocksfoot/lupin were mown at the end their second grazing (10 November 2016 – 13 December 2016).

3.4 Measurements

3.4.1 Pasture

The herbage yield of each paddock was measured as the difference between the pre-grazing herbage mass and the post-graze herbage mass when the same paddock was grazed previously. The yield was assumed as zero while the sheep were in the paddock. Yields were then summed across all grazing periods over this year to calculate annual dry matter production. This included herbage measurements taken every 2-3 weeks over the winter period when there were no sheep on the plots.

One day prior to the sheep being shifted into a new paddock, pre-graze herbage mass cuts and heights were taken to determine the herbage mass available for sheep intake. Post-graze cuts were done immediately after shifting the sheep to allow calculations of herbage growth over the regrowth period to be calculated (pre-graze herbage mass minus the post-grazing herbage mass the last time that that specific paddock was grazed). These were done by cutting three 0.5 m^2 quadrat samples in each paddock to 1-2 cm above ground level using battery powered clippers. All three samples from the one pasture type were grouped together and a fresh weight was obtained. The botanical composition was also determined by taking a subsample and sorting the leaves, petiole, stem and flowers of the sown legume, plus the leaves, sheaths and stems of the cocksfoot, Narrikup and Denmark sub clover cultivars, weeds, dead, white clover into separate piles. These sub samples and the remainder of the original sample were then dried for a minimum of 24 hours in a 70°C force-draft oven and a total dry weight and composition dry weights were obtained. These cuts were also completed for each paddock at the start of the growing season (11 July 2016, start of the grazing season (17 August 2016), end of the grazing season (1 June 2017) and end of the growing season (29 June 2017). Alongside these cuts, at the start of each new rotation and during mid-June and mid-July herbage mass was estimated using a sward stick (Jenquip, Feilding, New Zealand) calibrated for each pasture type and for each regrowth period using the pre- and post-graze herbage mass data. When mowing occurred post-grazing, a post-mowing quadrat cut was made, identical to the post-graze cut.

Sub clover establishment was measured during the first grazing rotation (1 August – 14 September 2017) of spring in the 2017/2018 growing season. Sub clover (leaf and petiole) was separated from the pre-graze pasture mass and split into Narrikup and Denmark cultivars. These were then dried and weighed to determine the proportion of each cultivar in the pre-graze herbage.

3.4.2 Soil moisture content

Soil moisture was recorded in three of the six paddocks (paddocks 1, 3 and 5) of both cocksfoot/lupin and lucerne pastures, each time the sheep were shifted, and at the same times as the herbage cuts and height stick measurements over winter. This was done by using a time domain reflectometer (Trace System, Soil Moisture Equipment, USA) for the top 0.2 m of the soil profile and at 0.1 m intervals from 0.2 m to 2.3 m depth using a neutron probe (Troxler, USA). Water use was calculated as rainfall minus the change in soil moisture content to 2.3 m depth since the previous measurement, and summed for the year (11 July 2016 to 29 June 2017). Maximum extraction depth was determined as the point where variation in soil moisture was nil at both the highest and lowest soil moisture contents. Water use efficiency was calculated as annual herbage yield divided by annual water use.

3.4.3 Leaf area index

To help explain any differences in the dry matter yield of the two pasture types, LAI was measured at the beginning of each grazing from 2 March 2017 to 22 May 2017. From the pre-graze samples, 10-20 leaves of each species (cocksfoot, lupin, sub clover and lucerne) and voluntary white clover were separated and individually photographed with a smartphone camera (Sim *et al.,* 2017). These images were then uploaded onto the digital software program Digimizer (Yu *et al.,* 2015), and the area of each leaf was obtained. Each leaf was then dried and weighed separately, and the specific leaf area was estimated by dividing the leaf area by the dry weight of the corresponding leaf. These were then multiplied by amount of dry weight in the sample and the percentage of leaf in the sample to determine the LAI of each species.

3.4.4 Nitrogen content

A sub sample of the mixed pre-graze sample and the leaves of each of the initially sown species (cocksfoot, lupin and lucerne) were separated from the pre-graze samples were dried and ground, to determine the N content using infrared reflectance spectroscopy (NIRS). This was then divided by 6.25 to calculate the N% in each sample. N yield was calculated by multiplying the N content by the DM yield, and then summed across each sampling date to calculate a N yield for each paddock. These were averaged to give an average cocksfoot/lupin and lucerne N yield value. Leaf N yield of cocksfoot and lucerne were determined by multiplying the N content by the proportion of leaf material in the sample.

3.5 Statistical Analysis

Each pasture type had six replicates, however due to being sampled on different dates each paddock was presented individually to determine seasonal trends.

Average herbage yield was calcualted by the sum of herbage yield over the year for each pasture type in each paddock, and then averaged across the six paddocks of the one pasture type. Average N yield, water-use and thermal time were also calculated this way. Significance (>95% difference) was then calculated using a one-way analysis of variance (ANOVA), (Minitab 17) to determine if the average accumulated lucerne and cocksfoot/lupin herbage yield, N yield, water use and growth per degree (base temperature of 3 °C) way were significancly different. A two-way ANOVA was used to determine if the SLA of each species at each sampling date were significantly different, before calculating LAI.

Chapter 4

Results

4.1 Annual dry matter yield

The total accumulated herbage yield was 10,617 kg DM/ha for the lucerne pasture compared to 6,433 kg DM/ha (P<0.001) for the cocksfoot/lupin pasture (Table 2.1). Average daily growth rate was 30 kg DM/ha/day for lucerne compared to 18.2 kg DM/ha/day (P<0.001) for the cocksfoot/lupin pasture.

Table 4.1 Annual dry matter yield, water use, nitrogen yield and herbage yield per thermal time in a lucerne pasture and cocksfoot/lupin/clover pasture during the 2016/2017 growing season (11 July 2016 – 29 June 2017) at Lincoln University, Canterbury.

	Lucerne	Cocksfoot/lupin	P value
Dry matter yield (kg/ha)	10617 ± 1194	6433 ± 1312	<0.001
Dry matter growth rates (kg/ha/day)	30.08 ± 3.7	18.22 ± 3.4	<0.001
Water use (mm/ha)	502.5 ± 21.0	497.8 ± 4.4	>0.05
Nitrogen yield (kg N/ha)	222.63 ± 86.60	86.84 ± 27.80	<0.001
Herbage yield per degree day (kg DM/ha/°Cd)	3.40 ± 0.42	2.06 ± 0.38	<0.001

Accumulated DM yields (Figure 4.1) for each of the six paddocks are presented individually due to being sampled on different dates. Three distinct seasonal growth patterns were clear in all six lucerne paddocks, with slow winter growth, rapid spring growth and a slower summer and autumn period. Lucerne dry matter growth in winter (11 July 2016 – early August) averaged 9.20 kg DM/ha/day. This increased rapidly over spring (early August – Mid-December) with an average 53.24 kg DM/ha/day growth rate. Dry matter production slowed in summer and on average remained low in autumn, growing an average 17.07 kg DM/day from mid-December to 29 June 2017.

The growth rate of cocksfoot/lupin also showed these same seasonal patterns with slow winter, rapid spring and slower summer and autumn production. Cocksfoot/lupin winter growth (11 July 2016 – mid August) averaged 5.16 kg DM/ha/day. This increased to an average 34.49 kg DM/ha/day over spring (mid-August – mid-December) before slowing down (8.89 kg DM/ha/day) over summer and autumn (mid-December – 29 June 2017).

Dry matter growth rates averaged 44%, 35% and 48% greater in lucerne than the cocksfoot/lupin pasture, for winter, spring and summer/autumn, respectively. Variation between the two pasture types in each paddock varied with the most variation (56%) in paddock 1 and the least (24%) in paddocks 5 and 6.

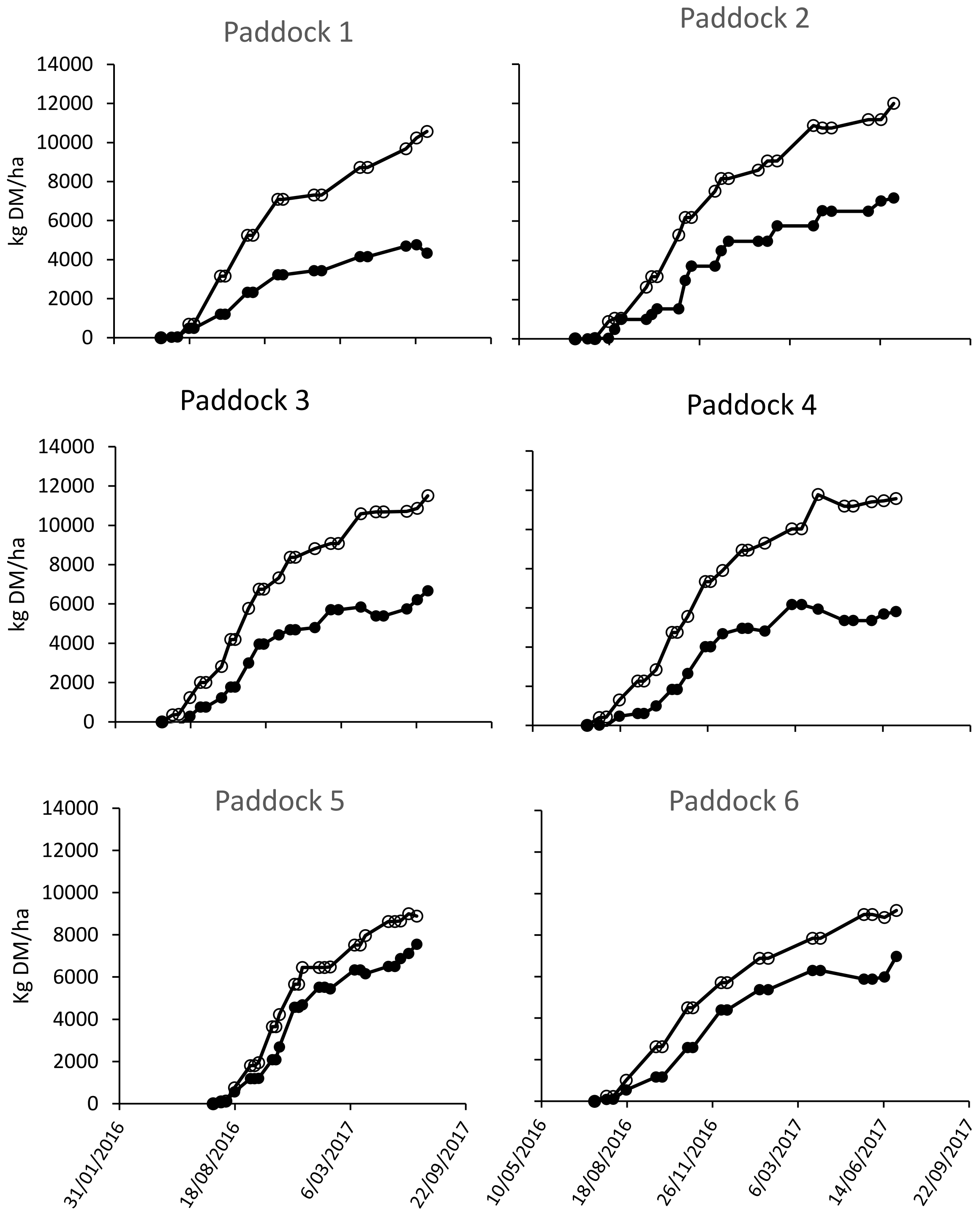

Figure 4.1 Accumulated herbage yield of cocksfoot/lupin/clover pasture (●) and lucerne pasture (○) over the 2016/2017 growing season (11 July 2016 and 29 June 2017) at Lincoln University, Canterbury.

4.2 Botanical composition

The proportion of live material in the lucerne pasture averaged 80% for the first August or September grazing of paddocks 1-4 (Figure 4.2). 99-100% of the pasture was live material from September to November in all paddocks, before decreasing to an average 75% live material from November. Paddocks 2-6 were dominated by dead material in February and March, with an average 41% live material. For the remainder of the year (April – 29 June) lucerne paddocks contained 82% live material.

Lucerne remained the dominant species throughout the growing season, with white clover (0-1%) contributing minimally (Figure 4.3). The weed content varied (0-25%) between both paddocks and sampling date, with the maximum proportion of weeds recorded in paddocks 5 (14%) and 6 (25%) in May. These paddocks continually contained more weed material than the other 4 paddocks, with autumn containing more weeds than spring and summer.

Leaf and petiole contributed to an average 78% of lucerne in August, then decreased to a constant 64% average for the remainder of the season (Figure 4.4). Stem contributed an average 34% over the year, with spring pastures containing slightly more (43%). Lucerne flower was present in late December through to early March, with most (1-15%) flowering in January.

The proportion of live material in the cocksfoot/lupin pasture averaged 62% between 11 July 2016 and October/November where it increased to an average 97% (Figure 4.5). Over summer and autumn, the proportion of dead material increased with an average 62% live material for the remainder of the year. The lowest proportion of live material (39% average in paddocks 3-6) occurred during February and March 2017.

Cocksfoot/lupin pastures showed no seasonal change in botanical composition, but cocksfoot did remain the dominant species (Figure 4.6**Error! Reference source not found.**). Cocksfoot reached 90-100% in some paddocks at the first spring grazing (paddocks 1-4) and in the last autumn grazing (4-6). Lupin reached a maximum 15-27% of composition in spring but was typically 3-11% before decreasing (0-3%) in late autumn. White clover appeared in late summer and autumn contributing <5%, except for paddock 3 in mid-April where 14% of the herbage mass was white clover. Sub clover was only present in paddocks 2 and 4 prior to the last grazing (11 April and 1 May respectively). Weed content remained under 5%.

Of the proportion of cocksfoot in the cocksfoot/lupin pasture, leaf and pseudostem contributed greater than 50% throughout the grazing period (Figure 4.7Figure 4.7), with winter, early spring and autumn pastures containing 0% stem. Stem production began in late October and remained in pastures until December or early January.

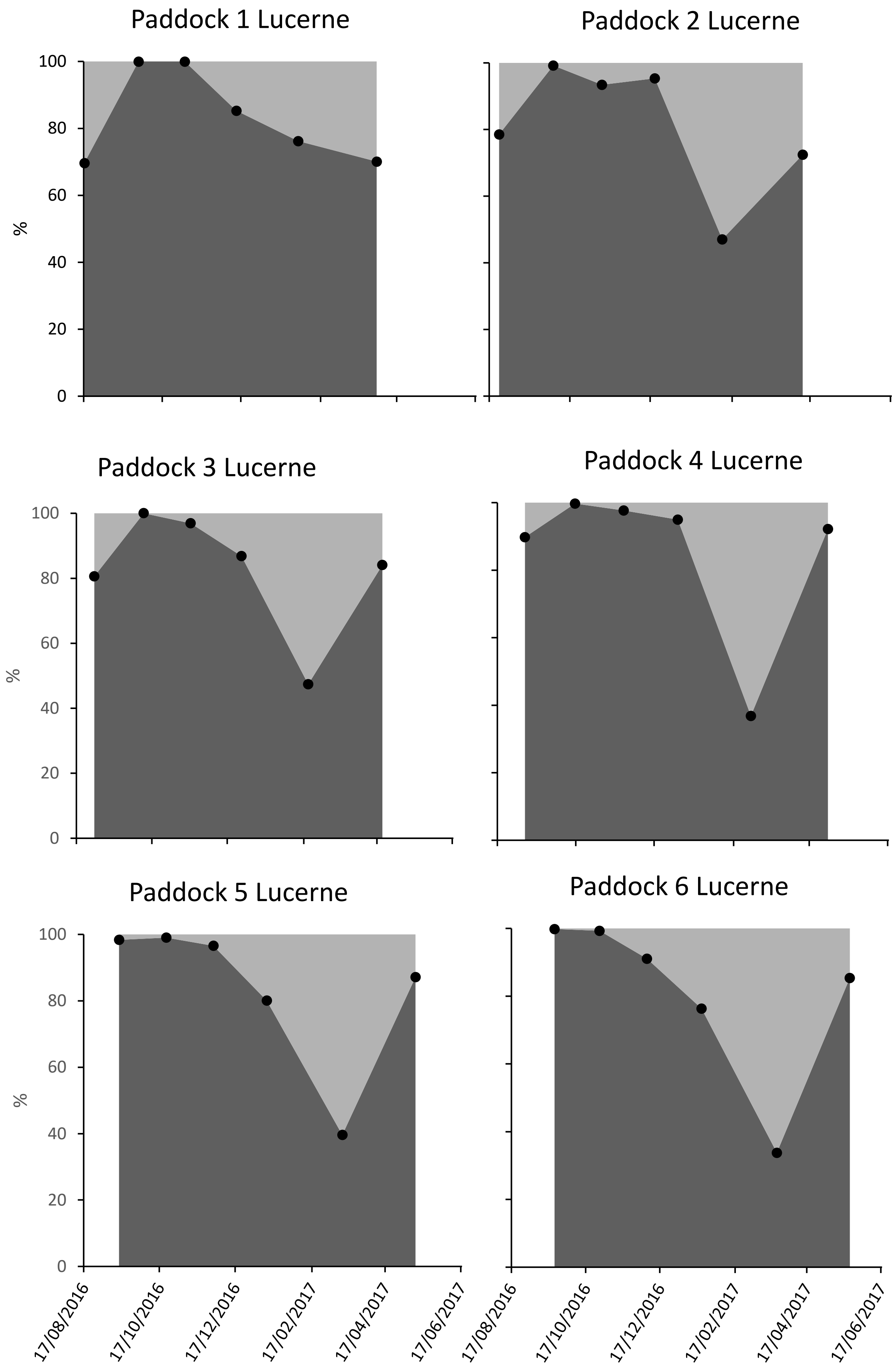

Figure 4.2 Proportion of live (dark grey) and dead (light grey) plant material in six lucerne pastures from 11 July 2016 – 29 June 2017 at Lincoln University, Canterbury.

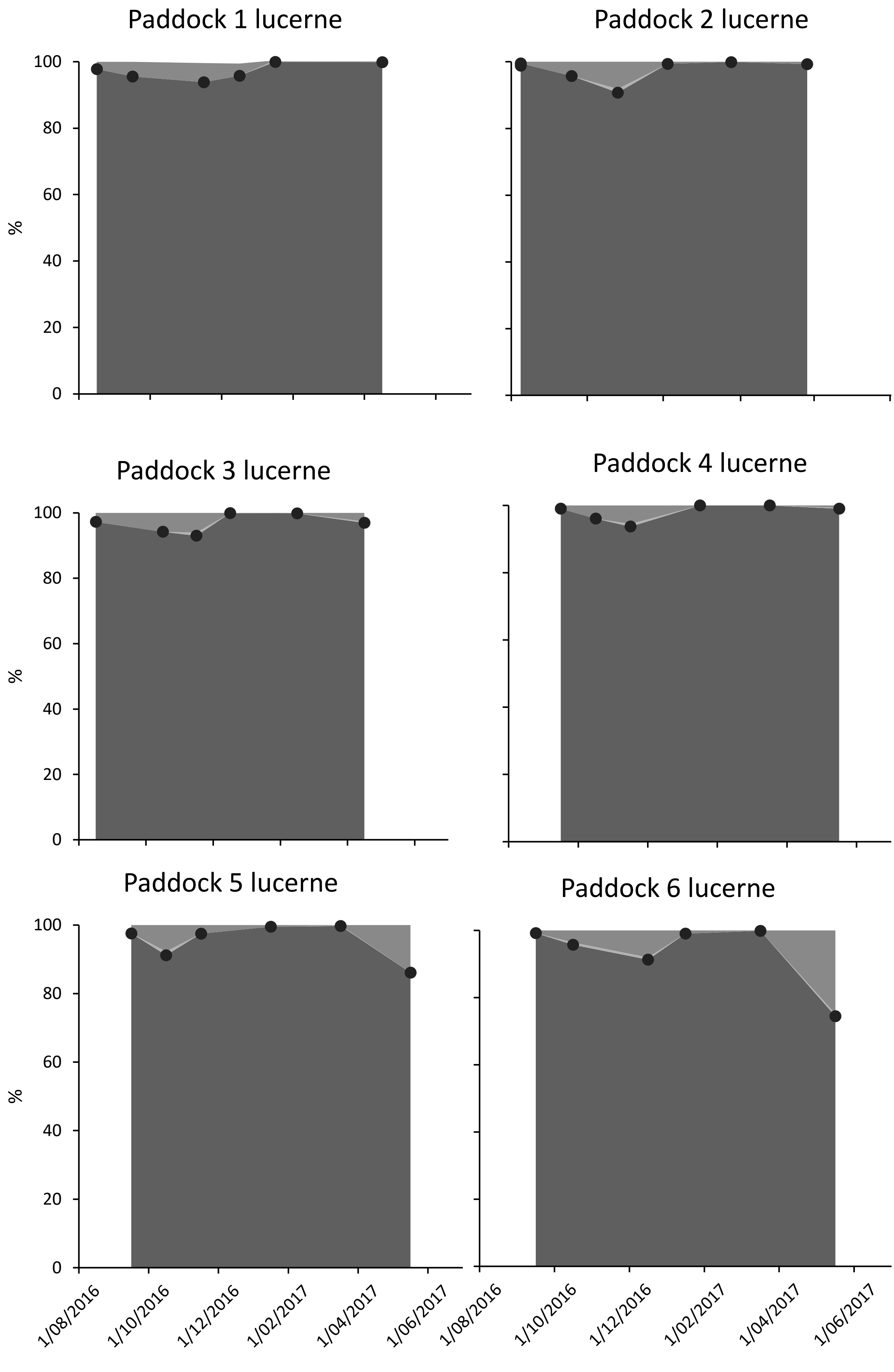

Figure 4.3 Proportion of lucerne (dark grey), white clover (black) and weeds (light grey) in six lucerne pastures from 11 July 2016 – 29 June 2017 at Lincoln University, Canterbury

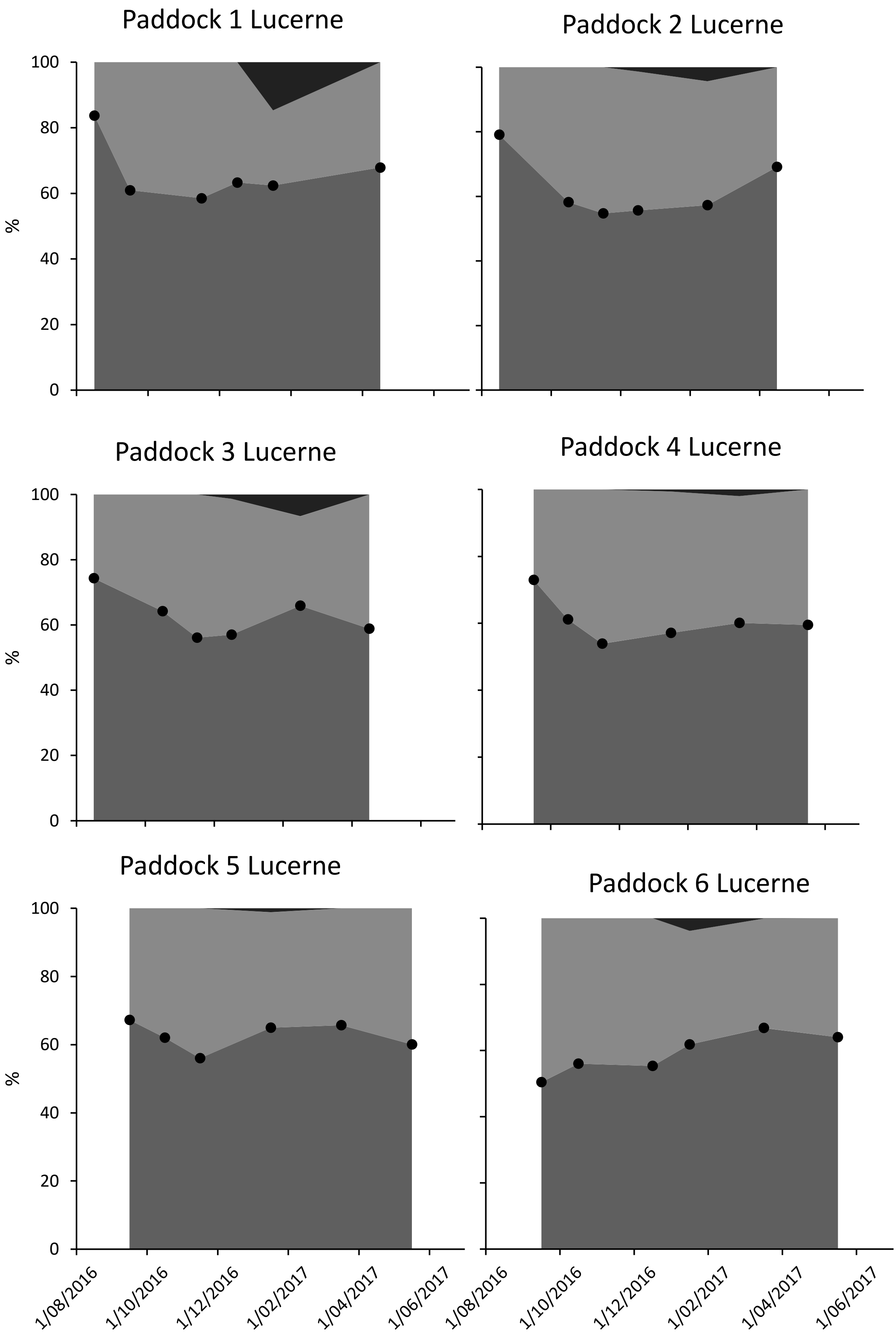

Figure 4.4 Proportion of lucerne leaf and petiole (dark grey), stem (light grey) and flower (black) in six paddocks from 11 July 2016 – 29 June 2017 at Lincoln University, Canterbury.

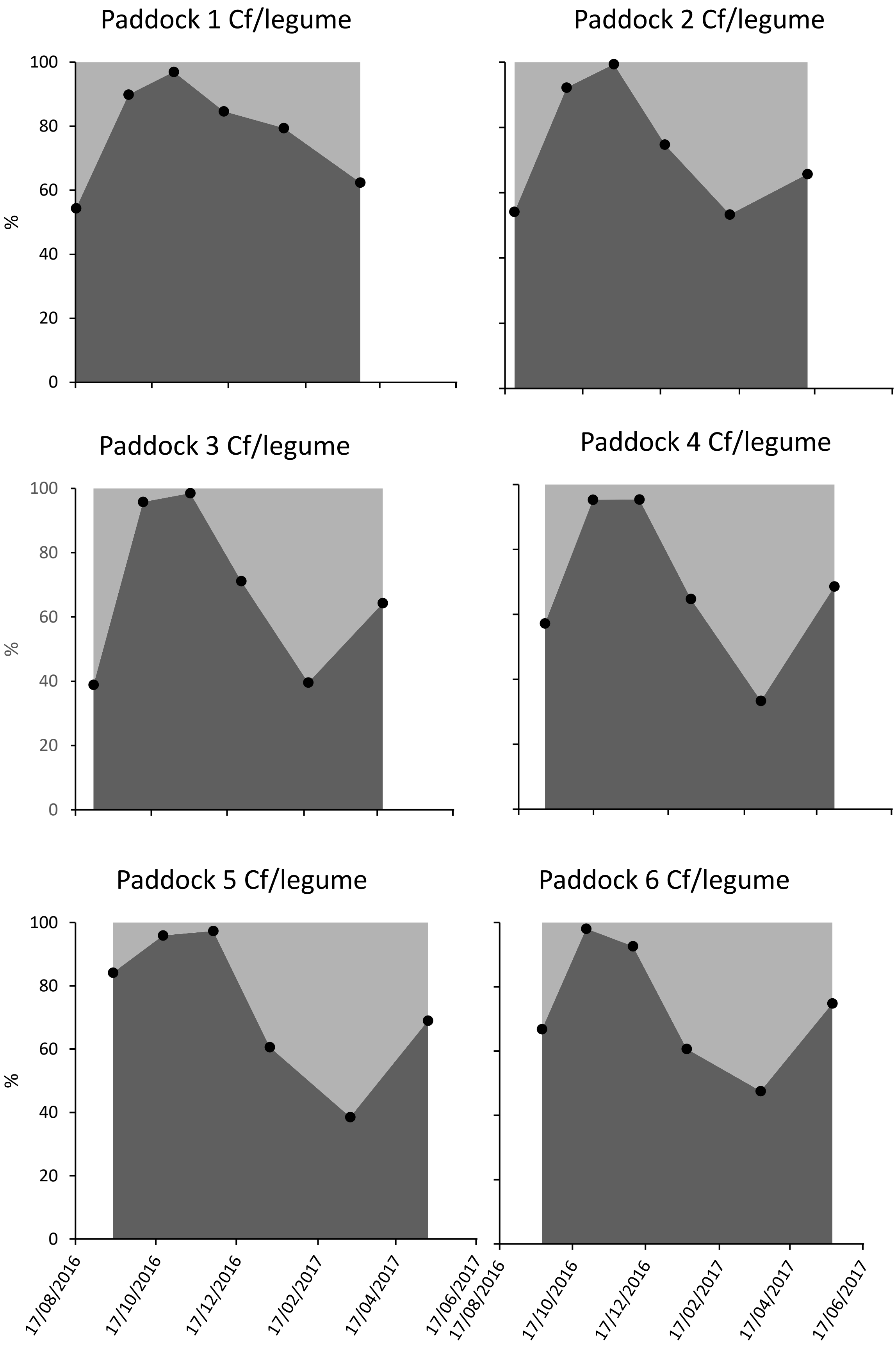

Figure 4.5 Proportion of live (dark grey) and dead (light grey) plant material in six cocksfoot/lupin/clover pastures from 11 July 2016 – 29 June 2017 at Lincoln University, Canterbury.

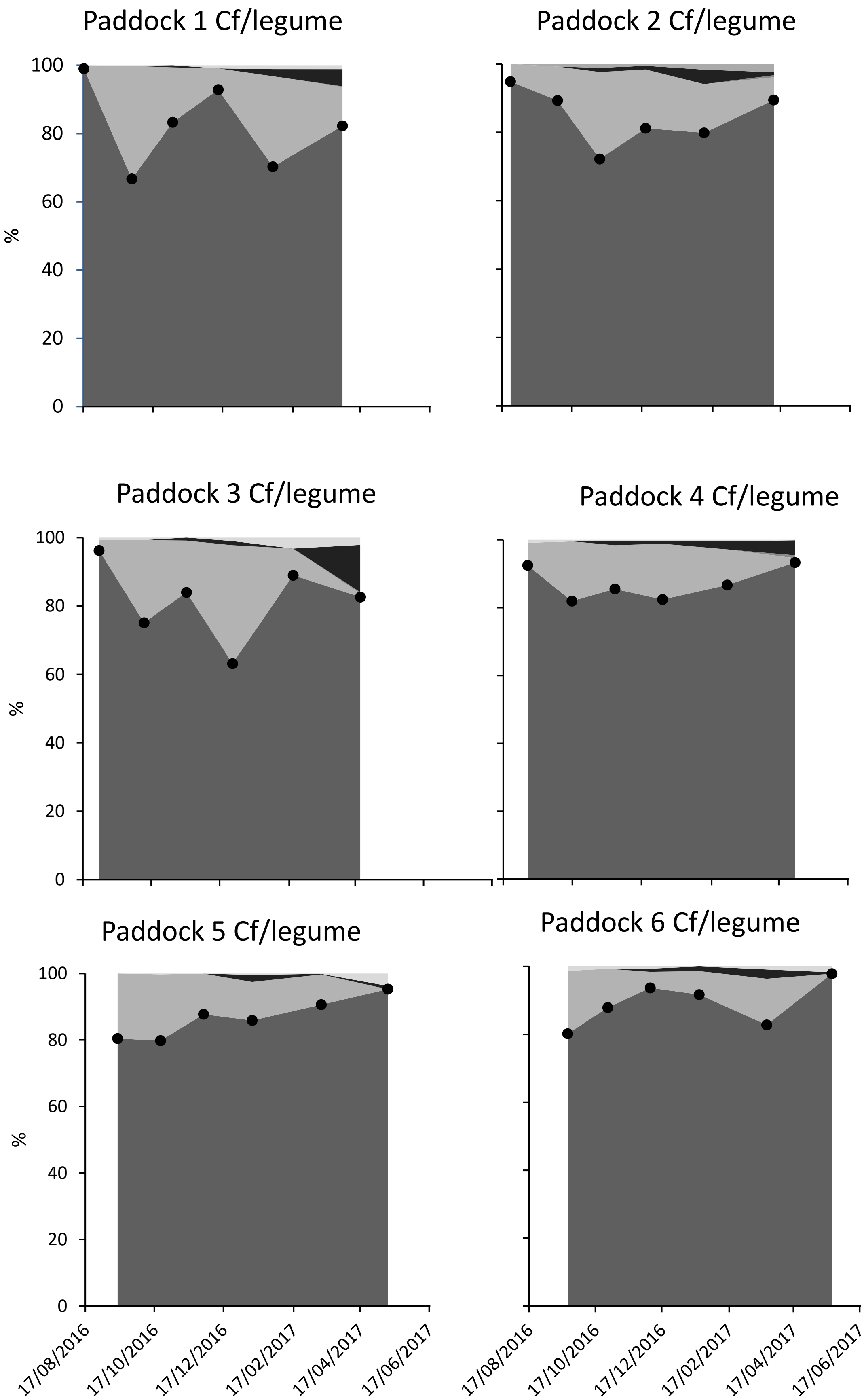

Figure 4.6 Proportion of white clover, cocksfoot, sub clover, lupin and weeds (darkest to lightest respectively) in a cocksfoot/legume pasture from 11 July 2016 – 29 June 2017 at Lincoln University, Canterbury.

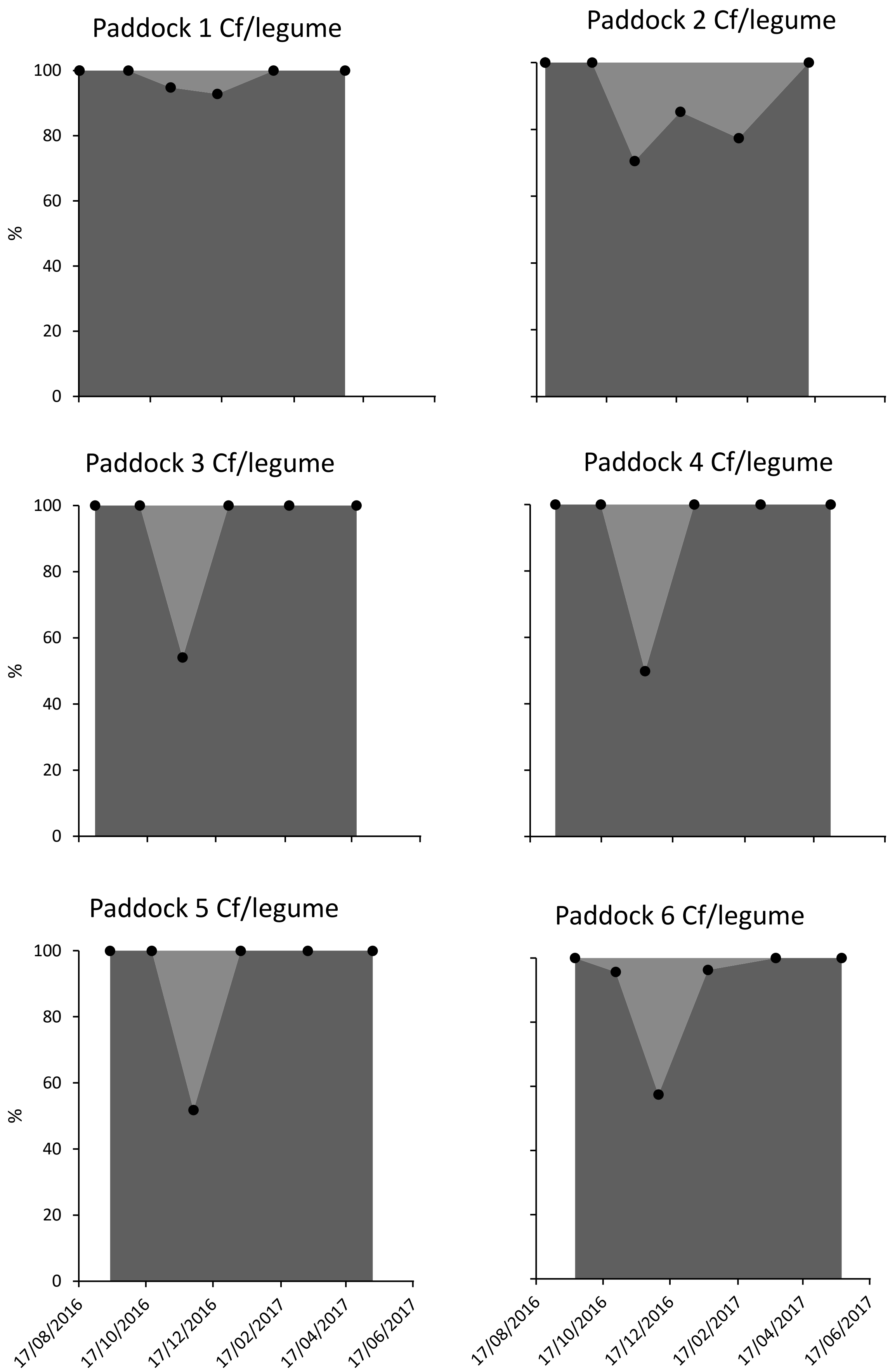

Figure 4.7 Proportion of cocksfoot leaf and pseudostem (dark grey) and stem (light grey) in six cocksfoot/lupin/clover pastures from 11 July 2016 – 29 June 2017 at Lincoln University, Canterbury.

4.3 Yield- thermal time relationship

Over the 355-day experiment a total of 3,123.40 C°d accumulated between 11 July 2016 and 29 June 2017. Lucerne grew an average 3.4 kg DM/ha/°Cd compared to the 2.06 kg DM/ha/°Cd in the cocksfoot/lupin pasture (Table 4.1). Lucerne grew an average 2.06 kg DM/ha/°Cd over winter (11 July to 17 August), compared with 1.21 kg DM/ha/°Cd in the cocksfoot/lupin pasture ($P>0.05$) (Figure 4.8). This increased over spring (mid-August – mid-December) for both pastures with the lucerne pasture growing 6.36 kg DM/ha/°Cd and the cocksfoot/lupin pasture growing 3.94 kg DM/ha/°Cd ($P>0.05$). This decreased for the remainder of the year (mid-December 2016 – end June 2017 with lucerne growing an average 1.75 kg DM/ha/°Cd and the cocksfoot/lupin pasture grew an average 0.88 kg DM/ha/°Cd ($P<0.01$). From this it appears soil moisture began limiting pasture production from the 13 December. Temperature was adequate but another factor limits pasture production.

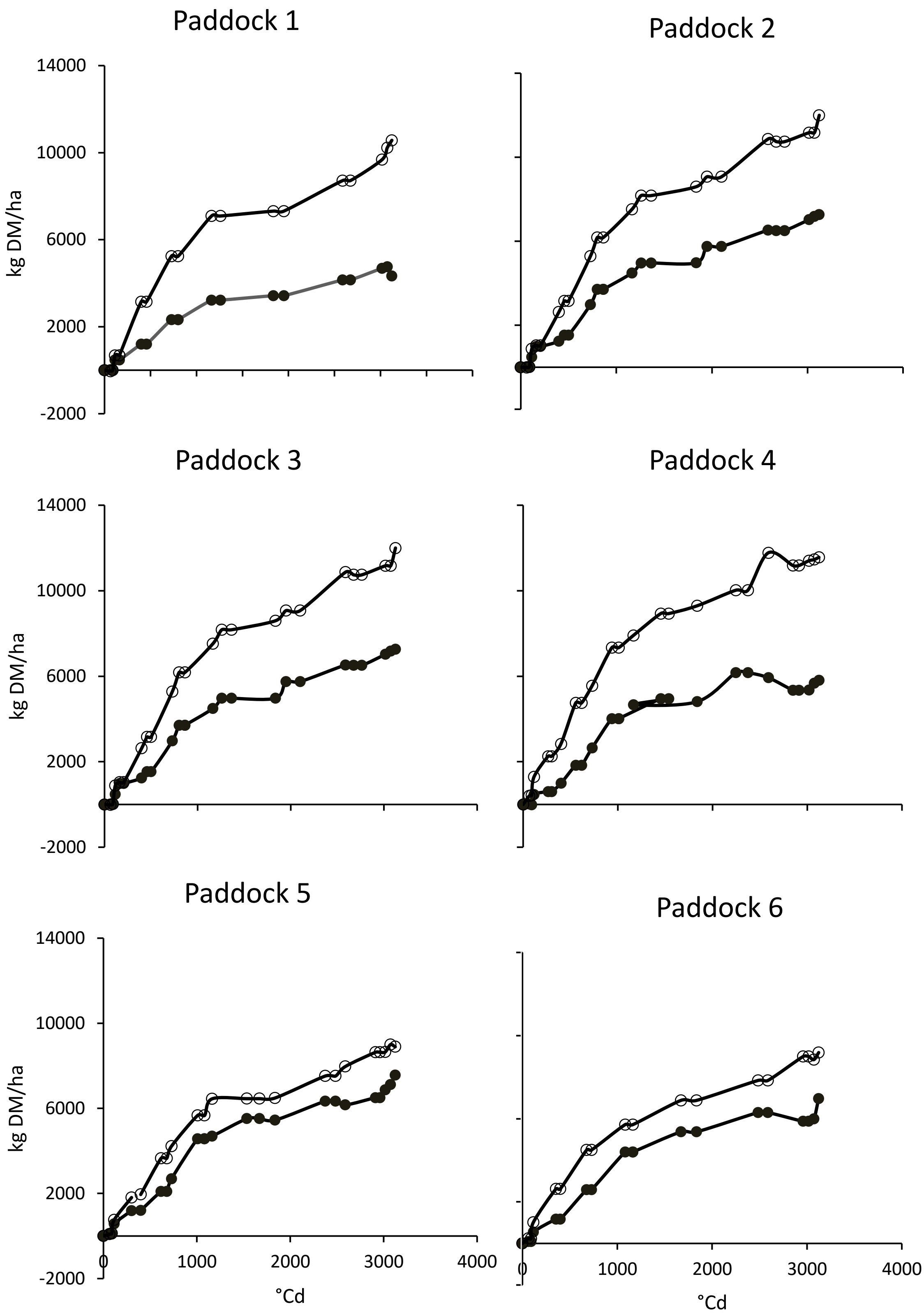

Figure 4.8 Herbage yield (kg DM/ha) over thermal time (°Cd) in six paddocks of cocksfoot/lupin/clover (●) and lucerne (○) pastures over the 2016/2017 growing season at Lincoln University, Canterbury.

4.4 Water extraction depth

Total soil moisture varied significantly ($P<0.05$) between the lucerne and cocksfoot/lupin pastures with a maximum 419.1 mm and 491.6 mm soil water respectively, in the top 230 cm on 29 June 2017 (Figure 4.9). The water content of lucerne pastures remained an average 80.6 mm lower than the cocksfoot/lupin pastures. Both pastures experienced their lowest water content on 2 March 2017, with a total soil moisture content of 217.1 mm in the lucerne pasture compared with 296.4 mm in the cocksfoot/lupin pasture. During the wettest (29 June 2017) and driest (2 March 2017) soil moisture content sample dates, there was significant ($P<0.05$) variation in the top 1.3 m of the soil profile for both pasture types (Figure 4.10). Between 1.3 m and 2.3 m into the soil profile, there was no difference ($P>0.05$) between the lucerne and cocksfoot/lupin pastures, indicating a similar extraction depth of approximately 1.3 m for both pastures.

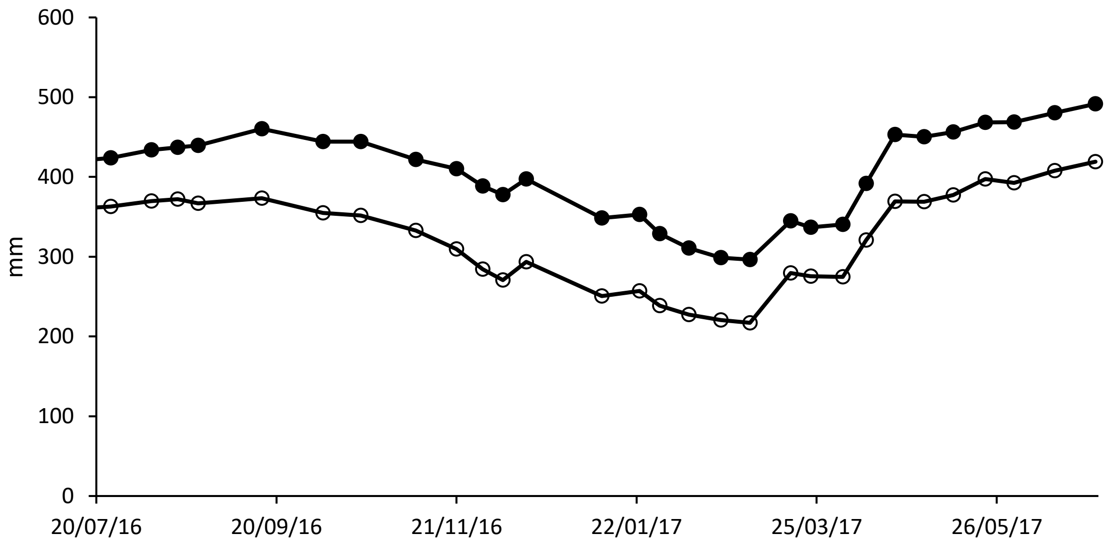

Figure 4.9 Total soil moisture content of the top 2.3 m of the profile in cocksfoot/lupin/clover pasture (●) and lucerne pasture (○) over the 2016/2017 growing season (11 July 2016 – 29 June 2017) at Lincoln University, Canterbury. Note: soil moisture was measured in three of the six paddocks (paddocks 1, 3 and 5) of each pasture type.

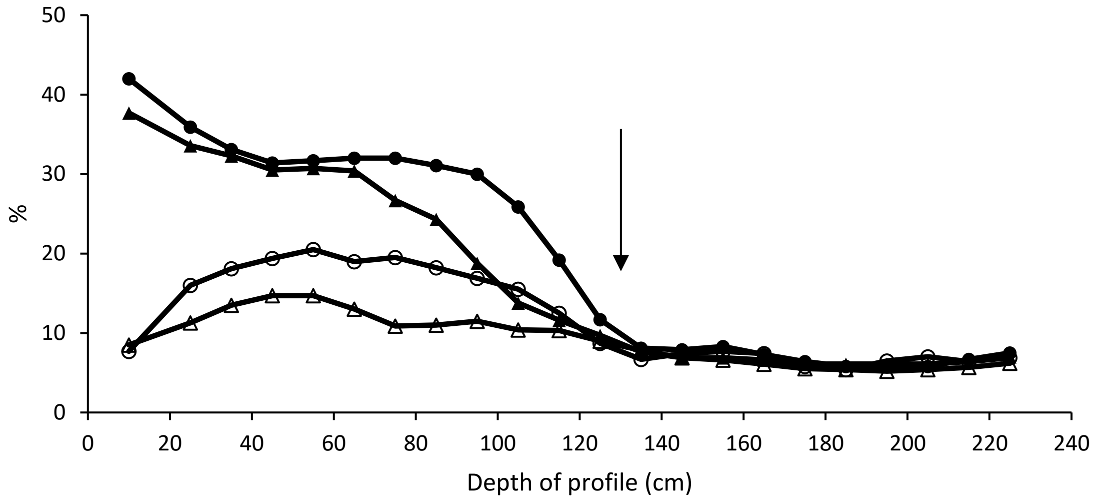

Figure 4.10 Maximum (29 June 2017) (● ▲) and minimum (2 March 2017) (○ △) soil moisture content for a cocksfoot/lupin/clover pasture (● ○) and lucerne pasture (▲ △) down a 2.3 m soil profile, over the 2016/2017 growing season (11 July 2017 – 29 June 2017) at Lincoln University, Canterbury. Black arrow indicates the point where root extraction ceases.

4.5 Water use

The amount of water used over the 2016/2017 year was the same (P>0.05) for both pasture types at 503 mm for lucerne and 498 mm for the cocksfoot/lupin pasture mix (Figure 4.11 4.11). Water use for both pastures was relatively low (0-34 mm accumulated) over the first 2 months of the trial (11 July – 15 September 2016), with water use averaging 0.70 and 0.45 mm/day for lucerne and cocksfoot/lupin respectively. After January and for the remainder of the experiment, lucerne and cocksfoot/lupin water used remained relatively similar (within 8%). During spring (15 September – 15 December) daily water use averaged 2.95 and 2.73 mm/day for lucerne and cocksfoot/lupin pastures respectively. Water use decreased after mid-December to 1.91 mm/day for lucerne and 0.90 mm/day for the cocksfoot/lupin pasture. From 23 January until the remainder of the experiment (29 June) water use decreased further, especially in lucerne, with 0.74 and 0.85 mm/day of water used for lucerne and cocksfoot/lupin, respectively.

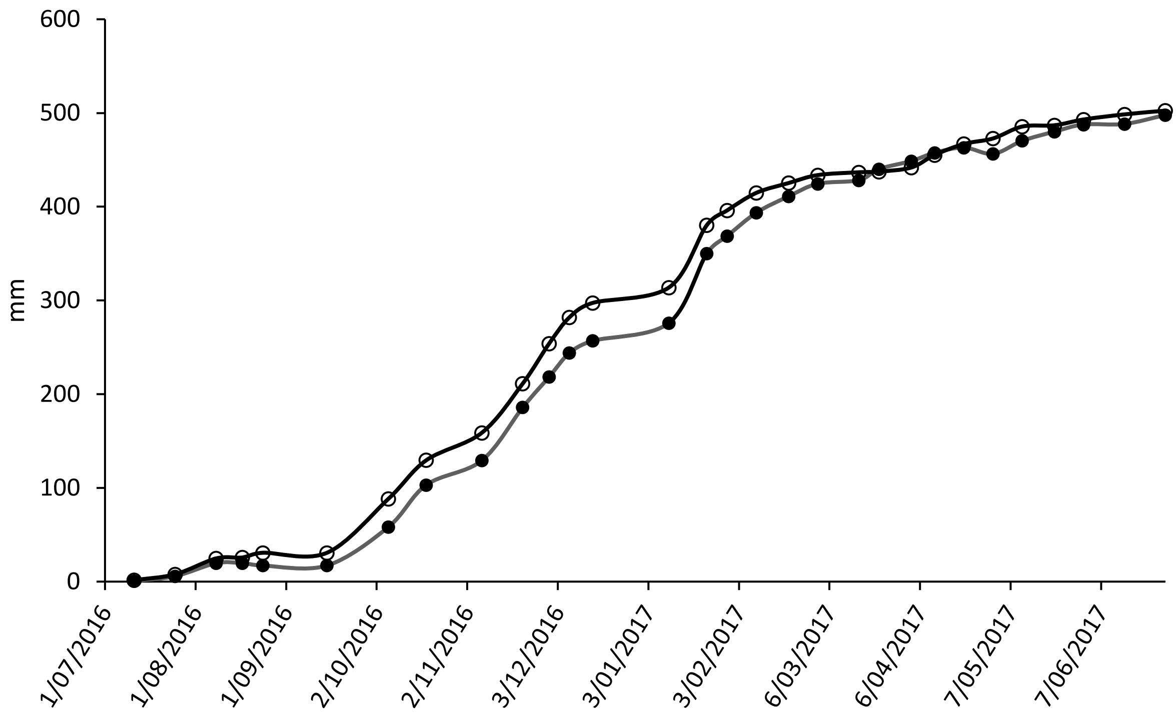

Figure 4.11 Water use (mm) of cocksfoot/lupin/clover pasture (●) compared to lucerne pasture (○) from 11 July 2016 to 29 June 2017 at Lincoln University, Canterbury.

The average water use efficiency (WUE) over the year was 20.5 kg DM/ha/mm for lucerne compared to 7.9 kg DM/ha/mm ($P<0.05$) for the cocksfoot/lupin pasture mix. 3 distinct seasonal patterns (winter, spring and summer/autumn) were present in both lucerne and cocksfoot/lupin pastures, excluding paddock 5 which only had two (winter/spring and summer/autumn) patterns (Figure 4.12). Lucerne WUE for winter averaged 6.35 kg DM/ha/mm compared with 3.40 kg DM/ha/mm in the cocksfoot/lupin pasture ($P>0.05$). Spring lucerne WUE increased rapidly with 23.33 kg DM/ha/mm produced, compared with 16.30 kg DM/ha/mm in the cocksfoot/lupin pasture ($P<0.001$). WUE decreased in summer and remained low in autumn with 16.46 kg DM/ha/mm in the lucerne pasture compared with 7.5 kg DM/ha/mm in the cocksfoot/lupin pasture ($P<0.001$).

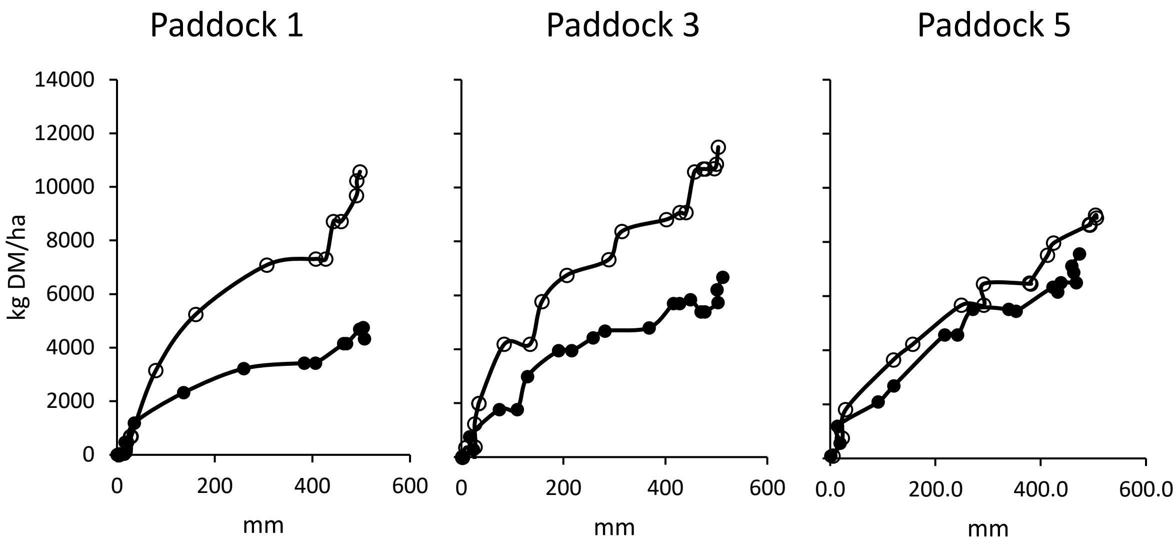

Figure 4.12 Relationship between accumulated dry matter production and water use of lucerne (○) and cocksfoot/lupin/clover pastures (●), measured in three paddocks from 11 July 2016 to 29 June 2017, at Lincoln University, Canterbury.

4.6 Nitrogen yield

Total N yield of lucerne was 222.63 kg N/ha compared with 86.84 kg N/ha in the cocksfoot/lupin pasture accumulated between 11 July 2016 – 29 June 2017 ($P<0.001$) (Figure 4.13). Lucerne showed an increase in N content over spring with an average 9.51 kg N/ha/day accumulated between July 2016 and December 2016, giving an average N yield of 54.37 kg N/ha. Autumn and spring N accumulation decreased to an average 1.67 kg N/ha/day with the N yield average decreasing to 17.81 kg N/ha.

Cocksfoot/lupin pasture also increased in N content over spring, with an average 2.23 kg N/ha/day accumulated, giving an average N yield of 13.75 kg N/ha from August to December 2016. N accumulation decreased over summer and autumn, with an average 1.79 kg N/ha/day accumulated. This increased the average N yield of herbage to 16.59 kg N/ha from December 2016 to June 2017.

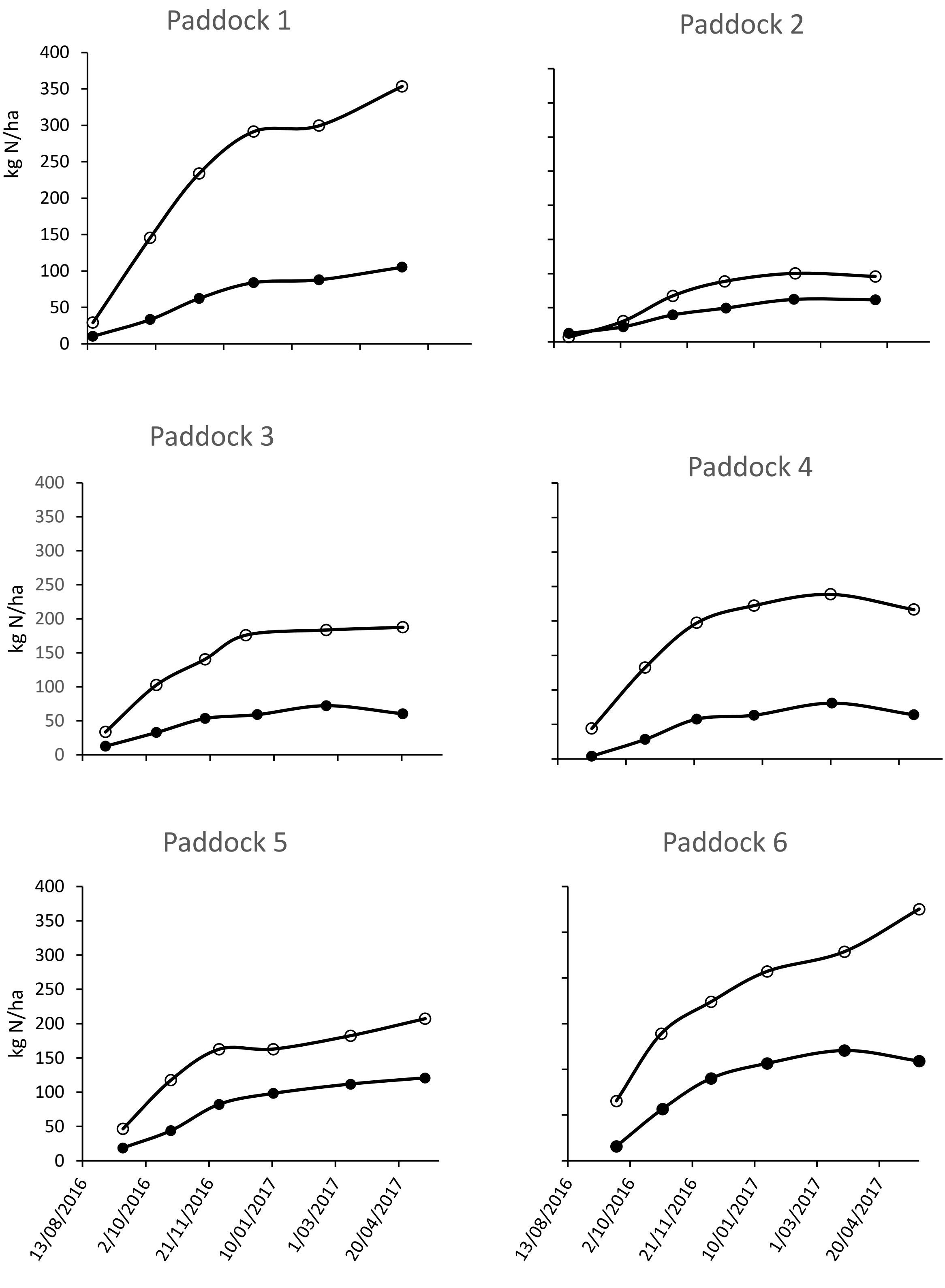

Figure 4.13 Nitrogen yield (kg N/ha) of pre-grazing cocksfoot/lupin/clover pasture (●) and lucerne pasture (○) over the 2016/2017 growing season (11 July 2016 – 29 June 2017 at Lincoln University, Canterbury

4.7 Leaf area index

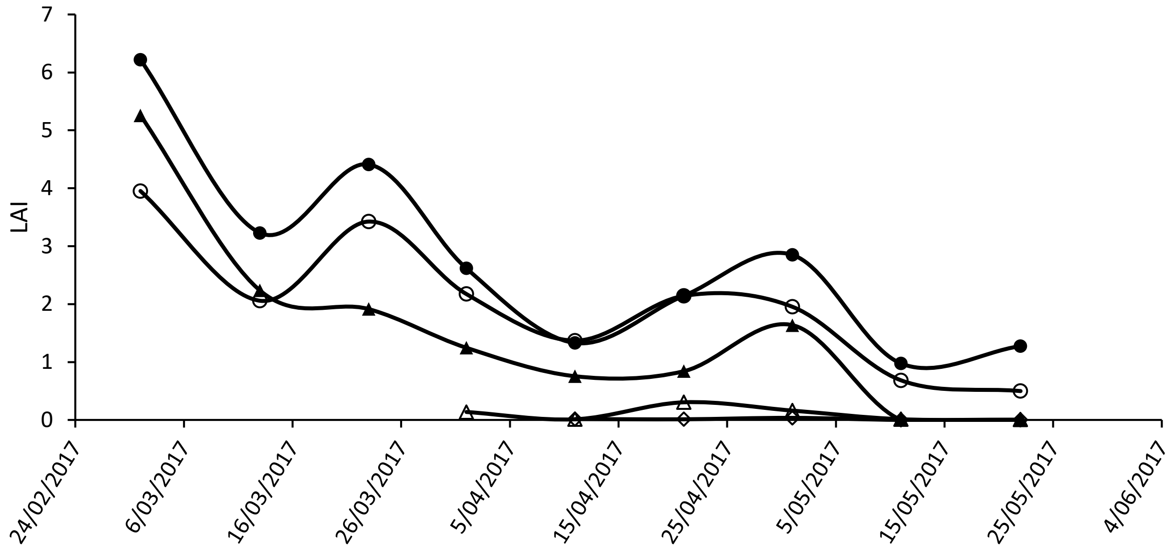

Figure 4.14 Leaf area index for cocksfoot leaves (●) and lucerne leaves (○) in a cocksfoot/lupin/clover pasture and lucerne pasture from 2 March 2017 – 22 May 2017 at Lincoln University, Canterbury.

The LAI of lucerne peaked in early March (4.0) and was lowest in mid-April (1.4), remaining an average 25% below the LAI for cocksfoot leaves. The LAI for cocksfoot leaves also peaked in early March (6.2) and was lowest at in mid- April (1.3). Lupin LAI (5.3) was greater than lucerne in early March, but remained lower for the remainder of the season, with no lupin present after mid-May. Sub clover and white clover had a LAI of <0.5 across all dates primarily due to the minimal clover content in the pastures. Species variation in LAI was greatest in early March (P<0.05), and lowest in mid- April.

4.8 Sub clover establishment

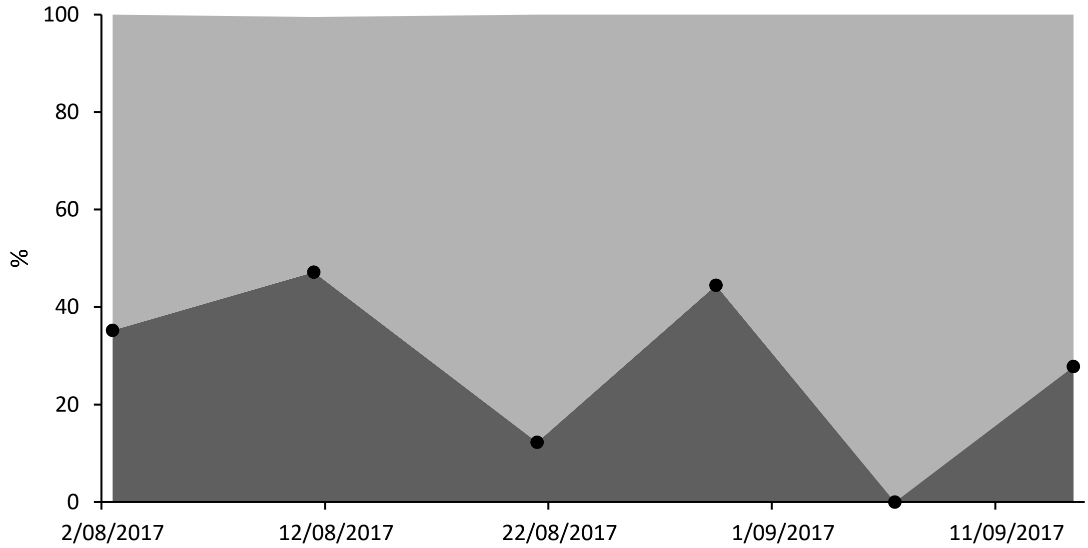

Figure 4.14 Proportion of Narrikup sub clover (●) and Denmark sub clover (○) in a cocksfoot/lupin/clover pasture mix in the first 2 months of spring after sowing at Lincoln University, Canterbury.

Sub clover cultivars Narrikup and Denmark (sown autumn 2016) contributed an average 2% total herbage yield in the first grazing rotation (3 August – 14 September 2017) of the 2017/2018 growing season. This varied throughout the six cocksfoot/lupin paddocks, ranging from 0.1% - 3.4%. Consistently the proportion of Narrikup (72%) was greater than the proportion of Denmark (28%) ($P<0.001$).

Chapter 5

Discussion

The aims of this study were to identify differences in the dry matter yield of a cocksfoot/lupin/clover pasture compared to a lucerne pasture and quantify reasons for these differences, conclude if lupin was a productive legume for the dryland South Island high country of New Zealand, and discuss the establishment of sub clover and determine if the cultivar Narrikup or the cultivar Denmark was more suited to this environment.

5.1 Dry matter production

The annual dry matter yield of lucerne was 10,617 kg DM/ha, 39% greater ($P<0.001$) than the cocksfoot/lupin pasture which produced 6,433 kg DM/ha (Table 4.1) in its fourth year of production, from 11 July 2016 to 29 June 2017. This is similar to the herbage yield accumulated in the second year of this trial, where lucerne yield (10,230 kg DM/ha) was 36% greater than the cocksfoot/lupin pasture (Black & Ryan-Salter, 2016). This increase was mostly due to the much faster growth rate of 6.36 kg DM/°Cd for lucerne compared to the 3.94 kg DM/°Cd for cocksfoot/lupin for a period of 1,048 °Cd, or 118 days, between 17 August and 13 December (**Error! Reference source not found.**). During this period lucerne grew 53.24 kg DM/ha/day, whereas cocksfoot/lupin grew at 34.49 kg DM/ha/day (Figure 4.1). These spring yields were about 40% and 41% of the total annual yields for lucerne and cocksfoot/lupin, respectively.

Consistently both lucerne pastures (Figure 4.2) and cocksfoot/lupin pastures (Figure 4.5) contained above 90% live material in spring, with minimal dead, especially in lucerne. Summer/early autumn and late winter pastures were dominated by dead material, with over 50% of the sward containing dead material in both pastures. This coincides with the dry matter yield received in each pasture, with spring growth greater than summer, autumn and winter in all 6 paddocks of each pasture type (Figure 4.1). The greater proportion of live material, the increased photosynthesis and therefore increased dry matter production.

5.1.1 Yield-thermal time relationship

Temperature is an essential factor for dry matter production, as typically, plants cannot grow at temperatures above 25 °C or below 5-10 °C (McKenzie *et al.,* 1999). Over the 2016/2017 growing season a total 3,123 °Cd (base temperature 3°C) were accumulated, with lucerne growing an average 3.4 kg DM/°Cd and cocksfoot/lupin growing 2.06 kg DM/°Cd (Figure 4.8). This shows lucerne was able to produce 1.34 kg DM/°Cd from the same environmental temperatures. Temperature had a positive effect on dry matter production in spring, with the lucerne pasture producing 6.36 kg DM/°Cd and the cocksfoot/lupin pasture producing 3.94 kg DM/°Cd in July and August 2016 and June 2017 temperatures fell below 5°C, therefore during these days dry matter accumulation was negative. Temperatures during spring period ranged from 6-21°C (Figure 3.2), within the range for most plant production. Daily temperatures in summer and autumn also remained below 25°C, therefore if all other environmental factors were favourable both lucerne and cocksfoot/lupin pastures could continue growing. However, this was not the case as the growth rate per degree day of both lucerne and cocksfoot/lupin pastures decreased. Lucerne growth from mid-December to late June averaged 1.75 kg DM/ha/°C compared with an average 0.88 kg DM/ha/°C in the cocksfoot/lupin pasture. This helped explain the increased winter to spring growth in both pastures and demonstrates the greater ability the lucerne pasture had at producing dry matter under optimal temperatures, compared with the cocksfoot/lupin pasture. Although the temperatures in summer and autumn were within the optimum range for cocksfoot and lucerne, as described in Section 2.5.2, dry matter production was slow during this period, as a result of the soil moisture deficit as described in Section 5.1.1.

5.1.2 Water

As outlined in Section 2.5, the most important environmental factors influencing the profitability of farming businesses and the choice of what pasture species to grow are: water, temperature, light interception and mineral nutrients (N) (Chapin *et al.,* 1987; Scott *et al.,* 1985). Lucerne water use for this 2016/2017 season was 503 mm with a WUE of 20.5 kg DM/ha/mm (Figure 4.11). Although a similar water use in the cocksfoot/lupin pasture (498 mm) (Figure 4.11), the WUE (7.9 kg DM/ha/mm) was significantly different, showing lucerne pastures can produce more dry matter than a cocksfoot/lupin pasture with the same amount of water use (Figure 4.12Figure 4.12). These findings are similar to those found in the second year of this experiment by Williams (2015), with the water use of lucerne (526 mm) similar to the water use of the cocksfoot/lupin pasture (473 mm). The WUE also followed the same trend, with the lucerne pasture producing 19 kg DM/ha/mm and the cocksfoot/lupin pasture producing 14.6 kg DM/ha/mm over the 2014/2015 growing season.

Seasonally the WUE for the lucerne pasture remained greater than the cocksfoot/lupin pasture in the spring, summer and autumn (Figure 4.12). Both lucerne and cocksfoot/lupin WUE were similar to the WUE found in the second year of this experiment (Williams, 2015). Lucerne produced 23 kg DM/ha/mm in both the 2014 (Williams, 2015) and 2016 (this experiment) spring, compared with the WUE of 17 and 16 kg DM/ha/mm in the 2014 and 2016 spring, respectively. These findings are consistent with the 24 kg DM/ha/mm WUE of lucerne and 17 kg DM/ha/mm WUE of cocksfoot

dominant pastures found by Moot *et al*. (2008). Summer and autumn WUE decreased but remained significantly different, with 16 and 8 kg DM/ha/mm from the lucerne and cocksfoot/lupin pastures, respectively. Decreases in the water use and WUE were expected due to the reduced rainfall between 23 January and 11 March 2017 (

Figure 3.1), decreasing the total soil moisture content over this period (Figure 4.9) 40 mm and 57 mm in the lucerne pasture and cocksfoot/lupin pasture respectively. Soil moisture and therefore water use increased after this point, but had negative effects on dry matter production over this period and for the remainder of the season. Throughout the season lucerne and cocksfoot/lupin appeared to extract water to the same level, 1.3 m into the soil profile (Figure 4.10). Lucerne dry mater growth rates (Figure 4.1) decreased from 53 to 17 kg DM/ha/day and cocksfoot/lupin growth rates decreased from 35 to 8.9 kg DM/ha/day during spring and summer/autumn, largely due to the reduced rainfall causing a decreased soil moisture, decreased water use and WUE.

5.1.3 Nitrogen

Annual dry matter yield (Table 4.1) was also influenced by the total N yield (Figure 4.13Figure 4.13). Lucerne accumulated an average 223 kg N/ha over the 2016/2017 season. This was significantly greater than the accumulated N content of the cocksfoot/lupin pasture, with 87 kg N/ha. This difference can be explained by the composition of the pastures, with an average 97% legume content in the lucerne pasture compared with 13% in the cocksfoot/lupin pasture. This varied throughout the year with the proportion of lupin, white and sub clover averaging 3% in winter, 18% in spring, 16% in summer and 10% in autumn (Figure 4.6). Lucerne pasture had less variation, with spring pastures containing the least legume content (95%) in most paddocks (Figure 4.3). As legumes are a natural source of N, (Lucas *et al.,* 2010) and these pastures were not fertilised, the greater legume content the greater the N available for plant uptake to abide in plant growth and development. Spring lucerne pastures contained an average 54.4 kg N/ha compared to the 21.4 kg N/ha in the cocksfoot/lupin pastures. This 61% difference is similar to the 62% difference in average herbage yield between the two pastures at this time, indicating there is a strong relationship between spring pasture production and N content. Late summer/early autumn and late winter pastures contained the least proportion of live material, legumes and N%, also indicating the importance of a high N yield for increased pasture production.

5.1.4 Leaf area index

Another factor influencing the dry matter production of the lucerne and the cocksfoot/lupin pastures in autumn was LAI. Predicting leaf or canopy (light interception and canopy arrangement) photosynthesis are two ways to predict pasture production. These are both influenced by the amount of leaf area available to capture light in a pasture. Of the dominating species in each pasture (cocksfoot and lucerne), leaf (including pseudostem or petiole) contributed to at least 50% of the lucerne and cocksfoot herbage in each paddock (Figure 4.4 and Figure 4.7). Lucerne leaves had a maximum LAI of 4.0 in March, within the range (3-4.5) for horizontal and vertical lucerne leaves (Varella, 2002). LAI during early March, when dry matter production was low, was 6.2. This is above 5.5, the LAI where maximum cocksfoot light interception occurred (Peri, 2002). Cocksfoot LAI decreased to 1.3 in April, suggesting light interception was maximised at this point. However, with reduced N and soil moisture photosynthesis was likely not maximised during this point, explaining some of the difference between spring and autumn production in the cocksfoot/lupin pasture. The lower the LAI the greater the light interception and therefore the greater the dry matter production (Peri, 2002). The difference between March and April LAI for cocksfoot and lucerne helped explain the dry matter production over this period. At the same point as rainfall increased soil moisture (mid-March) which increased water use, the LAI of lucerne and cocksfoot leaves decreased, all contributing to the slight increase in dry matter production in Autumn in some paddocks (Figure 4.1).

5.1.5 Lupin as a legume option for cocksfoot dominant pastures

Lupin content over the past 3 years of this experiment have decreased from 42%, 22% and 12% in year 1, 2 and 3, respectively. Average lupin content remained at 12%, with a higher content in spring (13%) than in summer/autumn (9%). It appeared the lupin plants died over the three years, and although not confirmed, this was possibly from crown and root rot, caused by *Fusarium heterosporum*, (Black & Ryan-Salter, 2016) which has been recognised as a cause of plant death in other lupin trials at Lincoln University (Kitessa, 1992). The grazing management may have also impacted the lupin persistence, as the grazing management was determined to fit best management practices for lucerne, of which lupin best practices may have been different. The persistence of lupin in more extensive, high country systems (Scott, 2014) has been greater than the persistence receives in this experiment. This suggests factors in these extensive trials, in colder environments may be more suited to lupin. Further research is required to investigate the drought tolerance of lupin, and determine if it can withstand hot, dry summers under intensive grazing. Research into the cause of the poor lupin persistence is also required as there are management and external factors than may contribute to this and could be somehow easily avoided.

Due to this decrease in lupin over four years, it cannot be recommended to use lupin as a legume to accompany cocksfoot pastures in the dryland South Island high country. Lupin seed is expensive and difficult to obtain, and the quality of seeds available now are poor. Seed breeding for pathogen resistance and possibly for an increased drought tolerance are required in the future before lupin could become a more commonly used legume.

5.1.6 Sub clover as a legume option for cocksfooot dominant pastures

Cocksfoot/sub clover pasture mixes have been proven to be a successful dryland grazing pasture, with greater dry matter yields for two consecutive years (Brown *et al*., 2006). During the first grazing rotation of cocksfoot/lupin pastures in spring 2017 (3 August – 14 September) sub clover contributed an average 2% to total herbage mass. The proportion of cultivars Narrikup and Denmark varied significantly with Narrikup contributing 72% and Denmark contributing 28% (Figure 4.). This result is similar to the emergence rate of Denmark and Narrikup cultivars in mixed cocksfoot dominant pastures, where the emergence rate for Narrikup (292 seedlings /m^2) was greater than the emergence rate for Denmark (155 seedlings /m^2) when sown at 10 kg/ha (Wright, 2015).

Although the sub clover is a minor component of the cocksfoot/lupin pasture at present, the potential to increase legume content in spring and autumn is there. Wright (2015) found Narrikup produced 760 kg DM/ha, more than the 220 kg DM/ha from Denmark during the first spring after establishment. This increased legume content was found to increase the cocksfoot production, with 150 and 80 kg DM/ha cocksfoot produced when mixed with Narrikup and Denmark respectively. This suggests sub clover, and especially the cultivar Narrikup is an ideal pasture legume for cocksfoot in dryland, unfertilised pastures at Lincoln University. A Combination of both Denmark and Narrikup could be successful in increasing the productivity of dryland cocksfoot pastures, due to the different flowering and germination times. Denmark, a late flowering cultivar is likely to produce more DM later in the spring, whereas Narrikup is more likely increase late winter and early spring DM. Further research on the persistence of these cultivars in a mix would quantify this and determine with more certainty the best cultivar/s to use.

5.2 General discussion

This experiment has outlined that a cocksfoot/lupin/clover pasture mix cannot produce a similar dry matter yield as a lucerne monoculture at Lincoln University. Although this experiment was not carried out in the South Island high country of New Zealand, these results obtained give a good indication a cocksfoot/lupin pasture in the high country will not perform as well as lucerne. Due to these results obtained it is recommended to grow lucerne pastures where possible in dryland areas. In areas where this is difficult, and for long term pastures, cocksfoot is a suitable option. Persisting well in dryland conditions over the past four years, cocksfoot has proven it is a suitable dryland pasture species. Increasing the legume content of a cocksfoot pasture has continued to be challenging, with the trialling of lupin as this legume being unsuccessful. Lupin content has decreased dramatically over the past 4 years, decreasing the N content of the cocksfoot/lupin pasture.

Establishment of sub clover in this cocksfoot/lupin pasture was successful, with increasing content of both Narrikup and Denmark cultivars in spring 2017. The establishment of Narrikup was greater than that of Denmark, therefore it is recommended to combine cocksfoot with the sub clover cultivar Narrikup for maximising dry matter production where lucerne is unsuitable.

5.3 Conclusions

- Accumulated dry matter yield was 39% greater in the lucerne than the cocksfoot/lupin pasture, with both pastures producing more dry matter in spring than winter, summer or autumn.

- Accumulated N yield in lucerne was 61% greater than accumulated N in the cocksfoot/lupin pasture, occurring primarily from the difference in spring (61%), even when the legume content in the cocksfoot/lupin pasture was at its greatest.

- Total water use was not significantly different ($P>0.05$) between the two pastures; however, water use efficiency was 7.9 kg DM/ha/mm water used greater ($P<0.05$) in the lucerne pasture than the cocksfoot/lupin pasture.

- Lupin is not a suitable pasture legume for cocksfoot dominant pastures in dryland Canterbury. By the fourth year after establishment, lupin contributed very little (12%) to the overall dry matter production, reducing the N content of the pasture.

- Sub cover is a more suitable legume option for cocksfoot dominant pastures, with the new cultivar Narrikup establishing faster than the commonly used cultivar Denmark.

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