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Autumn nitrogen effects on perennial ryegrass (*Lolium perenne* L.) and cocksfoot (*Dactylis glomerata* L.) pastures in dryland Canterbury

A dissertation submitted in partial fulfilment of the requirement for the Degree of Bachelor of Agricultural Science at Lincoln University by Mart-Marie Roux

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This research examined the effects of autumn nitrogen application at five rates (0, 50, 100, 200 and 400 kg N/ha) on dry matter production and the nutritive value of cocksfoot and perennial ryegrass, and the subterranean clover content of these pastures. The experiment was run as two experiments overlain on a nine-year old cocksfoot pasture and a five-year old perennial ryegrass pasture from 28 February 2012 to 17 August 2012. Average yields increased with increasing N application rate for both cocksfoot and perennial ryegrass. Accumulated yields ranged from 0.8 t DM/ha (control) to 5.6 t DM/ha (400 kg N/ha) in cocksfoot, and 1.7 ± 0.25 t DM/ha (control and 50 kg N/ha) to 5.4 t DM/ha (400 kg N/ha) in perennial ryegrass. These increases were largely contributed to increases in leaf extension of up to 100% in cocksfoot and 108% in perennial ryegrass. Pasture ME was reduced to 10.4 MJ/kg DM in cocksfoot and 10.2 MJ/kg DM in perennial ryegrass as a result of mowing pastures in winter and removing stored sugars in the leaves. Water use efficiency was increased from 3.7 to 25.5 kg DM/ha/mm PET in cocksfoot and from 8.0 to 24.7 kg DM/ha/mm PET in perennial ryegrass with the addition of 400 kg N/ha. Frequent grazings in rotations of 21-28 days in autumn are required to maintain persistence and production of subterranean clover. In this dissertation the physiological basis for pasture responses was examined to offer practical guidelines of autumn nitrogen application to dryland farmers.
Keywords: cocksfoot, *Dactylis glomerata*, dryland, dry matter, leaf extension, *Lolium perenne*, nitrogen, nitrogen recovery, perennial ryegrass, subterranean clover, temperature, *Trifolium subterraneum*, water use efficiency.
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1 INTRODUCTION

New Zealand’s dryland regions are defined as areas that receive less than 800 mm of rainfall annually, and in summer experience potential evapotranspiration (PET) in excess of rainfall (Brown and Green, 2003). PET values in the dry eastern parts of New Zealand such as Canterbury may be 300-500 mm over the growth season (Salinger, 2003). Perennial ryegrass (*Lolium perenne* L.) is the most commonly sown grass in New Zealand. It is usually sown as a mix with white clover (*Trifolium repens* L.) as this provides a productive and nutritional pasture for livestock grazing. Ryegrass/white clover pastures, however, are not well adapted to long periods of moisture stress (Brown and Green, 2003). Cocksfoot (*Dactylis glomerata* L.) is frequently sown in dryland areas of New Zealand as it is both drought tolerant and able to establish and grow under medium to low soil fertility (Smith *et al.*, 1998). Subterranean clover (*Trifolium subterraneum* L.) is recommended to be sown in pasture mixes with cocksfoot. It is a winter-active clover which compliments cocksfoot which is summer-active (Brown *et al.*, 2006).

In dryland Canterbury, feed deficits often also occur from autumn to winter as feed demand during this period exceeds feed supply (Beef & Lamb NZ, 2012). The dilemma for farmers is therefore to find possible methods of improving pasture growth rates during deficit periods. The main factor limiting pasture growth and production on a global scale is nitrogen (Grindlay, 1997). Dryland pastures in New Zealand are commonly moisture- and nitrogen-deficient, but fertiliser inputs of nitrogen are less frequent than on irrigated pastures. Nitrogen is a component of chlorophyll, amino acids (proteins), nucleic acids (Bojovic and Markovic, 2009) and many other plant structures, and is the major nutrient required for plant growth.

Sources of nitrogen in a pastoral system include clover N fixation, animal urine, soil mineralisation and the application of N fertiliser. Soils contain 0.1-0.6% N (between 2000 and 12000 kg N/ha) of which around 95% is present in the organic pool and unavailable to plants (McLaren and Cameron, 2010). Breakdown of organic N through biological soil processes (called mineralisation) releases between 10 and 500 kg N/ha/year of plant available N (nitrate – NO₃⁻; and ammonium – NH₄⁺).
Legumes have the ability to fix atmospheric nitrogen through a symbiotic relationship with rhizobia in their roots (Andrews et al., 2011). This fixed nitrogen then becomes available to the grass species when the clover dies and decomposes, or is deposited back onto the pasture through the urine of grazing animals. Decomposition of clovers is especially important in pastures with an annual legume component. Annual clovers, such as subterranean clover, complete their lifecycle within one year. After setting seed, these clovers die naturally (Clark, 2007). Decomposition by soil microbes releases nutrients, including nitrogen, in mineral forms (through mineralisation) which are available for plants to take up (McLaren and Cameron, 2010).

The urine of grazing ruminants is another rich source of nitrogen, with sheep urine depositing between 173 and 448 kg N/ha (Peri et al., 2002a). N in urine is in the form of urea (Sarelius and Greenway, 1975). Under moist conditions, urea is rapidly converted to ammonium carbonate which quickly dissociates into plant-available ammonium (McLaren and Cameron, 2010). A similar process occurs with the application of urea-N fertilisers. Other N fertilisers (including ammonium and nitrate fertilisers) are commonly applied in available N forms and therefore nearly immediately available for plant utilisation. The problem that arises with the use of N fertiliser is that the grass component of pastures tends to become dominant through rapid growth which may result in reduced clover persistence (Gerard et al., 2011). Applications of autumn nitrogen may therefore interfere with the autumn re-establishment of subterranean clover.

The main aim of this study was therefore to quantify the growth and development of cocksfoot and perennial ryegrass pastures with the application of autumn nitrogen. Any increases in DM production will also be investigated to determine which factor(s) were responsible for these increases. The study also examined the effects of pasture production responses to nitrogen on the yield and persistence of associated subterranean clover. Furthermore, the water use efficiency and physiological responses associated with additional nitrogen will be explained. This dissertation is structured in six chapters. Chapter 2 reviews literature on production parameters of cocksfoot and perennial ryegrass in New Zealand. Chapter 3 describes the experimental design, environmental conditions, treatments and statistical analyses. Chapter 4 presents the results of the experiments, Chapter 5 discusses the results in relation to the literature and Chapter 6 relates the findings of the research to on-farm implications.
2 REVIEW OF LITERATURE

2.1 Introduction
This chapter reviews literature on cocksfoot and perennial ryegrass pastures in New Zealand. It provides information about the potential production (growth and development) and quality of these pastures in a dryland environment in response to autumn nitrogen fertiliser. It will also consider subterranean clover as a companion legume, and the effect of nitrogen fertiliser on its growth and persistence.

2.2 Establishment and persistence
Cocksfoot is a small-seeded grass with a thousand seed weight of between 0.65 g (Lancashire and Brock, 1983) and 1.0 g (Moloney, 1993). Perennial ryegrass has a larger seed with a thousand seed weight of 1.87 – 2.48 g. Once established, cocksfoot persists longer than perennial ryegrass, particularly in dryland areas. Smith et al. (1993) found that the cocksfoot content in a sward increased from the first to second spring after sowing. This was similar to that reported by Korte et al. (1991) who found that cocksfoot content increased for three to four years after sowing. Figure 2.1 shows the annual yield of the sown grass component of five dryland pastures (cocksfoot/sub clover, CF/Sub; cocksfoot/balansa clover, CF/Bal; cocksfoot/white clover, CF/WC; cocksfoot/Caucasian clover, CF/CC; and ryegrass/white clover, RG/WC). It shows that the sown grass component of the RG/WC declined from 7.4 t DM/ha/year (70% of total yield) in 2002/03 to slightly more than 4 t DM/ha/year (about 45% of total yield) in 2005/06 and 2006/07. This was a consistent decline of 0.7 t DM/ha/year from establishment. The sown grass yield of cocksfoot/white clover (CF/WC) pastures decreased from 8.7 t DM/ha/year in 2002/03 to ~ 6 t DM/ha/year in 2005/06 and 6.3 t DM/ha/year in 2006/07. The sown grass yield of cocksfoot/sub clover (CF/SC) pastures dropped from 8.5 t DM/ha/year in 2002/03 to ~ 5.5 t DM/ha/year in 2005/06 and 6.1 t DM/ha/year in 2006/07. These results show that cocksfoot was a more suitable grass species for this area (dryland Canterbury) where summer moisture stress is a regular occurrence. Johnson et al. (1994) found that four years after establishment at Taranaki Agricultural Research Station, the yield of perennial ryegrass relative to its first year yield was only 30%. Cocksfoot maintained a yield of about 80% of its first year yield in the fourth year after establishment. Ryegrass yield declined from the first year after establishment, while cocksfoot yield increased into Year 2 and then decreased over the next two years.
To maintain persistence it is important to limit the stress factors to which pastures are exposed. Perennial ryegrass persistence is also influenced by insect pest attack (Popay and Thom, 2009). Ryegrass has low tolerance to insect pests, especially in areas with unreliable rainfall (Hume et al., 2009). Ryegrass persistence is therefore considerably reduced in summer dry areas of New Zealand where insect pest status is high. A study by Popay and Thom (2009) found that infection of ryegrass with ‘AR37’ novel endophyte (with which perennial ryegrass in the present study was infected) protected the plants from insect attack and allowed these pastures to persist during a 2008 drought in the Waikato. During that same drought, none of the pastures that were not infected with endophyte persisted and were therefore all re-sown the following year.

### 2.3 Annual dry matter yields

Annual and seasonal yields of pasture species may vary substantially in dryland regions due to variations in climatic factors (Salinger, 2003), soil fertility and pest attack. Other
factors such as available soil nitrogen and grazing intervals also affect total annual dry matter production of pasture grasses (Peri et al., 2002a). Average annual yields of perennial ryegrass under high fertility conditions range between 10 and 25 t DM/ha (Kemp et al., 1999). The large range shows the impact of the environment on ryegrass production. Dry summers in dryland areas result in ryegrass yields towards the lower end of the scale, while irrigated pastures yield up to 25 t DM/ha/year. In low fertility dryland conditions, average annual perennial ryegrass yields of 5.0-6.5 t DM/ha are common (Fasi et al., 2008). Cocksfoot annual yields of 5-7 t DM/ha (Stevens et al., 1992; Peri et al., 2002a; Mills et al., 2006) are typical in dryland environments where nitrogen and moisture are both limiting to growth. However, from 16.4 t DM/ha (Mills et al., 2006) to 23.5 t DM/ha (Peri et al., 2002a) of cocksfoot can be grown with the addition of nitrogen fertiliser at application rates of 300 kg N/ha/year or greater, even in dryland conditions.

Urine patches have a similar effect on pasture production as nitrogen fertiliser. Peri et al. (2002a) found that DM production under new urine patches was 380 kg/ha higher in summer and winter than non-urine control areas. In spring, the difference between pasture production for new urine patches and controls was up to 1970 kg DM/ha. The difference between urine patches and the control declined over time, with effects of urine on pasture production lasting an average of 77 days in summer, 133 days in autumn and winter (applied at 173 kg N/ha), and 105 days in spring (applied at 448 kg N/ha). Differences in N application rates through urine occurred because the concentration of nitrogen in urine in autumn was lower (3.46 g/L) than in spring (8.97 g/L), but no explanation for this difference was provided. The average response time of pastures to urine N application can be used as a guideline to estimate how long N fertiliser will influence pasture production.

2.3.1 Leaf appearance and leaf extension
Phyllochron is a measure of the interval between the appearance of successive leaves on a tiller (Wilhelm and McMaster, 1995), calculated as the number of growing degree days (°Cd) required for the production of one leaf (Frank and Bauer, 1995). Leaf appearance rate is calculated as the number of leaves produced per tiller per day (Belanger, 1998) and is primarily driven by temperature, with minimal effects of non-extreme levels of nutrient availability (Bauer et al., 1984). However, increasing availability of nitrogen has been shown to result in faster development and leaves appearing at a faster rate (Wilhelm and McMaster, 1995; Suplick et al., 2002). Belanger (1998) in a study in Canada found that
the leaf appearance rate (leaves/tiller/day) of timothy tended to increase with increasing N application rate, although this was not always the case. He found that the average leaf appearance rate with no N fertiliser application was 61% and 67% of the maximum mean leaf appearance rate of N-fertilised treatments in spring and summer, respectively. Black et al. (2002) estimated the phyllochron of perennial ryegrass to be 101 °Cd for the appearance of one leaf. Leaf appearance rate was also shown to increase with increasing mean temperature (Figure 2.2). At 5 °C, 0.05 leaves were produced per day (20 days per leaf), while 0.15 leaves/day were produced (5 days per leaf) at 15 °C. They also calculated the average base temperature for development of perennial ryegrass to be 2.4 °C. Mills (2007) calculated the base temperature of cocksfoot for growth to be 3 °C. The present study used a base temperature (Tb) of 3 °C for cocksfoot and perennial ryegrass as leaf appearance includes both development and an element of growth.

Figure 2.2  Leaf appearance rate (leaves/day) from the apical growing point of perennial ryegrass against temperature. Re-drawn from Black et al. (2002).

Leaf extension is more sensitive to nitrogen availability than leaf appearance (Belanger, 1998). With no nitrogen fertiliser, the leaf extension rate of timothy was around 40% in spring and summer of the maximum mean achieved by N-fertilised timothy. In spring, the mean leaf length of leaves in N fertilised treatments (210 kg N/ha) were 36% to 140% larger than leaves in unfertilised treatments. In summer, leaves in N-fertilised treatments
(between 120 and 180 kg N/ha) were on average 51% to 229% larger than leaves in unfertilised treatments. Leaf extension rate was also found to be closely related to temperature when nitrogen was not limiting. Leaf extension is important to plant growth and development as it results in an increase in the leaf area per unit of ground (leaf area index - LAI) (Watson, 1947). An increased LAI results in increased light absorption (Engel et al., 1987) as a larger proportion of the ground is covered in green leaf which results in an increased capacity for photosynthesis. Radiation use efficiency is therefore increased with increased N availability as a larger proportion of incoming radiation is intercepted and absorbed by green herbage as a result of an increase in leaf area index.

Nitrogen also influences photosynthesis rates through an increase in chlorophyll content and Rubisco activity (Peri et al., 2002b). Rubisco is an enzyme that regulates photosynthesis and photosynthesis rates have been reported to increase with increasing Rubisco content and activity (Bolton and Brown, 1980). Figure 2.3 shows that the net rate of photosynthesis ($P_{max}$) increased with increasing foliar nitrogen concentration, which was achieved through the application of nitrogen fertiliser at rates of up to 300 kg N/ha. For example, at a foliar N content of 20 kg N/kg DM (2%), the photosynthesis rate of cocksfoot was 0.4 (40%) of the maximum. An increase in foliar N content to 35 kg N/kg DM resulted in an increase in photosynthesis rate to 0.8 (80%) of the potential (maximum). Photosynthesis is related to both light interception and chlorophyll content, which are both increased with increasing nitrogen content. Thus, an increase in nitrogen application rate results in an increase in foliar nitrogen and enables plants to increase the rate of photosynthesis.
Figure 2.3  Response of the standardised rate of net photosynthesis ($P_{\text{max}_s}$) to foliage nitrogen concentration for cocksfoot grown under field conditions where temperature and water were non-limiting. $P_{\text{max}_s}=1$ corresponds to $P_{\text{max}}=27$ µmol CO$_2$/m$^2$/s. Fitted Weibull function model (thick line) and a three-part (1, 2 and 3) ‘broken stick’ model (thin line) are indicated. Redrawn from Peri et al. (2002b).

2.4 Seasonal dry matter production

Temperate cocksfoot cultivars such as those used in New Zealand tend to be summer-active and winter-dormant. Perennial ryegrass is slightly more cool-season-active than cocksfoot, but seasonal growth of ryegrass differs among cultivars. For example, Easton et al. (2001) reported that ‘Bronsyn’ perennial ryegrass produced about 3.3 t (30%) more dry matter per hectare annually than ‘PG31’ perennial ryegrass. This was largely a result of a 41% increase in DM production in summer and a 39% increase in autumn. Winter dry matter production was similar between the two cultivars. Fasi et al. (2008) found cultivar differences in annual yields of perennial ryegrass. Although no data were presented on ‘Extreme’ perennial ryegrass (the cultivar used in the present study), ‘Revolution’ perennial ryegrass produced 19% more dry matter annually than ‘Cannon’ perennial ryegrass. Stevens et al. (1992) reported seasonal production differences between cocksfoot and perennial ryegrass. They found that ‘Kara’ cocksfoot production in spring accounted for about 30% of total annual yield, compared with around 40% for ‘Nui’ perennial ryegrass. Cocksfoot summer production was, however, higher than ryegrass
with between 26 and 33% of annual yield for cocksfoot and around 20 to 22% of ryegrass annual yield accumulating in summer. The proportion of annual yield accumulated in autumn ranged from 31 to 37% for cocksfoot, and 22 to 28% for ryegrass. Winter production was, however, higher in ryegrass than cocksfoot. Contributions to annual yield were 12 to 19% for ryegrass and 7% for cocksfoot in winter.

### 2.5 Feed supply and demand

The seasonality of pasture production has been identified as a major constraint on livestock production systems (Field, 1980). There is variability in pasture production on a seasonal and annual basis as a result of variations in climatic conditions such as temperature and rainfall (Salinger, 2003). Daily growth rates of temperate pastures vary between seasons and with nutrient availability (Mills, 2007). Growth rates therefore tend to be lowest in winter when temperature limits pasture growth. In dryland environments, pasture growth rates are also limited by moisture, especially during summer. The main challenge to farmers is that the feed demand of sheep is often high when pasture growth rates are declining, for example during autumn flushing. Figure 2.4 shows that the main periods of feed deficit are from mid-summer through autumn into winter. In some years, however, summer and/or autumn rainfall may result in adequate feed supply. Winter deficits are the result of low temperatures which may slow the growth rates of pastures to a halt during mid-winter. Feed surpluses in spring may be conserved as hay or silage for use during times of feed shortage. However, this is often insufficient to fully meet the demand of animals for the entire year. N fertiliser can be used to manipulate pasture growth rates. This study focuses on the autumn and winter period as a tool to increase dry matter production and minimise feed shortages.
2.5.1 Manipulating pasture growth rates

The potential growth rate of a cocksfoot pasture not limited by nutrients (N) or moisture can be in excess of 75 kg DM/ha/day during spring and summer in Canterbury (Mills, 2007). In the same experiment the nitrogen-fertilised cocksfoot pastures produced a maximum of 95 kg DM/ha/day in spring under dryland conditions, but this declined to 8-9 kg DM/ha/day in summer. Daily winter growth rates of N fertilised dryland cocksfoot pastures were between 16 and 23 kg DM/ha/day. In contrast, unfertilised dryland cocksfoot produced a maximum of 68 kg DM/ha/day in spring and 3-5 kg DM/ha/day in winter. It is challenging to increase pasture growth rates during summer as moisture is the main factor limiting production. The findings by Mills (2007), however, show that there is potential to use N fertiliser to increase pasture growth rates and therefore yields during winter when moisture is not limiting. This is despite temperature limitations that may restrict the response.
2.6 Herbage Quality

When considering the performance of a pasture and its contribution to an animal production system, it is important to consider pasture production (yield) and quality. Pasture quality can be assessed by its metabolisable energy (ME) content. The ME content of New Zealand pastures is commonly between 8 and 12 MJ ME/kg DM (Litherland et al., 2002; McKenzie et al., 2003). Pasture ME is fairly seasonal, peaking in the cooler months (winter) when respiration is reduced and reaching a minimum in the hotter summer months (McKenzie et al., 2003). Figure 2.5 shows the seasonal variations in ME content of cocksfoot pastures. It illustrates that ME tends to decrease during summer and autumn and increase in winter. This is the result of reduced respiration rates in winter as nights are cooler than in summer and autumn. Mills (2007) found that, regardless of nitrogen treatment, the ME content of cocksfoot did not differ in winter. In summer, however, pastures that received nitrogen applications had a higher ME content than pastures that did not receive nitrogen fertiliser. McKenzie et al. (2003) found that the addition of nitrogen fertiliser tended to increase pasture ME content slightly, but seasonal effects were more substantial and evident. Pasture ME is also influenced by variations in stem, leaf and dead matter composition (Litherland et al., 2002) as lush green leaf is associated with a higher ME than stem and dead material. Turner et al. (2005) found no differences between the ME content of perennial ryegrass and cocksfoot. They reported that the mean ME of these two grasses was 10.9 MJ/kg DM in spring, 10.8 MJ/kg DM in summer and 11.2 MJ/kg DM in winter.
Figure 2.5  Metabolisable energy content (MJ ME/kg DM) of green ‘Wana’ cocksfoot dry matter at Lincoln University in 2003/04 and 2004/05 for pastures that were: irrigated and received nitrogen (●), irrigated and received no nitrogen (○), dryland with nitrogen (▼) and dryland with no nitrogen (▽). Error bars are maximum SEM for (a) irrigation effects, (b) nitrogen effects and (c) irrigation*nitrogen interactions in each season. From Mills (2007).

ME yield (the product of ME content and pasture yield) increased with increasing N application (Mills et al., 2006). In dryland conditions in Canterbury, the annual ME yield of cocksfoot when no nitrogen was applied was 45-53 GJ/ha compared with 143-161 GJ ME/ha in dryland cocksfoot pastures when N was applied at a rate of 800 kg N/ha in
multiple applications (Mills et al., 2006). Similar figures for perennial ryegrass are not readily available.

Pasture digestibility, which is directly related to ME (McDonald et al., 2002), can also be used as an indication of pasture quality. ME (MJ/kg DM) is calculated as 0.16 x organic matter digestibility or 0.15 x dry matter digestibility (McKenzie et al., 2003). Stem and dead matter are less digestible (43-69%) than grass leaf (>70%) (Hoogendoorn, 1986). Perennial ryegrass is a high quality forage grass (Hunt and Easton, 1989) which usually has a higher digestibility than cocksfoot. The digestibility of cocksfoot has been improved over the years through breeding for higher digestibility with new cultivars. The digestibility of cocksfoot, however, ranges from as low as 55% to up to 80% (8.8 to 12.8 MJ ME/kg DM) (Terry and Tilley, 1964; Stevens et al., 1992; Duru et al., 1999), depending on factors such as season (mainly as a result of temperature differences) and nutrient supply. Perennial ryegrass digestibility ranges from high 60’s to more than 80% (Terry and Tilley, 1964; Stevens et al., 1992), although values below 70% appear to be minimal.

Another quality component of pastures is their crude protein content. Crude protein (CP) is directly related to the nitrogen content of herbage, and calculated as 6.25 x herbage N% (Waghorn et al., 2007). Applications of nitrogen fertiliser therefore increase the nitrogen percentage and CP content of a pasture. A study by Peri et al. (2002b) found that the CP content of nitrogen-fertilised cocksfoot pastures in spring was 27% compared with 19% in pastures that did not receive nitrogen fertiliser. Mills (2007) found that the annual CP yield of cocksfoot pastures was increased from 0.6 t CP/ha to 2.7-3.8 t CP/ha through the addition of nitrogen fertiliser. In irrigated pastures, the N deficient cocksfoot pastures yielded 1.3 t CP/ha and the N-fertilised pastures 3.7-4.7 t CP/ha. The increase in CP yield was the result of both an increase in herbage CP content and an increase in DM yield in N-fertilised treatments.

2.7 Companion legumes

Pasture quality and yield can also be improved through the inclusion of legumes. Legumes have the ability to fix atmospheric nitrogen through a symbiotic relationship with rhizobia in their roots (Andrews et al., 2011). This fixation of nitrogen results in improved sward quality (Caradus et al., 1995) as the nitrogen (protein) content of the clover and the pasture
is increased. This results in greater feed intake by animals and an overall increase in production, largely as a result of increased palatability (Edwards et al., 1993).

The most common pasture mixture used in New Zealand consists of perennial ryegrass and white clover. However, perennial ryegrass can also be sown in mixtures with other clovers such as subterranean clover. White clover is unable to handle summer droughts (Knowles et al., 2003), and therefore struggles to persist in dryland farming areas (Brown and Green, 2003). Knowles et al. (2003) reported that moisture was the main factor affecting the persistence of white clover in pastures as the taproot dies 12-14 months after establishment (Brock et al., 2000).

Cocksfoot can be a dominant grass once established as it is competitive for moisture and has the ability to persist and remain productive longer than most other temperate pasture species in summer dry regions (Mills, 2007). For this reason legumes struggle to compete in cocksfoot dominant pastures. In dryland areas, subterranean clover is recommended to be sown in mixes with cocksfoot. This combination appears to work well as cocksfoot is a summer-active, winter-dormant grass, while subterranean clover is a winter-active clover (Widdup and Pennell, 2000). This means that cocksfoot and subterranean clover do not compete as vigorously for nutrients, space, light and moisture as cocksfoot and white clover. Cocksfoot and sub clover are more complementary with different growth patterns that can increase the overall yield and quality of a pasture, particularly in early spring (Brown et al., 2006). Perennial ryegrass is slightly more winter-active than cocksfoot, but the majority of its annual yield is produced in spring (Stevens et al., 1992). Thus, subterranean clover is also suitable for use in mixtures with perennial ryegrass, especially in dryland areas. Figure 2.6 shows the mean daily growth rates of perennial ryegrass, cocksfoot and subterranean clover when the grasses were either sown with or without subterranean clover in the mix at Ashley Dene (Ates et al., 2010). During periods of peak grass production (>60% sown grass content), approximately December to March, sub clover production was declining (<20% sown clovers) as plants were dying after setting seed. Then, as grass growth slowed down towards winter and early spring (<40% sown grasses), sub clover production increased to above 50%. The result of the activity of sub clover over winter and early spring resulted in the production of an additional 37 kg DM/ha/day in early spring (September) in pastures where sub clover was included. Mean annual pasture production was 34-45% higher in pastures where sub clover was included.
than in pastures without sub clover. Ryegrass pastures yielded 11 t DM/ha/year and cocksfoot pastures 9.7 t DM/ha/year with the inclusion of sub clover.

**Figure 2.6** Mean daily growth rates of (a) sown grasses and (b) sown clovers in pastures of perennial ryegrass with (●) and without (▼) subterranean clover, and cocksfoot with (○) and without (▽) subterranean clover. From Ates et al. (2010).

To maintain sub clover in pastures it is important to minimise competition between the grass and legume components of a pasture. For example, Woodfield and Caradus (1996) reported that dense grass growth resulted in competition between the grasses and white clover which reduced clover persistence. Light is important for the development of new white clover stolons, and shading results in fewer branched nodes and less developed stolons (Thompson, 1993). Dear et al. (1998) found that sub clover seedling weight was reduced in treatments where grass was not defoliated compared with treatments where grass was defoliated to 6 mm. In defoliated treatments, twice as much light reached clover seedlings, resulting in increased seedling growth rates. The rate of root development is also reduced when seedlings are shaded which makes them more susceptible to moisture stress. Seedling survival is therefore reduced by shading in dry environments. This makes it important to manage pastures to reduce competition for light, for example by frequent grazing, especially during spring, and set-stocking, depending on other management requirements. For sub clover establishment, hard grazing in summer and early autumn would allow adequate light penetration to seedlings. In this study, pastures were not grazed or mowed to minimise competition for light.
2.7.1 Subterranean clover – lifecycle and management requirements
Sub clover is an annual which has a high self-seeding ability under appropriate management (Ates et al., 2006). Sub clover plants germinate and establish in autumn, from January to May, depending on the timing of autumn rains (Moot et al., 2003). During the establishment period, pastures that contain sub clover should be spelled from grazing. Sub clover seedlings are ready to be grazed at the four-to six leaf stage (Costello and Costello, 2003; Thomas, 2003) which occurs about 434 °Cd after germination (Moot et al., 2003). The time (days) to ‘safe’ grazing of sub clover pastures therefore ranges from 26 to 53 days, depending on the date of first autumn rains (February to May). It is, however, beneficial to sub clover establishment for pastures to be ‘cleaned up’ during summer and early autumn to minimise competition for light, moisture and nutrients (Dear and Cocks, 1997) from other pasture species (mainly grasses). In the present study, this was achieved through cutting and removing herbage to a height of about 30 mm at the start of the experiment on 28 February (Section 3.4.1). Subsequent management of the pastures, however, was not aimed at minimising competition between sub clover and the sown grass for light.

2.8 Effects of N on clover content
In low input systems, legumes have a competitive advantage as they have the ability to fix nitrogen from the atmosphere. The addition of nitrogen fertiliser, however, enables the grasses in the sward to grow faster, thereby increasing their competitiveness. Rowarth et al. (1996) reported that the addition of nitrogen (between 50 and 100 kg N/ha) reduced clover content. The average clover content in the high N (100 kg N/ha) pastures was 5% in autumn compared with 25% in unfertilised pastures containing a mixture of four grass species (including cocksfoot and perennial ryegrass) and two clover species (red-and white clovers). Lambert and Clark (1986) reported that the addition of nitrogen to hill country pastures (species were not specified) resulted in a reduction of 19-28% in clover content as a result of shading. Studies by O’Connor and Gregg (1971) and McKenzie et al. (2003), however reported no effect of nitrogen fertilisation on clover content up to rates of 100 to 225 kg N/ha (three applications of 75 kg N/ha). The inconsistency in results between experiments was likely to be due to the effect of differences in grazing management. In the experiments where clover content was unaffected by the addition of nitrogen, pastures were possibly grazed harder to remove all herbage, while pastures that showed a reduction in clover content may have reached ceiling yield before being harvested. These details
were, however, not provided, with the exception of Lambert and Clark (1986) who reported that shading resulted in reduced clover content. Sub clover seedling weight has also been shown to decline in pastures where management allowed grasses to continue growing without defoliation (Dear et al., 1998). Although not a direct result of N fertiliser application, shading reduced the growth of both the roots and shoots of sub clover seedlings in undefoliated treatments.

2.9 Soil Fertility Requirements

Cocksfoot is suited to a lower input system than perennial ryegrass due to its ability to tolerate lower soil phosphate, sulphur and nitrogen fertility (Smith et al., 1998). Annual production may, however, be increased under higher fertility situations. For example, in an experiment at Lincoln University, cocksfoot annual yield increased from 5.0-7.5 t DM/ha under dryland conditions with no additional nitrogen to 15.1-16.4 t DM/ha when 800 kg of nitrogen was applied per hectare in eight applications of 100 kg N/ha (Mills et al., 2006). The application of 800 kg N/ha resulted in a yield response of 11.9 kg DM/kg N applied. The addition of irrigation water without N increased yield from 5.0-7.5 t DM/ha to 9.1-10.5 t DM/ha annually. Nitrogen was thus the main factor limiting dry matter production in these cocksfoot pastures. The maximum yield of cocksfoot, achieved when both moisture and nitrogen fertility were non-limiting, was 22.0 t DM/ha/year. On an annual basis, 65% of applied nitrogen was recovered in the irrigated and fertilised treatments and 52% of applied N was recovered in the fertilised dryland treatments. The remainder of the applied N was likely leached from the soil and/or lost as gaseous N (ammonia and gaseous nitrogen) through volatilisation and denitrification. Nitrate (NO$_3^-$) is negatively charged and therefore not held by soil particles. For this reason it leaches easily out of the soil profile (McLaren and Cameron, 2010).

Successful perennial ryegrass pastures require higher soil fertility, especially phosphate and nitrogen (Grant et al., 1981). Escuder and Cangiano (2007) in Argentina found that the annual yield of a ryegrass monoculture increased from approximately 3.5 t DM/ha under dryland conditions with no fertiliser to just under 8 t DM/ha with the addition of 300 kg N/ha/year. This translates into a response of 15 kg DM/ha/kg N applied at a rate of 300 kg N/ha. Lambert and Clark (1986), in a hill country sheep pastures study, found that the application of 37 kg N/ha in autumn resulted in an average yield response of 29 kg DM/kg N applied (species composition was not stated). From the costs of urea, cartage and
spreading provided by the authors, it was determined that the cost of producing 1 kg additional DM was on average $0.05. At current urea, cartage and spreading costs, however, the cost to produce 1 kg of additional DM would be $0.09.

2.10 Water use efficiency

Water use efficiency (WUE) may be defined in many different ways, but in agronomic terms is referred to as the ratio of biomass produced to potential evapotranspiration (PET) of a crop/pasture (Martin et al., 2006). In other words, it is a measure of the efficiency at which plants are able to convert water into dry matter, measured as kg DM/ha/mm of PET (Moot et al., 2008). The spring WUE of perennial ryegrass has been reported as 15 kg DM/ha/mm PET and cocksfoot as 17 kg DM/ha/mm PET at a dryland site in Canterbury (Moot et al., 2008). The addition of nitrogen fertiliser (300 kg N/ha) increased the WUE of cocksfoot to 38 kg DM/ha/mm PET. Increases in WUE with the addition of nitrogen is the result of an increase in pasture production without an increase in water use by the N fertilised pasture (Mills, 2007).

2.11 Impact of soil characteristics

Soil type and characteristics have the potential to substantially influence the production and persistence of a pasture. Lismore stony silt loam soils (the soil type in the present study) are fairly excessively drained with an available moisture capacity of 7-10% (McLenaghen and Webb, 2012). The available soil moisture capacity is the amount of water held in the soil between field capacity and permanent wilting point and is therefore available for plant extraction (McLaren and Cameron, 2010). A soil is at field capacity after a rainfall or irrigation event that completely fills the pore spaces of the soil, and is then left to drain until the water content of the soil remains fairly constant. Plants then extract moisture from the soil to the point where it becomes too hard for further moisture extraction, called the permanent wilting point. The soil moisture content at which permanent wilting of plants occurs is different among all soils, and generally higher in heavier (clay) soils and lower in more sandy soils. Stoker (1975) reported the moisture properties of a Lismore stony silt loam. Field capacity ranged from 23% at a depth of 225-300 mm to 33% in the top 75 mm of soil. Wilting point was reported to be at a moisture content of 10.4% (in the top 75 mm) to 11.7% at a depth of 150-225 mm. The moisture available for plant extraction was therefore between 12% and 22% (average 17%), amounting to 52 mm to a depth of 300 mm (about 40 mm to a depth of 200 mm). This is
higher than the 7-10% available moisture capacity reported by McLenaghen and Webb (2012). For the purposes of this study, the data presented by Stoker (1975) will be used as a guide.

2.12 Pests and diseases

Pests, weeds and diseases have the potential to cause major production losses in pastures. Insect pests are of considerable importance in dryland areas of New Zealand, including Canterbury. The major pasture pests in Canterbury include Argentine stem weevil (*Listronotus bonariensis*), grass grub (*Costelytra zealandica*), pasture mealybug (*Balanococcus poae*) and porina (*Wiseana* spp.). Ryegrass is particularly susceptible to insect pest attack in dryland areas where moisture limitations also stress plants. Cocksfoot is more tolerant of pest attack than ryegrass (Flay and Garrett, 1942), but may also suffer from large insect invasions.

Historically pasture pests were controlled through the use of DDT (Dichloro-Diphenyl-Trichloroethane) from the 1940’s (Popay, 2011). This was banned in New Zealand in 1970 and subsequently the chemical control of pasture pests has become uneconomic. Plant resistance and tolerance to pasture pests have consequently become important attributes to minimise damage to pastures and losses to pasture production. Cocksfoot and endophyte infected perennial ryegrass are therefore commonly used to minimise the impact of pests.

Endophytes have been developed and used around the world to provide ryegrass with improved resistance against pest attack. For example, ‘AR1’ and ‘AR37’ are two novel endophyte strains in New Zealand (Popay and Gerard, 2007; Popay and Thom, 2009). Claims are that ‘AR37’ provides protection against a wider range of insect pests than ‘AR1’ (Jensen and Popay, 2004).

There are several diseases that affect clover production in New Zealand. Clover rusts caused by *Uromyces* species are relatively common in all parts of New Zealand (Harvey and Harvey, 2009). In most cases they do not kill the clover plants or foliage, but can cause reductions in herbage quality. Another fungus with the potential to cause clover foliage death, and more prevalent in Canterbury than in other parts of the country is *Leptosphaerulina trifolii* (*L. briosiana*), commonly known as Pepper Spot (Harvey and
Harvey, 2009). This fungus causes small black spots on the leaves and petioles of clovers which may result in premature death of the herbage, especially under cool, moist conditions. Infected plants usually have a build-up of coumestans, a phytoestrogen which may reduce animal fertility. Clovers infected with any type of disease should therefore not be grazed prior to or during mating.

2.13 Conclusions

The following conclusion can be drawn from the literature review:

- Nitrogen applications allow for improved pasture production of cocksfoot and perennial ryegrass, even in areas where summer moisture deficits are common.
- Autumn nitrogen applications have the potential to increase autumn, winter and early spring pasture growth.
- Yield responses to N fertiliser are greater at lower N application rates.
- Subterranean clover is sensitive to competition for light and has reduced production when shaded by fast-growing grasses.

The current study quantifies the effects of different rates of autumn nitrogen applications on the yield, quality and composition (particularly subterranean clover) of existing cocksfoot and perennial ryegrass pastures, from autumn to early spring. The aim is to explain the physiological basis for pasture responses and offer practical guidelines for autumn application of nitrogen fertiliser for dryland farmers.
3 MATERIALS AND METHODS

3.1 Experimental Site

This dissertation examines pasture production in two experiments in adjacent paddocks. One was within a nine year old cocksfoot pasture and the other a four year old perennial ryegrass pasture.

The experiments were conducted at Ashley Dene Research Farm, C9A(S) and C9B(S) paddocks, Canterbury, New Zealand (43°38’64-59” S, 172°19’42-54” E) within a total area of 6.9 ha of flat land.

3.2 Soil

The soil at both experimental sites was an excessively drained Lismore stony silt loam (McLenaghen and Webb, 2012). Depth to stones at the sites ranges from 0.45-0.75 m. The topsoil is typically 0.2 m of friable stony silt loam overlying very stony silt and/or sandy loam subsoils. The available water holding capacity of the soil is 17% in the top 300 mm (about 52 mm) (Stoker, 1975).

3.3 Site History

3.3.1 Experiment 1 - Cocksfoot

The cocksfoot experimental site in Paddock C9A(S) was previously sown in lucerne from 1991 to 1999, and then used for the production of winter feeds from 2000 to 2002. In October 2002, ‘Vision’ cocksfoot was sown in mixes with ‘Aries HD’ AR1 perennial ryegrass and ‘Demand’ white clover into a cultivated seed bed at different sowing rates and combinations (Figure 3.1). The white clover component of the mixes did not persist (Table 3.1) or contribute significantly to pasture yield. Data were only from 2011 and 2012, but it reportedly became evident during 2004 and 2005 that white clover was not persisting. Ates et al. (2010) reported that by March 2005, white clover ground cover was <0.1%. Therefore two subterranean clover cultivars (‘Campeda’ and ‘Leura’) and ‘Bolta’ balansa clover were overdrilled in March 2005, except for four strips 10 m wide (marked as “no O/D annual clover” in Figure 3.1) which were left as controls. Sowing rates were 5 kg ‘Campeda’ sub, 5 kg ‘Leura’ sub and 3 kg ‘Bolta’ balansa per hectare. The strips where the two cocksfoot blocks for this experiment were located are indicated in grey in
Figure 3.1. A complete plan of the layout and dimensions of blocks and plots is given in Appendix 6.1.

Table 3.1 Cocksfoot (CF) and white clover (WC) contribution to total pasture yield from July 2011 to April 2012 of paddocks where the cocksfoot experiment was located. Sowing rates indicated are the rates of perennial ryegrass (RG), cocksfoot (CF) and white clover (WC) that were sown in October 2002. (Smith, Unpublished data).

<table>
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<th>Component</th>
<th>Sowing rate (kg/ha)</th>
<th>Component contribution to total yield (%)</th>
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<tr>
<td></td>
<td>RG:CF:WC</td>
<td>Jul-12</td>
</tr>
<tr>
<td>CF</td>
<td>0:2:2</td>
<td>30.6</td>
</tr>
<tr>
<td></td>
<td>5:2:2</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>10:2:2</td>
<td>29.3</td>
</tr>
<tr>
<td></td>
<td>15:2:2</td>
<td>30.7</td>
</tr>
<tr>
<td></td>
<td>10:0:2</td>
<td>8.2</td>
</tr>
<tr>
<td>WC</td>
<td>0:2:2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>5:2:2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>10:2:2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>15:2:2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>10:0:2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 3.1 Paddock plan of C9A(S) with sowing mixtures and sowing rates of perennial ryegrass, cocksfoot and white clover in October 2002. Grey areas indicate the strips where the two cocksfoot blocks were located.
### 3.3.2 Experiment 2 – Perennial ryegrass site

The perennial ryegrass experiment was located in the C9B(S) paddocks at Ashley Dene. In April 2008, these paddocks were sown in ‘Extreme’ AR37 perennial ryegrass and subterranean clover. The four paddocks were each split in two with two subterranean clover cultivars sown in each of the half-paddocks. Perennial ryegrass was sown at 15 kg/ha, and each subterranean clover cultivar at 10 kg/ha (Figure 3.2). The subterranean clover cultivars were ‘Woogenellup’, ‘Campeda’, ‘Denmark’ and ‘Goulburn’. The rough locations of the two perennial ryegrass blocks of this experiment are marked in shaded areas in Figure 3.2. A complete plan of the layout and dimensions of blocks and plots is given in Appendix 6.2.

Figure 3.2  Paddock plan for C9B(S) showing subterranean clover combinations. The grey areas indicate approximately where Blocks 1 and 2 of the perennial ryegrass experiment were located.

### 3.4 Experimental Design and Treatments

For this study a nitrogen experiment was overlain on each of the cocksfoot and perennial ryegrass pastures. Both experiments were in a randomised complete block design with 20 plots of cocksfoot and ryegrass allocated to two blocks in each experiment. There were
two replicates of each of five nitrogen treatments (0, 50, 100, 200 and 400 kg N/ha) in each block, giving a total of 40 plots. The 10 plots in each block were 2.5 x 10 m, giving a total experimental area of 50 m² per experiment.

### 3.4.1 Rotation 1

Experimental sites were marked out and mown with a Briggs & Stratton 650 Series Ready Start 190 cc Lawn Master push mower on 28 February 2012. Calcium-ammonium nitrate (CAN) fertiliser was applied by hand at rates of 0, 50, 100, 200 and 400 kg N/ha on 29 February 2012, which was therefore Day 0 of Rotation 1. Pasture mass was measured weekly with a Jenquip pasture capacitance probe to obtain between-harvest DM yields from calibrations obtained at each destructive harvest. The capacitance probe, however, experienced some interference with the magnetic fields of a main power line that runs across or close to all plots. There was therefore doubt over the accuracy of these values, and for this reason, only dry matter (DM) yields from destructive harvests were used in analyses.

Time Domain Reflectometry (TDR) stainless steel rods were inserted into each plot to a depth of 0.2 m. Weekly TDR soil moisture measurements were taken from 16 March to 10 July 2012. The time between measurements was extended during prolonged periods of rainfall (when soils were saturated and not yet drained to field capacity).

Five tillers per plot were marked for the measurement of leaf extension and leaf appearance on 6 March 2012. A 300 mm ruler was used to measure the length of each emerging leaf per marked tiller until the ligule became visible and no further extension of the leaf occurred. Leaf appearance was recorded at the emergence of each leaf from the pseudostem. Rotation 1 ended on 4 April, 35 days after the initial N application.
Plate 3.1 View of cocksfoot pasture being mown for the start of the first rotation on 28 February 2012.

Plate 3.2 View of ryegrass pasture being mown for the start of the first rotation on 28 February 2012.
3.4.2 Rotation 2
Plots were mown on 7 April 2012, and the second rotation was subsequently started. A rising plate meter (RPM) replaced the capacitance probe in Rotations 2 and 3. However, the herbage lodged from wet and windy conditions, and RPM measurements were inaccurate to determining pasture yields between harvests, so again only destructive harvest data were used. Leaf extension, leaf appearance and TDR measurements were taken as in Rotation 1, and destructive harvests performed on 25 April and 21 May. The rotation was ended on 24 May 2012, which was 85 days after the initial N application.

Plate 3.3 View of the ryegrass (Block 2) being mowed on 7 April 2012.

3.4.3 Rotation 3
Mowing for the start of the third rotation was on 25 May 2012. RPM and TDR measurements were taken at 14 to 28 day intervals because growth and development were slower as temperature declined (Figure 3.3a). Leaf extension and appearance measurements ceased at the end of Rotation 2. A destructive harvest occurred on 17
August 2012 with the help of four PLSC321 students, and marked the end of both Rotation 3 and the experiment, 170 days after the initial N application.

### 3.5 Soil Fertility

Two separate soil tests were taken, one for a general soil profile, and another to determine the mineral nitrogen content of each treatment. The first test was taken on 4 April 2012 to a depth of 75 mm with five cores sampled from each 0 kg N/ha treatment per block. Two samples of five cores in each block were then added together to give one sample per block. Results from the first soil test are presented in Table 3.2. The test indicated that magnesium (Mg) and sodium (Na) levels were lower than optimum in all blocks. However, plants are only Na-deficient when soil levels are ≤0.05 me/100 g (McLaren and Cameron, 2010). Soil Na levels in this study all exceeded 0.10 me/100 g. Magnesium deficiency in plants is only observed at soil Mg levels of ≤0.15 me/100g. In this study, soil Mg levels exceeded 0.60 me/100 g. The second test on 3 May 2012 took 10 soil cores per treatment to a depth of 75 mm in each block (five from each plot). Results from the second test are presented in Table 3.3. Soil mineral N data were provided as mg N/kg soil, and therefore converted to kg N/ha using Equation 3.1:

**Equation 3.1**

\[ N \text{ (kg/ha)} = N \text{ (mg/kg)} \times \text{sampling depth (cm)} \times \text{volume weight (g/mL)} \times 0.1 \]

### Table 3.2 Mineral N results of all N treatments for all cocksfoot and ryegrass blocks taken in May 2012 to a depth of 75 mm, from paddocks C9A and C9B at Ashley Dene Research Farm.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>CF block 1</th>
<th>CF block 2</th>
<th>RG block 1</th>
<th>RG block 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.5</td>
<td>5.5</td>
<td>5.6</td>
<td>4.8</td>
</tr>
<tr>
<td>50</td>
<td>6.1</td>
<td>8.3</td>
<td>11.2</td>
<td>5.6</td>
</tr>
<tr>
<td>100</td>
<td>5.3</td>
<td>6.2</td>
<td>9.1</td>
<td>8.8</td>
</tr>
<tr>
<td>200</td>
<td>17.4</td>
<td>28.3</td>
<td>30.0</td>
<td>35.3</td>
</tr>
<tr>
<td>400</td>
<td>60.6</td>
<td>72.5</td>
<td>46.0</td>
<td>129.2</td>
</tr>
</tbody>
</table>
Table 3.3 Soil test results of 0 kg N/ha treatments of each cocksfoot and ryegrass block taken in April 2012 to a depth of 75 mm, from paddocks C9A and C9B at Ashley Dene Research Farm.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Units</th>
<th>Optimum range</th>
<th>CF block 1</th>
<th>CF block 2</th>
<th>RG block 1</th>
<th>RG block 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td></td>
<td>5.8 - 6.2</td>
<td>5.8</td>
<td>6.1</td>
<td>5.7</td>
<td>5.8</td>
</tr>
<tr>
<td>Olsen P</td>
<td>mg/L</td>
<td>20 - 30</td>
<td>29</td>
<td>35</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>K</td>
<td>me/100 g</td>
<td>0.30 - 0.50</td>
<td>0.59</td>
<td>1.08</td>
<td>0.58</td>
<td>0.63</td>
</tr>
<tr>
<td>Ca</td>
<td>me/100 g</td>
<td>3.0 - 9.0</td>
<td>7.9</td>
<td>8.5</td>
<td>6.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Mg</td>
<td>me/100 g</td>
<td>1.00 - 1.50</td>
<td>0.72</td>
<td>0.95</td>
<td>0.62</td>
<td>0.61</td>
</tr>
<tr>
<td>Na</td>
<td>me/100 g</td>
<td>0.20 - 0.40</td>
<td>0.13</td>
<td>0.12</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>CEC</td>
<td>me/100 g</td>
<td>12 - 25</td>
<td>15</td>
<td>16</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Total base saturation</td>
<td>%</td>
<td>55 - 75</td>
<td>63</td>
<td>69</td>
<td>53</td>
<td>55</td>
</tr>
<tr>
<td>Volume weight</td>
<td>g/mL</td>
<td>0.60 - 1.00</td>
<td>1.01</td>
<td>0.92</td>
<td>0.93</td>
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</tr>
<tr>
<td>Mineral N</td>
<td>kg/ha</td>
<td>3.8</td>
<td>11.0</td>
<td>5.6</td>
<td>4.8</td>
<td></td>
</tr>
</tbody>
</table>

### 3.6 Meteorological Data

Meteorological data were measured on-site at Ashley Dene. Long-term monthly average air temperature and rainfall data were obtained from Broadfields meteorological station and were for the period of 1975-2009. The mean monthly air temperature of 2011 and 2012 followed the long-term trend (Figure 3.3a). For the experimental period (February 2012 to August 2012) the mean air temperature was 10.1 °C compared with the long term mean of 10.2 °C over the same months.

Seasonal rainfall distribution in 2011 and 2012 also followed the long-term trends (Figure 3.3b). For the experimental period (February 2012 to August 2012) rainfall totalled 366 mm, compared with a long-term mean of 386 mm. Annual rainfall from July 2011 to June 2012 totalled 619 mm, slightly less than the long-term mean of 630 mm.
Figure 3.3   Mean monthly (a) air temperature and (b) rainfall for 2011 (■) and 2012 (□) at Ashley Dene, Canterbury. Long term means (—) are for the period from 1975-2009, and were obtained from the Broadfields meteorological site, about 14 km north-east of the experiment site.
Plate 3.4  View from Plots 1 to 10 of perennial ryegrass Block 1 in C9B(S) Paddock 1 at Ashley Dene after a snow event on 6 June 2012.

3.7 Soil Moisture

Soil moisture content (%) to a depth of 0.2 m was measured weekly (except during periods of regular rainfall where soils were not drained to field capacity) with Time Domain Reflectometry (TDR). There were no differences among treatments in both the cocksfoot and perennial ryegrass experiments with the exception of cocksfoot on four occasions (30 March, 5 April, 4 May and 17 May). On these dates, the general trend was for the soil moisture content of the control (0 kg N/ha) and 50 kg N/ha treatment to be slightly higher than that of the 100 and 200 kg N/ha treatments, with 400 kg N/ha treatment moisture content being similar to all other treatments. Treatment means for soil moisture content (%) of cocksfoot are given in Appendix 6.3, and those for perennial ryegrass are given in Appendix 6.4. Soil moisture percentages were roughly 50% field capacity on 30 March to 5 April and 26 April to 24 May in both treatments (Figure 3.4).
Figure 3.4  Mean soil moisture content (%) across all cocksfoot (●) and perennial ryegrass (○) pastures treated with five rates of N (0, 50, 100, 200 and 400 kg N/ha). Rainfall (grey bars) is from 16 March to 10 July 2012.

Plate 3.5  View of TDR (Time Domain Reflectometer) used to measure soil moisture content.
3.8 Measurements

3.8.1 Dry matter (DM) production
DM cuts during destructive harvests were taken from 0.2 m² quadrats with electric shears to ground level. At each harvest, previously harvested areas were avoided as they remained visible for the duration of each rotation. Harvest areas were selected as representative areas of each plot. Samples were stored in a cooler at about 4 °C and processed within seven days of each harvest. During processing, sub-samples of the destructive harvests were sorted into their components (sown grass, white clover, subterranean clover, other grasses, other clovers, dead material and weeds). Sub-samples were obtained through thoroughly mixing the bulk sample and using a quartering method as described by Cayley and Bird (1996). Leaf or stem components that were >50% dead were included in the ‘dead’ fraction. These sub-samples were dried in a forced air oven for 48 hours at around 60 °C with the bulk sample, and then weighed. DM yield (kg/ha) was then calculated from the total sample weight of each plot using Equation 3.2. The sown grass and subterranean clover sub-samples were kept for nutritive value analysis. Sub clover samples were, however, too small to analyse through NIRS and these samples were therefore discarded.

Equation 3.2 \[ DM \text{ yield (kg/ha)} = \text{total sample DM (g/0.2 m}^2) \times 50 \]

The sample weight was multiplied by 50 as the sample weight was divided by 1000 g/kg to get the sample weight in kg. The quadrat size of 0.2 m² was multiplied by 50000 (1 ha = 10000 m² and 5 x 0.2 m² = 1 m²) to get a value in kg/ha. Therefore, 50000/1000 = 50.

3.8.2 Pasture composition
Pasture botanical composition was determined at every destructive harvest by sorting the sub-samples into the specified components. During weighing, each sorted component was weighed separately. Component weights were then added together to get a sub-sample weight which was used to determine the proportion of each component in the sample using Equation 3.3:

Equation 3.3 \[ \text{Component } \% = \frac{\text{weight of component in subsample (g)}}{\text{Total subsample weight (g)}} \times 100 \]
Plate 3.6 View of sorted sub-sample with four different components (subterranean clover, dead material, sown grass (ryegrass) and other grasses) of perennial ryegrass Plot 4 after a destructive harvest on 4 April 2012.

3.8.3 Nutritional and foliar analysis
Green cocksfoot and perennial ryegrass samples from botanical separations were used for nutritional analysis. Samples were ground to pass through a 1 mm stainless steel sieve and analysed by near infrared spectroscopy (NIRS). Protein content was used to determine the N% using Equation 3.4 and metabolisable energy (ME) content determined using Equation 3.5:

Equation 3.4 \[ N\% = \frac{CP}{6.25} \]

Equation 3.5 \[ \text{ME (MJ/kg DM)} = \frac{(\text{DMD} + 3) \times \text{OM}}{100 \times 0.16} \]
3.8.4 N and ME yields
N yield (kg/ha) of cocksfoot and perennial ryegrass pastures was determined using Equation 3.6:

\[
\text{Equation 3.6} \quad \text{N yield (kg/ha)} = \frac{\text{N}\% \times (\text{SG yield} + \text{OG yield} + \text{W yield})}{1000}
\]

Where SG is sown grass, OG is other grass and W is weed. Yield is in kg DM/ha and therefore N yield is calculated as g/ha, which is the reason for dividing the answer by 1000 to get N as kg/ha. It was assumed that the N% of other grasses and weeds was similar to the N% of the sown grass (Morris, 2011).

ME yield (GJ/ha) of cocksfoot and perennial ryegrass was determined using Equation 3.7:

\[
\text{Equation 3.7} \quad \text{ME yield (GJ/ha)} = \frac{\text{ME content (MJ ME/kg DM)} \times \text{SG yield (kg DM/ha)}}{1000}
\]

3.9 Water use efficiency
As an indication of the efficiency of use of moisture by the different treatments of cocksfoot and perennial ryegrass, total accumulated dry matter yield was divided by total potential evapotranspiration (PET) recorded at Broadfields from 29 February to 17 August.

3.10 Nitrogen cost analysis
An analysis based on the cost of urea fertiliser and the cost of cartage and spreading of the fertiliser on-farm was performed. Fertiliser costs were derived from the cost of urea purchased at $799/t urea (Ravensdown, 2012). As urea contains 46% nitrogen, the cost per tonne of N is $1737 or $1.74/kg of nitrogen. It therefore would cost a farmer $87/ha to apply 50 kg N/ha as urea, $174/ha to apply 100 kg N/ha, $348/ha to apply 200 kg N/ha and $696/ha 400 kg N/ha as urea. The cost of cartage and spreading was obtained from the 2008 Financial Budget Manual (Chaston, 2008). The charges for cartage and spreading from Boag Contracting in Rakaia were $11.50/ha for application rates up to 500 kg/ha, and $15.50/ha for rates exceeding 500 kg/ha. The total cost per hectare for the application of urea to achieve N rates of 50, 100, 200 and 400 kg N/ha would therefore be $98.50, $185.50, $359.50 and $711.50, respectively. These costs and yield responses per kg N
applied in each treatment were then used to determine which application rate(s) were the most cost-effective. To obtain the yield response for each treatment, the accumulated DM yield of the 0 kg N/ha control of each replicate from 29 February to 17 August was subtracted from the accumulated DM yield of each N treatment in each replicate.

### 3.11 Statistical Analyses

Data were analysed for each experiment, separately, in Genstat 14.0 in a generalised One-way ANOVA in randomised blocks where N fertiliser rate was the treatment (0, 50, 100, 200 or 400 kg N/ha). There were four replicates. Where ANOVA was significant, means were separated by Fisher’s protected least significant difference (LSD) at $\alpha = 0.05$.

Equation for yield accumulation (kg DM/ha) over time, total accumulated leaf extension per tiller (mm) over time and accumulated N yield (kg N/ha) over time were fitted using an exponential standard curve in Genstat.

Linear regression was used to quantify seasonal differences in the relationship between accumulated DM yield and accumulated thermal time (Tt). Coefficients for slopes of regressions fitted to the data of each plot were analysed by ANOVA.
4 RESULTS

4.1 Pasture Production

4.1.1 Total yield accumulation

4.1.1.1 Experiment 1 - Cocksfoot

The mean total accumulated dry matter production of cocksfoot pastures over three rotations differed (P<0.001) among all treatments. The average total DM accumulated over the 160 days of this experiment ranged from 0.81 t DM/ha (control – 0 kg N/ha) to 5.56 t DM/ha when 400 kg DM/ha was applied (Figure 4.1). The difference in DM production between the control and N-treated treatments was evident 21 days after N application. By Day 79, the 200 and 400 kg N/ha treatments had produced 4383 ± 250 kg DM/ha, which was higher (P<0.001) than all other treatments. The effect of N on DM production was still evident at the end of the third rotation (after 160 days of re-growth). The yield accumulation of the 400 kg N/ha treatment produced 870 kg DM/ha in Rotation 3. This was higher (P<0.001) than all other treatments. The 200 kg N/ha treatment produced 374 kg DM/ha and the control, 50 and 100 kg N/ha treatments 100 ± 44.5 kg DM/ha.
Figure 4.1  Accumulated yield of cocksfoot pastures under five nitrogen application rates of 0, 50, 100, 200 and 400 kg N/ha over time from nitrogen application on 29 February 2012 to the end of the experiment on 17 August 2012. Data points represent harvest dates and arrows indicate end of Rotations 1, 2 and 3. Error bars represent LSD values. Curve parameters and regressions are given in Appendix 6.5.

4.1.1.2  Experiment 2 – Perennial ryegrass

The mean accumulated DM production of perennial ryegrass pastures over three rotations was different (P<0.001) among all treatments with the exception that the control and 50 kg N/ha treatments were similar. The 400 kg N/ha treatment produced an average of 5.37 t DM/ha over the 160 days of re-growth. The control and 50 kg N/ha treatments produced 1.74 ± 0.25 t DM/ha. Differences were also evident by Day 21 when total yield accumulation averaged 1.20 ± 0.10 t DM/ha in the 100, 200 and 400 kg N/ha treatments. This was 66% greater than the dry matter accumulation of the 50 kg N/ha treatment (0.73 t DM/ha), which produced 0.36 t DM/ha more than the control. The effect of N on DM production was still evident at the end of the experiment when N was applied at rates of 100 kg N/ha and higher. The 400 kg N/ha treatment produced 942 kg DM/ha, the 200 kg N/ha treatment 357 kg DM/ha and the control, 50 and 100 kg N/ha treatments 174 ± 35.5 kg DM/ha in Rotation 3.
Figure 4.2  Accumulated yield of ryegrass pastures under five nitrogen application rates of 0, 50, 100, 200 and 400 kg N/ha over time from nitrogen application on 29 February 2012 to the end of the experiment on 17 August 2012. Data points represent harvest dates and arrows indicate end of Rotation 1, 2 and 3. Error bars represent LSD values. Curve parameters and regressions are given in Appendix 6.6.

4.1.2 Mean daily growth rates

4.1.2.1 Experiment 1 - Cocksfoot

N treatment affected the mean daily growth rates of cocksfoot pastures throughout the experimental period (Figure 4.3). On 21 March, the average growth rates of all N-treated plots were higher (P<0.001) than the growth rate of the control plots. By the end of the experiment (Day 160), the difference in average growth rate among N-treatments and the control had disappeared except for the 200 and 400 kg N/ha treatments. The mean growth rate of the control, 50 and 100 kg N/ha treatments from 25 May to 17 August was 1.2 ± 0.53 kg DM/ha/day compared with 4.4 and 10.4 kg DM/ha/day produced by the 200 and 400 kg N/ha treatments, respectively. The mean growth rate over 160 days of re-growth from 29 February 2012 to 17 August 2012 was different among all treatments. The mean growth rate over 160 days of re-growth was non-linear throughout the experiment, but increased with increasing N application rate, and ranged from 5.1 kg DM/ha/day (control) to 34.7 kg DM/ha/day (400 kg N/ha). The mean growth rate of the 50 kg N/ha treatment
was 15.0 kg DM/ha/day, the 100 kg N/ha treatment 20.7 kg DM/ha/day, and the 200 kg N/ha treatment 27.8 kg DM/ha/day.

**Figure 4.3** Pasture growth rates of cocksfoot pastures for the five nitrogen treatments (0, 50, 100, 200 and 400 kg N/ha) over the experimental period from 29 February 2012 to 17 August 2012. Arrows indicate end of Rotations 1, 2 and 3. Error bars represent LSD values at each destructive harvest.

**4.1.2.2 Experiment 2 – Perennial ryegrass**

The mean daily growth rates of perennial ryegrass pastures followed a similar pattern to the cocksfoot (Figure 4.4). All N-treated pastures produced more DM on a daily basis (P<0.001) than the control plots until 25 April. By the end of the experiment, only the 200 and 400 kg N/ha treatments had faster average growth rates than the control treatment. The mean growth rates of the control, 50 and 100 kg N/ha treatments in Rotation 3 (25 May to 17 August) was 2.1 ± 0.42 kg DM/ha/day, compared with 4.2 and 11.2 kg DM/ha/day produced by 200 and 400 kg N/ha treatments, respectively. The mean daily growth rates of pastures over the 160 days of the experiment (from 29 February to 17 August) were again non-linear and different (P<0.001) among treatments. The exception was the control and 50 kg N/ha treatments which had similar growth rates of 10.9 ± 1.57 kg DM/ha/day. The 100 kg N/ha treatment produced an average of 18.4 kg DM/ha/day,
while the 200 and 400 kg N/ha treatments produced an average of 24.9 and 33.6 kg DM/ha/day, respectively.

![Pasture growth rates of perennial ryegrass pastures for the five nitrogen treatments (0, 50, 100, 200 and 400 kg N/ha) over the experimental period from 29 February 2012 to 17 August 2012. Arrows indicate end of Rotations 1, 2 and 3. Error bars represent LSD values at each destructive harvest.](image)

**Figure 4.4** Pasture growth rates of perennial ryegrass pastures for the five nitrogen treatments (0, 50, 100, 200 and 400 kg N/ha) over the experimental period from 29 February 2012 to 17 August 2012. Arrows indicate end of Rotations 1, 2 and 3. Error bars represent LSD values at each destructive harvest.

### 4.1.3 Accounting for temperature effects through the use of thermal time

Thermal time (Tt) was accumulated over the experimental period using a base temperature of 3 °C and an optimum temperature of 23 °C for growth of both cocksfoot and perennial ryegrass (Mills, 2007).

#### 4.1.3.1 Experiment 1 – Cocksfoot

The yield accumulation of cocksfoot against thermal time (Tt, °Cd) shown in Figure 4.5 was different (P<0.001) among all treatments. The control accumulated 1.0 kg DM/ha/°Cd compared with 3.3 kg DM/ha/°Cd in the 50 kg N/ha treatment, 4.6 kg DM/ha/°Cd in the 100 kg N/ha treatment, 5.6 kg DM/ha/°Cd in the 200 kg N/ha treatment and 6.4 kg DM/ha/°Cd in the 400 kg N/ha treatment (Appendix 6.7) in Rotations 1 and 2. The data for regrowth after the destructive harvest to end Rotation 2 did not follow the
previous linear growth and was therefore excluded from the regression. The reason for this will be explained in the next chapter.

\[\text{Figure 4.5} \quad \text{Dry matter (DM) yield accumulation of cocksfoot pastures under 0, 50, 100, 200 and 400 kg N/ha against accumulated thermal time (Tt) with a base temperature of 3 °C for growth. Regression lines were fitted to data from Rotations 1 and 2 (---), and joined to Rotation 3 (--) without fitting a regression. Regressions are given in Appendix 6.7. Arrows indicate the end of Rotations 1, 2 and 3. Error bars represent LSD values at each destructive harvest.}\]

\[\text{4.1.3.2 Experiment 2 – Perennial ryegrass}\]

The DM accumulation of perennial ryegrass against Tt (Figure 4.6) was different among treatments. Mean yield accumulations were 1.5 kg DM/ha/°Cd in the control, 2.9 kg DM/ha/°Cd in the 50 kg N/ha treatment, 3.9 kg DM/ha/°Cd in the 100 kg N/ha treatment, 5.0 kg DM/ha/°Cd in the 200 kg N/ha treatment and 6.0 kg DM/ha/°Cd in the 400 kg N/ha treatment (Appendix 6.8) in Rotations 1 and 2. Again, regressions were only fitted to the end of Rotation 2.
4.1.4 Yield accumulation in relation to N application rate

4.1.4.1 Experiment 1 - Cocksfoot

The yield response of cocksfoot pastures achieved with the addition of nitrogen fertiliser, and the cost per kg of DM produced are presented in Table 4.1. The application of 50 kg N/ha resulted in a yield response of 31.8 kg DM/kg N applied. The 400 kg N/ha treatment achieved the lowest response with 11.9 kg DM produced per kg of N applied, based on the total costs. The total cost (Section 3.10) to produce one kilogram of dry matter was highest in the 400 kg N/ha treatment ($0.15/kg DM), followed by the 200 kg N/ha treatment ($0.10/kg DM). It was most cost-effective to apply between 50 and 100 kg N/ha as it cost $0.07 ± 0.008 to produce 1 kg of DM.
Table 4.1 Cocksfoot pasture yield response to nitrogen application, including the cost of urea per kg DM produced and total cost per kg DM produced.

<table>
<thead>
<tr>
<th>N application rate (kg N/ha)</th>
<th>Yield response (kg DM/kg N applied)</th>
<th>Fertiliser cost ($)/kg DM produced</th>
<th>Total cost ($)/kg DM produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>31.8 a</td>
<td>0.06 c</td>
<td>0.07 c</td>
</tr>
<tr>
<td>100</td>
<td>25.1 ab</td>
<td>0.07 c</td>
<td>0.07 c</td>
</tr>
<tr>
<td>200</td>
<td>18.2 bc</td>
<td>0.10 b</td>
<td>0.10 b</td>
</tr>
<tr>
<td>400</td>
<td>11.9 c</td>
<td>0.15 a</td>
<td>0.15 a</td>
</tr>
<tr>
<td>e.s.e.</td>
<td>2.87</td>
<td>0.008</td>
<td>0.008</td>
</tr>
</tbody>
</table>

4.1.4.2 Experiment 2 – Perennial ryegrass

The yield response of ryegrass pastures and the cost to produce 1 kg of DM are presented in Table 4.2. The 50 and 100 kg N/ha treatments produced $17.0 \pm 1.65$ kg DM/kg N applied. This was higher than the 10.0 kg DM produced by the 400 kg N/ha treatment per kg of N applied. The yield response of the 200 kg N/ha treatment was similar to all treatments. It was least cost effective to apply 400 kg N/ha as it cost $0.18$ to produce 1 kg DM compared with $0.12 \pm 0.009$/kg DM produced in the 50, 100 and 200 kg N/ha treatments.

Table 4.2 Ryegrass pasture yield response to nitrogen application, including the cost of urea per kg DM produced and total cost per kg DM produced.

<table>
<thead>
<tr>
<th>N application rate (kg N/ha)</th>
<th>Yield response (kg DM/kg N applied)</th>
<th>Fertiliser cost ($)/kg DM produced</th>
<th>Total cost ($)/kg DM produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>18.3 a</td>
<td>0.10 b</td>
<td>0.11 b</td>
</tr>
<tr>
<td>100</td>
<td>15.7 a</td>
<td>0.11 b</td>
<td>0.12 b</td>
</tr>
<tr>
<td>200</td>
<td>13.1 ab</td>
<td>0.12 b</td>
<td>0.12 b</td>
</tr>
<tr>
<td>400</td>
<td>10.0 b</td>
<td>0.18 a</td>
<td>0.18 a</td>
</tr>
<tr>
<td>e.s.e.</td>
<td>1.65</td>
<td>0.018</td>
<td>0.009</td>
</tr>
</tbody>
</table>

4.2 Leaf extension

4.2.1.1 Experiment 1 - Cocksfoot

The total accumulated leaf extension per cocksfoot tiller for Rotations 1 and 2 is presented in Figure 4.7. From Day 6 in Rotation 1 there were differences in accumulated leaf extension as the control (0 kg N/ha) treatment was shorter than all the N treatments. Total accumulated leaf extension of cocksfoot treatments by the end of Rotation 1 (over a 27-day period) were similar for 100, 200 and 400 kg N/ha treatments and averaged $564 \pm 30.9$...
mm. This was longer than both the control and 50 kg N/ha treatment which had mean accumulated leaf extensions of 260 and 358 mm. In Rotation 2, leaf extension was measured over 41 days. The mean accumulated leaf extension of the 200 and 400 kg N/ha treatments was 324 ± 23.3 mm which was longer (P<0.001) than the control, 50 kg N/ha and 100 kg N/ha treatments which had an average accumulated leaf extension of 166 ± 23.3 mm. The total accumulated leaf extension of cocksfoot tillers over 68 days (Rotations 1 and 2) was 911 ± 37.5 mm in the 200 and 400 kg N/ha treatments. This was longer (P<0.001) than the total accumulated leaf extension of the 100 kg N/ha treatment which had a mean leaf extension of 724 mm, and the control and 50 kg N/ha treatments which had a mean total accumulated leaf extension of 455 ± 37.5 mm over 68 days.

**Figure 4.7** Total accumulated leaf extension per tiller of cocksfoot pastures over time at different N application rates (0, 50, 100, 200 and 400 kg N/ha) during Rotations 1 (27 days) and 2 (41 days). Error bars represent LSD values at the end of each Rotation. Curve parameters and regressions are given in Appendix 6.9.

### 4.2.1.2 Experiment 2 – Perennial ryegrass

The total accumulated leaf extension per ryegrass tiller for Rotations 1 and 2 is presented in Figure 4.8. Differences between the accumulated leaf extension of the control treatment and the N treatments were evident from Day 9 in Rotation 1. The mean accumulated leaf extension per tiller over the 27-day period in Rotation 1 was longest in the 400 kg N/ha
treatment at 468 mm. The 100 kg N/ha treatment was similar to both 50 kg N/ha and 200 kg N/ha treatments, but longer than the 190 mm of extension per tiller in the control. Over 41 days in Rotation 2, the 400 kg N/ha treatment again had the longest leaf extension of 282 mm. Average accumulated leaf extension in the control treatment (132 mm) was shorter than all N treatments with the exception of the 50 kg N/ha treatment. The total accumulated leaf extension per tiller over 68 days (Rotations 1 and 2) was 750 mm in the 400 kg N/ha treatment. This was longer than the 543 ± 29.5 mm mean leaf extension of the 100 and 200 kg N/ha treatments and the 360 ± 29.5 mm mean leaf extension of the control and 50 kg N/ha treatments.

![Figure 4.8](image)

**Figure 4.8** Total accumulated leaf extension per tiller of ryegrass pastures over time at different N application rates (0, 50, 100, 200 and 400 kg N/ha) during Rotations 1 (27 days) and 2 (41 days). Error bars represent LSD values at the end of each Rotation. Curve parameters and regressions are given in Appendix 6.10.

### 4.3 Leaf appearance rates (phyllochron)

Leaf appearance per unit of thermal time was different (P<0.001) among treatments in cocksfoot and perennial ryegrass in Rotation 1. In cocksfoot, the fastest leaf appearance rate was 0.015 ± 0.0006 leaves/°Cd (100, 200 and 400 kg N/ha) and the slowest from the control at 0.010 leaves/°Cd (Figure 4.9a). In perennial ryegrass, leaf appearance rates
ranged from 0.008 leaves/°Cd (control) to 0.011 leaves/°Cd (400 kg N/ha) (Figure 4.9b). In Rotation 1, the phyllochron (calculated as 1/leaf appearance rate) decreased (P<0.001) with increasing N application rate for cocksfoot and perennial ryegrass. Cocksfoot required 69 °Cd for the production of one leaf in the 100, 200 and 400 kg N/ha treatments and 126 °Cd/leaf in the control. In perennial ryegrass the phyllochron ranged from 95 °Cd/leaf in the 400 kg N/ha treatment to 126 °Cd/leaf in the control.

In Rotation 2, leaf appearance rates were similar among treatments in cocksfoot and perennial ryegrass. Leaf appearance rates were low and the phyllochrons were close to 200 °Cd/leaf in cocksfoot and perennial ryegrass (Figure 4.10).

**Figure 4.9** Leaf appearance rate of (a) cocksfoot and (b) perennial ryegrass pastures at N application rates 0 kg N/ha (●), 50 kg N/ha (○), 100 kg N/ha (▼), 200 kg N/ha (△) and 400 kg N/ha (■) in Rotation 1. Error bars represent LSD values of the number of leaves per tiller at the end of Rotation 1. Regressions for cocksfoot are given in Appendix 6.11 and for perennial ryegrass in Appendix 6.12.
**Figure 4.10** Leaf appearance rate of (a) cocksfoot and (b) perennial ryegrass pastures at N application rates 0 kg N/ha (●), 50 kg N/ha (○), 100 kg N/ha (▼), 200 kg N/ha (△) and 400 kg N/ha (■) in Rotation 2. Error bars represent LSD values of the number of leaves per tiller at the end of Rotation 2. Regressions for cocksfoot are given in Appendix 6.13 and perennial ryegrass in Appendix 6.14.

**4.4 Pasture botanical composition**

**4.4.1 Pasture component yields**
The pasture component yields of cocksfoot and ryegrass pastures at different N application rates are shown in Figure 4.11.
Figure 4.11  Botanical composition of (1) cocksfoot and (2) ryegrass pastures with yields of each component illustrated at five nitrogen treatments (0, 50, 100, 200 and 400 kg N/ha) at the end of (a) Rotation 1, (b) Rotation 2 and (c) Rotation 3. Error bars represent LSD values for total DM yield at the end of each rotation.
4.4.1.1 **Sown grass**

In Experiment 1 (cocksfoot) there was no difference in sown grass as a proportion of total yield among treatments at the end of Rotations 1 and 2 (Figure 4.11), which shows grass responded equally in all treatments. Towards the end of Rotation 3 the sown grass proportion was higher (P<0.05) in the 400 kg N/ha treatment (74%) than in the control, 50 and 100 kg N/ha treatments, which were similar at 51 ± 5.2%. At the end of Rotation 1 (4 April 2012), the cocksfoot yield of all N treatments was, however, greater than the control (648 kg DM/ha). The 400 kg N/ha treatment (2240 kg DM/ha) also had a higher cocksfoot yield than the 50 kg N/ha treatment (1541 kg DM/ha). At the end of Rotation 2 (21 May 2012), the cocksfoot yield was highest in the 200 and 400 kg N/ha treatments with a mean cocksfoot yield of 1569 ± 101.4 kg DM/ha. The 100 kg N/ha treatment (1141 kg DM/ha) also had a higher cocksfoot yield than the control, but the cocksfoot yield of the 50 kg N/ha treatment was similar to the control (861 kg DM/ha). There was no difference in cocksfoot yield among the control, 50 and 100 kg N/ha treatments for Rotation 3. These three treatments yielded an average of 458 kg DM/ha in cocksfoot. The 200 and 400 kg N/ha treatments had mean cocksfoot yields of 850 and 1305 kg DM/ha.

In Experiment 2 (perennial ryegrass), the ryegrass yield in Rotation 1 was 2203 kg DM/ha in the 400 kg N/ha treatment. This was higher than all other treatments. The 50, 100 and 200 kg N/ha treatments yielded an average of 1367 ± 153.3 kg DM/ha which was higher (P<0.001) than the 416 kg DM/ha ryegrass yield of the control. The contribution of ryegrass to total pasture yield in the 50, 200 and 400 kg N/ha treatments (74 ± 4.8%) were similar and higher (P<0.05) than the control (54%). The contribution of ryegrass to total pasture yield in the 100 kg N/ha treatment was similar to the control, 100 and 200 kg N/ha treatments and less than the 400 kg N/ha treatment. In Rotation 2, the ryegrass yield in all treatments was higher than the control, except the 50 kg N/ha treatment which had a similar ryegrass yield to the control (791 ± 201.1 kg DM/ha). In the control treatment, the contribution of ryegrass to total pasture yield (50%) was lower than the 100, 200 and 400 kg N/ha treatments (77 ± 6.5%). The yield contribution of ryegrass in the 50 kg N/ha treatment was similar to all treatments. In Rotation 3, the 400 kg N/ha (1491 kg DM/ha) and 200 kg N/ha (660 kg DM/ha) treatments only had a higher ryegrass yield than the control treatment. The control, 50 and 100 kg N/ha treatments had a mean ryegrass yield of 350 ± 103.7 kg DM/ha. The contribution of ryegrass to total pasture yield was 80% in the 400 kg N/ha treatment and averaged 40 ± 8.2% for all other treatments.
4.4.1.2 *Subterranean clover*

In Experiment 1, it became evident during Rotation 3 that sub clover plants were infected with a fungus which caused death in the leaves and petioles of infected plants. Samples were analysed by PLANTwise Services Ltd in Lincoln. The causal fungus was diagnosed as Pepper Spot (*Leptosphaerulina trifolii*). Plate 4.1 shows an infected plant that was removed from the cocksfoot experimental area, as well as some ascospores removed from the perithecia on infected leaves.

![Illustrations of (a) a diseased sub clover plant and (b) ascospores from the Pepper Spot fungus.](image)

The subterranean clover yield in Experiment 1 (cocksfoot) was similar among all treatments in Rotation 1, and averaged $45 \pm 11.3$ kg DM/ha. In Rotation 2, there was again no difference in the sub clover yield among treatments, although there was an indication ($P=0.059$) that the average sub clover yield of the control at 30 kg DM/ha was higher than the $7 \pm 7.5$ kg DM/ha in all other treatments. The proportion of sub clover as a contribution to total pasture yield was, however, higher ($P<0.05$) at 3.1% in the control than the $0.01 \pm 0.73$% in the N treatments. In Rotation 3, the sub clover yield was low across all treatments and averaged $1 \pm 3.0$ kg DM/ha, due to the fungal infection.
In Experiment 2, the sub clover yield in Rotation 1 averaged 251 ± 66.7 kg DM/ha with no differences among treatments. The contribution of sub clover to total pasture yield was higher in the control (26%) than in the 100, 200 and 400 kg N/ha treatments (11 ± 3.3%). The contribution of sub clover to total pasture yield in the 50 kg N/ha treatment was similar to all treatments. In Rotation 2, the sub clover yield of all N treatments was similar (55 ± 52.1 kg DM/ha) but lower than the 374 kg DM/ha in the control. The contribution of sub clover to total pasture yield was highest in the control (24%). The mean contribution of sub clover to total pasture yield in the N treatments was 3 ± 2.9%. In Rotation 3, the sub clover yield was 307 kg DM/ha in the control. This was higher than the average of all the N treatments which had a mean sub clover yield of 25 ± 44.4 kg DM/ha. The contribution of sub clover to total pasture yield was again highest in the control (32%). The N treatments contained an average of 3 ± 4.2% sub clover.

4.4.1.3 Other grasses

The other grasses that were present in the pastures of Experiments 1 and 2 were the annual grasses annual poa (*Poa annua* L.) and hair grass (*Vulpia bromoides* L.). Perennial brome grasses (*Bromus* spp.) were also present in both Experiments, and the perennial ryegrass (*Lolium perenne* L.) found in the cocksfoot experiment were also classified as ‘other grasses’.

In Experiment 1, there was no difference in the yield of other grasses among treatments in Rotations 1, 2 and 3. The other grass yield components averaged 311 ± 123.7 kg DM/ha in Rotation 1, 218 ± 93.3 kg DM/ha in Rotation 2 and 72 ± 44.3 kg DM/ha in Rotation 3.

There was also no difference in the yield of other grasses among treatments in Rotations 1, 2 and 3 in Experiment 2. The mean other grass yields were 196 ± 97.8 kg DM/ha in Rotation 1, 162 ± 95.8 kg DM/ha in Rotation 2 and 152 ± 92.9 kg DM/ha in Rotation 3.

4.4.1.4 Weeds

There was no difference in weed yield among treatments in Experiment 1 in Rotations 1, 2 and 3. The mean weed yields were 21 ± 17.7 kg DM/ha in Rotation 1, 11 ± 10.8 kg DM/ha in Rotation 2 and 3 ± 2.7 kg DM/ha in Rotation 3.
In Experiment 2, there was again no difference in weed yield among treatments in Rotations 1, 2 and 3. The mean weed yields were 15 ± 13.7 kg DM/ha in Rotation 1, 8 ± 11.7 kg DM/ha in Rotation 2 and 2 ± 1.8 kg DM/ha in Rotation 3.

4.4.1.5 Dead matter
In the cocksfoot experiment, there was no difference in dead matter yield in Rotations 1, 2 and 3. The average dead yield across all treatments was 87 ± 30.2 kg DM/ha in Rotation 1, 272 ± 42.8 kg DM/ha in Rotation 2 and 358 ± 39.1 kg DM/ha in Rotation 3. In Rotation 3, however, the contribution of dead matter to total yield was higher (P<0.01) in the control, 50 and 100 kg N/ha treatments. Dead matter contributed an average of 42 ± 3.7% to total pasture yield in these three treatments, and 22 ± 3.7% to total pasture yield of the 200 and 400 kg N/ha treatments.

In the perennial ryegrass experiment, there was again no difference in dead matter in Rotations 1, 2 and 3. The mean yield in Rotation 1 was 107 ± 22.8 kg DM/ha, Rotation 2 240 ± 35.0 kg DM/ha and 335 ± 47.2 kg DM/ha in Rotation 3. In Rotation 2, dead matter contributed an average of 11 ± 2.0% to total pasture yield, which was lower than the contribution of dead matter to the total yield of the control pastures (20%). In Rotation 3, dead matter contributed 41 ± 3.8% to total pasture yield of the 50 and 100 kg N/ha treatments. In the control, 200 and 400 kg N/ha treatments, dead matter contributed 22 ± 3.8% to total pasture yield.

4.5 Nutritive value

4.5.1 Nitrogen content

4.5.1.1 Experiment 1 – Cocksfoot
The N content of cocksfoot in Rotations 1 and 2 increased (P<0.001) with increasing N application rate. At the end of Rotation 1, the N content of the control was 2.7%, which was lower than all N treatments. The 400 kg N/ha treatment had the highest N content of 4.4%. At the end of Rotation 2, the N content of the control was again lower than all N treatments at 1.8% N. The N content of the 50 and 100 kg N/ha treatments was 2.3 ± 0.09% N. The highest N was 3.3% in the 400 kg N/ha treatment. By the end of the
experiment (17 August) the N content of the 400 kg N/ha treatment (4.1%) was highest (P<0.01) and all other treatments were similar (3.4 ± 0.10%).

4.5.1.2 Experiment 2 – Perennial ryegrass
In Rotations 1 and 2, the N content of perennial ryegrass pastures tended to increase (P<0.001) with increasing N application rate. By the end of Rotation 1, the control had the lowest N content at 2.1%. The 50 and 100 kg N/ha treatments had an N% of 2.7 ± 0.13%, and the 200 and 400 kg N/ha treatments 3.5 ± 0.13% N. By the end of Rotation 3 the control had the lowest N (2.3%), while the 100, 200 and 400 kg N/ha treatments had a similar N content of 4.3 ± 0.19%. At the end of Rotation 3, the only difference in N content among treatments was that the 400 kg N/ha treatment (4.3%) had a higher (P<0.01) N content than all other treatments, which had a similar N content (3.2 ± 0.20%).

4.5.2 Pasture metabolisable energy content
4.5.2.1 Experiment 1 - Cocksfoot
The metabolisable energy content of cocksfoot pastures was similar among all treatments on all harvest dates throughout the measurement period, except on 25 April (Figure 4.12). The ME content of the 50 kg N/ha treatment was lower than all other treatments except the 100 kg N/ha treatment. At this time the control, 100, 200 and 400 kg N/ha treatments had a similar ME content of 11.0 ± 0.10 MJ/kg DM.

Pasture ME differed (P<0.001) across harvest dates. The mean ME across all treatments was similar in early autumn (21 March) and winter (21 May) at 11.5 ± 0.06 MJ ME/kg DM. ME in late autumn (25 April) was lower at 11.0 MJ ME/kg DM. ME was lowest in spring with a mean content of 10.4 MJ ME/kg DM.
Figure 4.12 Metabolisable energy (ME) content (MJ/kg DM) of cocksfoot grass at five harvest dates (21 March, 4 April, 25 April, 21 May and 17 August) in 2012 under five nitrogen treatments (0, 50, 100, 200 and 400 kg N/ha). Error bars represent LSD values at each harvest date.

4.5.2.2 Experiment 2 – Perennial ryegrass

The ME content of ryegrass pastures was similar among treatments on the 21 March and 4 April harvest dates (Figure 4.13). On 25 April it appeared that ME decreased with increased N application rate. The control, 50 and 100 kg N/ha treatments had a higher ME content than the 200 kg N/ha treatment. The ME of the 400 kg N/ha treatment was similar to that of the 50, 100 and 200 kg N/ha treatments, but lower than the control. On 21 May, the ME content of the control, 50 and 100 kg N/ha treatments was similar (12.4 ± 0.08 MJ ME/kg DM) and higher than the 200 and 400 kg N/ha treatments (11.9 ± 0.08 MJ ME/kg DM).

There was again a tendency (P<0.001) for the pasture ME to decrease into late autumn, increase into winter and then decline again into spring. The mean ME content of all treatments was similar on 21 March and 25 April at 11.6 ± 0.08 MJ ME/kg DM. On 4 April and 21 May, the mean pasture ME was higher than on all other dates at 12.1 ± 0.08 MJ ME/kg DM. Pasture ME was lowest on 17 August at 10.8 MJ ME/kg DM.
Metabolisable energy accumulation

The mean accumulated metabolisable energy (GJ ME/ha) and accumulated protein (kg/ha) of cocksfoot and perennial ryegrass pastures are given in Table 4.3.

The accumulated ME/ha increased with increasing N application rate. In cocksfoot, all N treatments accumulated more ME than the control. The 400 kg N/ha treatment had the highest accumulated ME over the experimental period from 29 February to 17 August. It accumulated 62 GJ ME/ha compared with the control which accumulated 24 GJ ME/ha. For perennial ryegrass, the control accumulated less ME than all treatments except for the 50 kg N/ha treatment which accumulated a similar amount of ME (30 ± 4.2 GJ ME/ha) over the experimental period. The 400 kg N/ha treatment had the highest ME accumulation of 68.7 GJ ME/ha.
Table 4.3 Accumulated metabolisable energy and protein yields of cocksfoot and ryegrass at different N application rates (0, 50, 100, 200 and 400 kg N/ha). Values with different letter subscripts are significantly different ($\alpha = 0.05$).

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>ME (GJ/ha)</th>
<th>Protein (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cocksfoot</td>
<td>Ryegrass</td>
</tr>
<tr>
<td>0</td>
<td>24.2&lt;sub&gt;d&lt;/sub&gt;</td>
<td>23.9&lt;sub&gt;d&lt;/sub&gt;</td>
</tr>
<tr>
<td>50</td>
<td>36.8&lt;sub&gt;c&lt;/sub&gt;</td>
<td>36.4&lt;sub&gt;cd&lt;/sub&gt;</td>
</tr>
<tr>
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<td>47.0&lt;sub&gt;b&lt;/sub&gt;</td>
<td>42.0&lt;sub&gt;bc&lt;/sub&gt;</td>
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<tr>
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<td>53.8&lt;sub&gt;b&lt;/sub&gt;</td>
<td>53.0&lt;sub&gt;b&lt;/sub&gt;</td>
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<td>61.7&lt;sub&gt;a&lt;/sub&gt;</td>
<td>68.7&lt;sub&gt;a&lt;/sub&gt;</td>
</tr>
<tr>
<td>e.s.e.</td>
<td>2.39</td>
<td>4.16</td>
</tr>
</tbody>
</table>

4.5.4 Accumulated nitrogen yield

4.5.4.1 Experiment 1 - Cocksfoot

N accumulation increased over time and with increasing N application rate (Figure 4.14). By 21 March (Day 21), all treatments had accumulated more N than the control, and the 100 and 400 kg N/ha treatments had accumulated more N than the 50 kg N/ha treatment. The 200 kg N/ha treatment had accumulated a similar amount of N as the 50, 100 and 400 kg N/ha treatments. By 4 April (Day 35), all the N treatments had accumulated more N than the control. The 100, 200 and 400 kg N/ha treatments had also accumulated more N than the 50 kg N/ha treatment. On 21 May (Day 82), the 400 kg N/ha treatment had the highest N accumulation (151 kg N/ha), followed by 100 and 200 kg N/ha which had accumulated 114 ± 7.9 kg N/ha. The 50 kg N/ha treatment (75 kg N/ha) also had a higher N accumulation than the control (34 kg N/ha). The N accumulation by the end of the experimental period of 170 days (on 17 August) was different among treatments. The 400 kg N/ha treatment accumulated the largest amount of N (221 kg N/ha) during the experiment, while the control accumulated the least amount of N (58 kg N/ha). Thus, the 50 kg N/ha treatment recovered 44 kg N/ha, the 100 kg N/ha treatment recovered 75 kg N/ha, the 200 kg N/ha treatment recovered 109 kg N/ha and the 400 kg N/ha treatment recovered 163 kg N/ha. Recovery data are presented in Table 4.4.
Table 4.4 Total accumulated N (kg N/ha) of all treatments (0, 50, 100, 200 and 400 kg N/ha) and percentage retrieval of applied N of each N treatment (50, 100, 200 and 400 kg N/ha) up to the end of Rotation 3 (17 August 2012). Values with different letter subscripts are significantly different ($\alpha = 0.05$).

<table>
<thead>
<tr>
<th>N applied (kg N/ha)</th>
<th>Accumulated N (kg/ha)</th>
<th>% N retrieved</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cocksfoot</td>
<td>Ryegrass</td>
</tr>
<tr>
<td>0</td>
<td>58 e</td>
<td>53 c</td>
</tr>
<tr>
<td>50</td>
<td>102 d</td>
<td>77 c</td>
</tr>
<tr>
<td>100</td>
<td>133 c</td>
<td>93 c</td>
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<tr>
<td>200</td>
<td>167 b</td>
<td>140 b</td>
</tr>
<tr>
<td>400</td>
<td>221 a</td>
<td>217 a</td>
</tr>
<tr>
<td>e.s.e.</td>
<td>7.3</td>
<td>13.3</td>
</tr>
</tbody>
</table>

Figure 4.14 Accumulated nitrogen (N) yield (kg N/ha) of cocksfoot over time across five treatments (0, 50, 100, 200 and 400 kg N/ha). Error bars represent LSD values at four harvest dates. Curve parameters and regressions are given in Appendix 6.15.

4.5.4.2 Experiment 2 – Perennial ryegrass

As expected the N accumulation of ryegrass pasture was also higher with increasing N application rate (Figure 4.15). By the end of the 170-day experimental period (17 August),
the control, 50 and 100 kg N/ha treatments had accumulated a similar amount of N (Table 4.4). The 400 kg N/ha treatment had accumulated the highest N yield at 217 kg N/ha. The retrieval of applied N was 24 kg N/ha in the 50 kg N/ha treatment, 40 kg N/ha for the 100 kg N/ha treatment, 87 kg N/ha for the 200 kg N/ha treatment and 164 kg N/ha for the 400 kg N/ha treatment.

![Figure 4.15](Accumulated nitrogen (N) yield (kg N/ha) of ryegrass over time across five treatments (0, 50, 100, 200 and 400 kg N/ha). Error bars represent LSD values at four harvest dates. Curve parameters and regressions are given in Appendix 6.16.)

### Figure 4.15
Accumulated nitrogen (N) yield (kg N/ha) of ryegrass over time across five treatments (0, 50, 100, 200 and 400 kg N/ha). Error bars represent LSD values at four harvest dates. Curve parameters and regressions are given in Appendix 6.16.

#### 4.5.5 Nitrogen retrieval
It was assumed that the 0 kg N/ha treatment represent N in the soil available to the pasture from animal returns and mineralisable soil N. These values were therefore subtracted from the retrieved N values of the N treatments to determine the percentage of applied N that was retrieved. The mean accumulated N and the percentage of applied N retrieved by cocksfoot and ryegrass pastures are given in Table 4.4.
In the cocksfoot, the 50 kg N/ha treatment recovered a higher percentage of applied N than the 200 and 400 kg N/ha treatments. The 100 kg N/ha treatment also retrieved a higher proportion of applied N than the 400 kg N/ha treatment. The 50 kg N/ha treatment recovered 88% of applied N, which was more than the 41% retrieved by the 400 kg N/ha treatment.

There was no difference in the percentage of applied N retrieved by the different ryegrass treatments. The mean retrieval of applied N was 43 ± 9.6% across all N treatments.

4.5.6 Water use efficiency
Water use efficiency (WUE) increased (P<0.001) with increasing N application rate for cocksfoot and perennial ryegrass (Table 4.5). The exception was that the WUE of perennial ryegrass with 50 kg N/ha added was 8.0 ± 1.15 kg DM/ha/mm PET which was similar to the control. The highest WUE in perennial ryegrass was 24.7 kg DM/ha/mm PET in the 400 kg N/ha treatment. In cocksfoot, the lowest WUE was 3.7 kg DM/ha/mm PET (control) and the highest was 25.5 kg DM/ha/mm PET (400 kg N/ha).

Table 4.5 Water use efficiency (WUE – kg DM/ha/mm PET) of cocksfoot and perennial ryegrass pastures at five rates of N (0, 50, 100, 200 and 400 kg N/ha) over the experimental period (29 February to 17 August 2012). Values with different letter subscripts are significantly different (α = 0.05).

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>WUE (kg DM/ha/mm PET)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cocksfoot</td>
<td>P. ryegrass</td>
</tr>
<tr>
<td>0</td>
<td>3.7 e</td>
<td>6.3 d</td>
</tr>
<tr>
<td>50</td>
<td>11.0 d</td>
<td>9.7 d</td>
</tr>
<tr>
<td>100</td>
<td>15.2 c</td>
<td>13.5 c</td>
</tr>
<tr>
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5 DISCUSSION

The objective of this study was to quantify the effects of autumn nitrogen fertilisation on the yield, quality and composition of cocksfoot and perennial ryegrass pastures.

5.1 Dry matter production

The maximum yield of both cocksfoot (5.6 t DM/ha) (Figure 4.1) and perennial ryegrass (5.4 t DM/ha) (Figure 4.2) was achieved with the addition of 400 kg N/ha as a single application in autumn. Control pastures produced 15% (cocksfoot – 0.8 t DM/ha) and 26% (perennial ryegrass – 1.37 t DM/ha) of the potential at 400 kg N/ha. The mean pasture growth rates over 160 days of re-growth were highest in the 400 kg N/ha treatments in both experiments. For cocksfoot it ranged from 5.1 kg DM/ha/day (control) to 34.7 kg DM/ha/day (400 kg N/ha) (Figure 4.3). In perennial ryegrass, mean pasture grow rates over 160 re-growth days from 29 February to 17 August was 10.9 ± 1.57 kg DM/ha/day (control and 50 kg N/ha) to 33.6 kg DM/ha/day (400 kg N/ha) (Figure 4.4). The fact that the average growth rate over the experimental period and the accumulated DM yield of perennial ryegrass pastures with the addition of 50 kg N/ha was similar to the control suggests that N application rates in excess of 50 kg N/ha were required to achieve an economic response in DM production. The minimum growth rates by the controls in both experiments were similar to those reported by Brown et al. (2006) (<10 kg DM/ha/day) over a similar period for cocksfoot and perennial ryegrass pastures with a clover component.

In Rotation 3, the DM production of the control, 50 and 100 kg N/ha treatments of perennial ryegrass were similar (174 ± 35.5 kg DM/ha), while the 200 kg N/ha treatment produced 357 kg DM/ha and the 400 kg N/ha treatment produced 942 kg DM/ha. In cocksfoot, the DM production of the control, 50 and 100 kg N/ha treatments were again similar (100 ± 44.5 kg DM/ha). The 200 kg N/ha treatment produced 374 kg DM/ha and the 400 kg N/ha treatment produced 870 kg DM/ha. This suggests that there was a carry-over effect of N into winter through autumn applications exceeding 200 kg N/ha in both cocksfoot and perennial ryegrass pastures. This is in agreement with reports by Peri et al. (2002a) that N depositions of 173 kg N/ha in autumn and winter as urine resulted in yield responses in cocksfoot pastures for 133 days. In the present study, the response appeared to last in excess of 160 days at applications of 200 and 400 kg N/ha. Yield responses into
and beyond winter are explained by soil test results in May (Table 3.2). These showed that the mineral N content of the soil was below 10 kg N/ha for the control, 50 and 100 kg N/ha treatments. The exception was the 50 kg N/ha perennial ryegrass treatment in Block 1 which had an N content of 11.2 kg N/ha. In contrast, the soil mineral N content of 200 and 400 kg N/ha treatments were in excess of 30 kg N/ha except the 200 kg N/ha cocksfoot treatments in Blocks 1 (17 kg N/ha) and 2 (28 kg N/ha), but these were nevertheless higher than the lower N treatments. In other words, the application of 200 and 400 kg N/ha in February resulted in N still being available in May and this was used by pastures in the 200 and 400 kg N/ha treatments for increased winter DM production.

5.1.1 Explaining increases in dry matter
The majority of the cocksfoot DM was accumulated in Rotation 1. During this period, DM yields were 464 kg DM/ha (control), 1487 kg DM/ha (50 kg N/ha), 2006 kg DM/ha (100 kg N/ha), 2332 kg DM/ha (200 kg N/ha) and 2648 kg DM/ha (400 kg N/ha). Increased N availability results in increased leaf extension and increased foliar N content which allows for increased rates of photosynthesis. Leaf extension results in an increased leaf area index, which results in increased light interception for an increase in radiation use efficiency (Section 2.3.1). Increased DM accumulation through the addition of N fertiliser was therefore the combined effect of an increase in leaf extension and an increase in photosynthesis (as a result of an increased foliar N content). To establish which of these had the largest impact on DM production, leaf N% and leaf extension data were used. Leaf N content of cocksfoot pastures were increased from 2.7% (control) to 3.4% in the 50 kg N/ha treatment in Rotation 1. Using the relationship between photosynthesis and foliage N content (Figure 2.3) published by Peri et al. (2002b) as a guide, it was established that this increase in foliage N% would have resulted in an increase in net photosynthetic rate from about 70% of maximum photosynthesis to about 80% of the maximum (a 14% increase). At the same stage, leaf extension was increased from 260 mm/tiller in the control to 358 mm/tiller in the 50 kg N/ha treatment (a 38% increase) (Figure 4.7). An increase in leaf extension resulted in an increase in light interception as there were larger leaves to cover a larger proportion of ground area. As the increase in leaf extension was larger than the increase in leaf N%, it is likely that an increase in leaf extension and therefore an increase in light interception had a larger contribution to the 220% increase in DM production than the increase in foliar N%. There was no difference between the yield of the 50 kg N/ha treatment and the 100 kg N/ha treatment. The yield
increase from 50 kg N/ha to 200 kg N/ha (1487 to 2332 kg DM/ha) resulted from an increase in foliar N from 3.4% to 3.8%, equivalent to an increase from about 80% to 83% net photosynthesis, and leaf extension of 358 mm to 590 mm/tiller. Once again, increases in leaf extension and light interception had the largest impact on the observed increase in DM yield. Figure 2.3 illustrates that, once foliar N content reached around 3.5% (35 g N/kg DM), there was little increase in the rate of photosynthesis with a further increase in foliar N content.

Perennial ryegrass DM yield was increased from 508 kg DM/ha in the control to 1396 kg DM/ha with the addition of 50 kg N/ha in Rotation 1. Foliar N content during this period was 2.1% in the control and 2.6% in the 50 kg N/ha treatment. This increase in foliar N% would have resulted in an increase in the net photosynthesis rate from about 50% to about 70%, and an increase in leaf extension from 150 mm/tiller to 208 mm/tiller (Figure 4.8). Thus, the 175% increase in DM production was the result of a 40% increase in photosynthesis rate and 39% increase in leaf extension. So, an increase in foliar N content and leaf extension (light interception) through the addition of 50 kg N/ha contributed about equally to the observed increase in DM production. The relatively large contribution of an increase in foliar N% to the increase in DM production was due to the N% being below 3.5% and therefore an increase in foliar N content resulted in a relatively linear increase in photosynthesis rate. Once again, there was no difference between the yields of the 50 and 100 kg N/ha treatments. The difference in DM yield between the 50 kg N/ha and the 200 kg N/ha treatments was the result of an increase in foliar N content from 2.6% to 3.3% (from about 70% to 78% photosynthesis rate) and a leaf extension increase from 208 mm/tiller to 285 mm/tiller. As with cocksfoot, the increase in DM yield through an increase in N application rate from 50 kg N/ha to 200 kg N/ha resulted largely from an increase in leaf extension (37%) and therefore increased light interception rather than an increase in N% and photosynthesis rate (11% increase).

In cocksfoot, total accumulated leaf extension over 68 days was similar between the control and the 50 kg N/ha treatment (455 ± 37.5 mm/tiller). The addition of a further 50 kg N/ha (100 kg N/ha treatment) resulted in a 59% increase in leaf extension. The addition of 200-400 kg N/ha resulted in a 100% increase in leaf extension beyond the leaf extension achieved through the addition of 0-50 kg N/ha. In perennial ryegrass, total accumulated leaf extension was again similar between the control and 50 kg N/ha treatment (360 ± 29.5
mm/tiller). With the application of 100-200 kg N/ha, leaf extension was increased by 51%, and the addition of 400 kg N/ha resulted in an increase of 108% in leaf extension. The increases in leaf extension over 68 days of measurement for cocksfoot and perennial ryegrass were similar to the 36-140% increases in leaf extension in spring through the addition of 210 kg N/ha reported by Belanger (1998).

In Rotation 1, an increase in leaf appearance rate also contributed to increased DM production. Leaves appeared at a faster rate in high N treatments (100, 200 and 400 kg N/ha) in cocksfoot which, coupled with increased leaf extension, resulted in increased herbage production. These data suggest that leaf appearance is not exclusively a developmental process, but includes an element of growth. A phyllochron of 69 °Cd/leaf appeared to be the fastest achieved through the addition of N fertiliser as the leaf appearance of the 400 kg N/ha treatment did not exceed that of the 100 and 200 kg N/ha treatments (Figure 4.9). In perennial ryegrass, the lowest phyllochron (95 °Cd/leaf) was achieved with the application of 400 kg N/ha. At this stage, the N content of perennial ryegrass herbage in the 400 kg N/ha treatment was 3.5%, suggesting that further N applications were unlikely to result in a further increase in perennial ryegrass leaf appearance rate as N was non-limiting. However, regression lines did not fit the data points well. Figure 5.1 was constructed by excluding the last two data points from the regression, and fits were improved. The two data points that were excluded corresponded to a period (end March/early April) when moisture levels dropped to 11-15% (Figure 3.4). This suggests that leaf appearance was limited by moisture stress during that period, and not N level.
Figure 5.1  Leaf appearance rate of perennial ryegrass pastures at five rates of N application (0, 50, 100, 200 and 400 kg N/ha) in Rotation 1 with regressions fitted to data excluding the last two data points. The error bar represents the LSD value of the number of leaves per tiller at the end of Rotation 1. Regressions are given in Appendix 6.17.

In Rotation 2, leaf appearance rates were similar among treatments for both cocksfoot and perennial ryegrass (Figure 4.10). Leaf numbers were low in all treatments and did not exceed two leaves per tiller. Cao and Moss (1989) reported that the leaf appearance rate of wheat and barley decreased with decreasing daylength. The phyllochron was on average 42% higher with a daylength of 8 hours than when the daylength was 24 hours. Thus, the reduced rates of leaf appearance in the present study were likely the result of reduced photoperiod (daylength) during late autumn/early winter.

5.1.2 Seasonal growth patterns
Seasonal differences in growth were evident. The maximum cocksfoot growth rate of 75.7 kg DM/ha/day was achieved in the 400 kg N/ha treatment from 21 March to 4 April (Figure 4.3). The lowest growth rate in cocksfoot was 1.2 ± 0.53 kg DM/ha/day (control, 50 kg N/ha and 100 kg N/ha) from 21 May to 17 August. This was similar to growth rates reported by Mills et al. (2006). The growth rate of dryland cocksfoot without N application was lowest (<10 kg DM/ha) from June to August in 2004 and from April to
August 2005 when rainfall during autumn was lower than in 2004. The maximum growth rate achieved in their study was about 70 kg DM/ha/day from April to May with the addition of 800 kg N/ha in eight applications of 100 kg N/ha. At this stage of the experiment, 500 kg N/ha had been applied from 29 September 2003 to April 2004. The growth rate achieved from March to April was similar to the maximum growth rate over the same period in the current study with the application of 400 kg N/ha.

In perennial ryegrass, the maximum growth rate of 72.6 kg DM/ha/day (400 kg N/ha) was achieved from 21 March to 4 April, and the lowest was 2.1 ± 0.42 kg DM/ha/day from 21 May to 17 August (Figure 4.4). The growth rates of unfertilised control pastures were similar to reports by Li et al. (2011). They also reported that the mean growth rate of pastures in dryland Canterbury with low inputs range from <5 kg DM/ha/day in winter to a maximum of about 40 kg DM/ha/day in spring and summer. In autumn, their growth rates tended to be around 20 kg DM/ha/day.

5.1.3 Water use efficiency

The application of nitrogen resulted in cocksfoot and perennial ryegrass pastures utilising available moisture more efficiently (Table 4.5). In cocksfoot, the WUE increased with increasing N application rate and ranged from 4 kg DM/ha/mm PET (control) to 26 kg DM/ha/mm PET (400 kg N/ha). These values were lower than the 17 kg DM/ha/mm (dryland with no N fertiliser) and 38 kg DM/ha/mm (dryland with 300 kg N/ha) reported by Moot et al. (2008). In perennial ryegrass the WUE also increased with increasing N application rate, and ranged from 8.0 ± 1.2 kg DM/ha/mm PET (control and 50 kg N/ha) to 25 kg DM/ha/mm PET (400 kg N/ha). Moot et al. (2008) reported the WUE of perennial ryegrass without N fertilisation as 15 kg DM/ha/mm which was again higher than the results of the present study. The WUE in the present study were calculated using PET as an indication of water use, while Moot et al. (2008) measured actual water use. The WUE of the present study was also a measure of the autumn, winter and early spring (29 February to 17 August) average, while Moot et al. (2008) reported the spring WUE. WUE in spring is often higher than other times of the year as neither moisture nor temperature are limiting to pasture growth (Tonmukayakul, 2009). WUE values of cocksfoot/white clover in Canterbury in autumn and winter were reportedly 7 kg DM/ha/mm PET and 15 kg DM/ha/mm PET (114% higher) in spring (Tonmukayakul, 2009). In the same experiment, perennial ryegrass/white clover pasture used water at an efficiency of 5 kg
DM/ha/mm PET in autumn and winter and 14 kg DM/ha/mm PET (180% higher) in spring, illustrating the seasonal differences. In autumn growth is often limited by moisture stress and in winter by temperature which results in lower WUE.

5.2 Temperature and moisture effects

To eliminate the effects of temperature on pasture growth, pasture yields were regressed against thermal time (Tt). Cocksfoot growth rates ranged from 1.0 kg DM/°Cd (control) to 6.4 kg DM/°Cd (400 kg DM/ha) (Figure 4.5) in Rotations 1 and 2. Rotation 3 data points were excluded as the regression fitted with these points included did not fit well. It was established that this was the result of the removal of all herbage as treatments were mown on 25 May 2012. Mowing or grazing of pastures results in the removal of leaf area. As a result, pastures go through a lag phase of relatively slow growth (Valentine and Matthew, 2008). As this occurred during winter after mowing in May, the rate of pasture growth was limited by light interception as leaf appearance was also likely reduced as a result of reduced daylength (as discussed in Section 5.1.1). Mills et al. (2006) reported that dryland cocksfoot with no nitrogen fertilisation produced 3.3 kg DM/ha/°Cd and 7.0 kg DM/ha/°Cd when 800 kg N/ha was added (drought periods were excluded). These were higher than in the present study, especially at the 0 kg N/ha rates. It is likely that soils in the present study were more N deficient (mean mineral N of 6.3 kg N/ha) than soils in the study by Mills et al. (2006), as their background soil N was 95 kg N/ha before the start of the experiment. Spring growth rates of cocksfoot/sub clover pastures have been reported as 5.9 kg DM/ha/°Cd (Tonmukayakul, 2009). This was higher than the growth rates of the control, 50 and 100 kg N/ha treatments, similar to the 5.6 kg DM/ha/°Cd in the 200 kg N/ha treatment and lower than the 6.4 kg DM/ha/°Cd produced by the 400 kg N/ha treatment in the present study. Pastures in the study by Tonmukayakul (2009) had adequate moisture available during the period from July to November (>25%). In both these studies (by Mills et al. (2006) and Tonmukayakul (2009)), moisture was non-limiting to DM production, while pastures in the present study were occasionally subjected to short periods (maximum 8 days) of moisture deficits (11-12% moisture content) during April and May (Figure 3.4) which likely resulted in reduced growth/°Cd. Soil moisture in the present study did, however, not drop below the permanent wilting point of around 10% reported by Stoker (1975).
Perennial ryegrass growth rates ranged from 1.5 kg DM/ha/°Cd (control) to 6.0 kg DM/ha/°Cd (400 kg N/ha) (Figure 4.6) in Rotations 1 and 2. Once again data from Rotation 3 were excluded from the regression as low leaf area in Rotation 3, the result of herbage removal at the end of Rotation 2 (25 May), limited growth. The growth rates during Rotations 1 and 2 were lower than those reported by Fasi et al. (2008) (Section 2.4). They reported spring ryegrass growth rates at Lees Valley, Canterbury, of 2.5-4.2 kg DM/ha/°Cd when no N was applied and 8.3-10.3 kg DM/ha/°Cd when 150 kg N/ha was applied. The cocksfoot growth rates at Lees Valley were also higher than the present study at 3.1 kg DM/ha/°Cd with no nitrogen fertiliser and 9.0 kg DM/ha/°Cd with the addition of 150 kg N/ha. These growth rates were reported for spring which means that again moisture was likely non-limiting to pasture growth over that period. The perennial ryegrass pastures in the present study were also subjected to short periods of moisture deficit, similar to the cocksfoot pastures, during April and May. Again, this was likely the cause of lower growth rates in the present study.

5.3 Yield response

5.3.1 Nitrogen use efficiency
Cocksfoot pastures recovered between 41% (400 kg N/ha) and 88% (50 kg N/ha) of applied N (Table 4.4). These pastures produced 11.9 kg DM/kg N applied (400 kg N/ha) to 31.8 kg DM/kg N applied (50 kg N/ha). Ryegrass pastures recovered 43 ± 9.6% of applied N at all N application rates (Table 4.4). It is likely that the N that was not retrieved by the pastures was leached during water drainage after heavy rainfall events (during April and June). The yield response of perennial ryegrass per kg of applied N ranged from 10.0 kg DM/kg N applied (400 kg N/ha) to 18.3 kg DM/kg N applied (50 kg N/ha). Fasi et al. (2008) reported yield responses of 19.4 kg DM/kg applied N for cocksfoot and 13.4-27.9 kg DM/kg applied N for perennial ryegrass, depending on cultivar and sowing rate, with the application of 150 kg N/ha (Section 2.4). The response of cocksfoot was similar to an application rate of 200 kg N/ha in the present study (18.2 kg DM/kg applied N). The response of perennial ryegrass at the lower end of the scale (13.4 kg DM/kg applied N) was similar to an N application rate of 200 kg N/ha in the present study (13.1 kg DM/kg applied N). None of the treatments in the present study achieved a response as high as 27.9 kg DM/kg applied N. Lambert and Clark (1986) reported an average yield response of 29.0 kg additional DM/kg applied N when 37 kg N/ha was applied in autumn. This was
similar to the response of cocksfoot pastures with the application of 200-400 kg N/ha (28.6 ± 2.87 kg DM/kg N).

In the present study, N use efficiency was highest at application rates of 50 to 100 kg N/ha for cocksfoot, and 50, 100 and 200 kg N/ha in perennial ryegrass. Cocksfoot N use, however, appeared to be more efficient than perennial ryegrass, particularly at rates of 50, 100 and 200 kg N/ha. Cocksfoot yielded 28.5 ± 2.87 kg DM/kg applied N (Table 4.1) compared with 17.0 ± 1.65 kg DM/kg applied N in perennial ryegrass (Table 4.2) at rates of 50-100 kg N/ha. The yield response of cocksfoot at 200 kg N/ha (18.2 kg DM/kg applied N) was similar to the yield response of perennial ryegrass at an application rate of 50 kg N/ha. This suggests that cocksfoot pastures were more N deficient than perennial ryegrass pastures and therefore gave a larger yield response.

5.3.2 Cost analysis
The cost of producing one additional kg of DM was determined from fertiliser, and cartage and spreading costs (Section 3.10). In cocksfoot it was most cost effective to apply 50 to 100 kg N/ha, at a cost of $0.07 ± 0.008/kg additional DM. In perennial ryegrass it was most cost effective to apply 50 to 200 kg N/ha, at a cost of $0.12 ± 0.009/kg additional DM produced. It was cheaper to produce additional cocksfoot DM than perennial ryegrass at rates of 50 to 100 kg N/ha. The maximum cost per additional kg of dry matter produced was at a rate of 400 kg N/ha for both cocksfoot and perennial ryegrass. It cost $0.15/kg DM in cocksfoot and $0.18/kg DM in ryegrass. Lambert and Clark (1986) applied 37 kg N/ha in autumn at a cost of $0.05/kg additional DM produced at urea and cartage/spreading costs of 1986. At current prices, this would be equivalent to $0.09/kg additional DM produced. This is similar to the cost of the production of one kg additional DM at a rate of 200 kg N/ha in cocksfoot and 50 kg N/ha in perennial ryegrass ($0.10/kg DM).

It may appear uneconomic to apply high rates of N (≥200 kg N/ha) to both cocksfoot and perennial ryegrass pastures when considering that the cost of production per additional kg of dry matter in cocksfoot is slightly more than doubled from 50-100 kg N/ha to 400 kg N/ha. The cost per additional kg of DM produced in ryegrass was 50% higher at 400 kg N/ha than at 50-200 kg N/ha. When considering the cost of purchasing in conserved feeds such as hay and/or silage, it may be more economical to produce the herbage with strategic
nitrogen fertiliser applications. The cost of conserved feeds ranged from $0.12 to $0.32/kg DM (Pangborn, 2010). Conserved feeds tend to be of lower quality than fresh pasture as conservation cannot improve quality, and may substantially reduce it (Litherland and Lambert, 2007). The average ME content of pasture, maize and lucerne silages tested by FeedTech (Litherland and Lambert, 2007) was 10.5 to 10.7 MJ ME/kg DM. Hay, however, tends to have an average ME of around 9 MJ/kg DM. The crude protein content of conserved herbages are more variable and range from 5 to 25%, depending on initial pasture quality and conservation processes. Strategic N applications to achieve rates of 200 to 400 kg N/ha/year may therefore be a more preferred and economic method of producing high quality forage during periods when feed demand is often higher than feed supply under low input conditions.

5.4 Nutritive value

5.4.1 Metabolisable energy

Nitrogen fertilisation had little effect on pasture ME content. In cocksfoot, the only difference in ME content was on 25 April when the ME content of the control, 200 and 400 kg N/ha treatments was higher than the ME of the 50 kg N/ha treatment (Figure 4.12). The ME content of cocksfoot pastures ranged from 10.4 MJ/kg DM (spring) to 11.6 MJ/kg DM (winter), and were within the range of 10.2-12.4 MJ ME/kg DM reported by Mills (2007).

In perennial ryegrass, differences in ME content among pastures were evident on 25 April and 21 May (Figure 4.13). Perennial ryegrass ME ranged from 10.8 ME/kg DM (spring) to 12.4 MJ/kg DM (control, 50 and 100 kg N/ha treatments in winter). The tendency was for ME content to decline with increasing N application rate. This is commonly observed in pastures where leaves are large as the sugar content is diluted. The ME content of perennial ryegrass appeared to be higher than that of cocksfoot. This agrees with reports by Terry and Tilley (1964) and Stevens et al. (1992) that perennial ryegrass usually has a higher digestibility (ME content) than cocksfoot (Section 2.6). The daily ME requirements of 65 kg pregnant ewes range from 15 to 23 MJ ME/day (Beef & Lamb NZ, 2012). Considering that sheep can consume up to 4% of their liveweight in DM (Court et al., 2010), it means that up to 2.6 kg DM can be consumed by a 65 kg ewe. In other words, this ewe can consume a maximum of 26.5 MJ ME/day when consuming cocksfoot pasture
at an ME of 10.2 MJ/kg DM (as this was the lowest ME content of both pastures). Therefore, both cocksfoot and perennial ryegrass pastures should be able to sustain pregnant ewes.

The ME content of cocksfoot and perennial ryegrass pastures decreased from winter into spring when the ME of both species reached its lowest during the experiment. This was the result of pastures being mown on 25 May at the end of Rotation 2. The removal of herbage resulted in a reduced leaf area index which meant that these pastures utilised stored sugars for growth and development rather than photosynthates as photosynthesis was reduced. It is likely that control, 50 and 100 kg N/ha treatments of cocksfoot and perennial ryegrass did not reach canopy closure by the end of Rotation 3 as growth in these treatments during the period from 25 May to 17 August was minimal (100 ± 44.5 kg DM/ha in cocksfoot and 174 ± 35.5 kg DM/ha in perennial ryegrass). Over the same period, the 400 kg N/ha treatments produced 870 kg DM/ha in cocksfoot and 942 kg DM/ha in perennial ryegrass.

The accumulated ME yield of cocksfoot and perennial ryegrass increased with increasing N application rate (Table 4.3). In cocksfoot, the highest ME yield was 61.7 GJ/ha (400 kg N/ha) and the lowest 24.2 GJ/ha (control). Mills (2007) reported the annual ME yield of dryland cocksfoot was 53 GJ/ha without N fertiliser and 143 GJ/ha with the addition of 800 kg N/ha/year. Direct comparisons between her data and data from the present study were not possible as ME yield accumulation was not reported on a seasonal basis. In perennial ryegrass, the highest ME yield was 68.7 GJ/ha (400 kg N/ha) and the lowest 30.2 GJ/ha (control and 50 kg N/ha treatment).

5.4.2 Crude protein
The CP content of cocksfoot pastures tended to increase (P<0.05) with increasing N application rate. However, this difference declined with time, and by the end of the experiment (17 August) the only difference was that the CP content of the 400 kg N/ha treatment (25.6%) was higher than all other treatments (21.5 ± 0.65%). Accumulated CP yield ranged from 360 kg/ha (control) to 1383 kg/ha (400 kg N/ha) in cocksfoot and 497 ± 45.8 kg/ha (control and 50 kg N/ha) to 1359 kg/ha (400 kg N/ha) in perennial ryegrass (Table 4.3). Mills (2007) reported the annual accumulated CP yield of dryland cocksfoot to be 600 kg/ha without N fertilisation and 2700 kg/ha with the addition of 800 kg N/ha
annually. Once again no seasonal data were provided for direct comparison with data from the present study.

5.5 Botanical composition

5.5.1 Subterranean clover content
Subterranean clover plants in cocksfoot pastures were largely killed by a fungal infection (Pepper Spot - *Leptosphaerulina trifolii*) and sub clover content averaged 1 ± 3.0 kg DM/ha across all treatments by the end of the experiment (Figure 4.11). Initially, at the end of Rotation 1, sub clover content was similar across all N treatments (1.6 ± 1.16%) and higher in the control (8.7%). In Rotation 2, sub clover death was becoming evident, but there was still a higher proportion of sub clover in control plots (3.1%) than in N treated plots (0.1 ± 0.73%).

In the perennial ryegrass experiment, sub clover content was reduced with increasing N application (Figure 4.11). The sub clover yield in ryegrass was not different in Rotation 1, with a mean yield of 251 ± 66.7 kg DM/ha. However, the contribution of sub clover to total pasture yield was higher in the control (26%) than at application rates of 100 kg N and higher (11 ± 3.3%). In Rotation 3, the sub clover yield of the control treatment was 307 kg DM/ha compared with 25 ± 44.4 kg DM/ha in the treatments that received N fertiliser. The contribution of sub clover to total pasture yield by the end of Rotation 3 was also higher in the control (32%) than in N-treatments (3 ± 4.2%). Data from literature are inconsistent with some (for example Rowarth *et al.* (1996) and Lambert and Clark (1986)) reporting reductions in clover content with the addition of N fertiliser, while others (for example O’Connor and Gregg (1971) and McKenzie *et al.* (2003)) reported no change in clover content (Section 2.8). During the present study, pastures were managed to produce high herbage yields (of about 2.5-3.0 t DM/ha in the 400 kg N/ha treatments) and mown once lodging occurred in the 200 and 400 kg N/ha treatments. This management was less detrimental to the persistence of clover. At high rates of N, grasses produced substantially larger leaves (Section 4.2) which enabled increased light interception at the expense of the sub clover which were lower down in the sward. Clover plants require space and light to reach their growing points for the development of stolons (Thompson, 1993). Sub clover is particularly susceptible to shading, with reductions in root and shoot growth. Clover production is therefore not reduced as a direct result of N fertiliser, but rather as a result of
increased grass growth. In control pastures, grass growth was limited by N deficiency which meant that clover plants were not affected by shading. This gave clover in the perennial ryegrass experiment the opportunity to absorb enough light to persist and develop runners which were also able to branch. Under different management of frequent removal of herbage such as under frequent grazing or set-stocking grazing management, the contribution of clover to total pasture yield would likely have been higher due to increased persistence and production.

### 5.5.2 Dead matter
With the exception of sown grass and subterranean clover, the botanical composition of pastures remained fairly similar during the experiment. The contributions of the various components to total DM yield did not change significantly. The dead matter content and yield, however, tended to increase with time (Section 4.4.1.5). Pastures in this experiment were not grazed with sheep (or other livestock) as the main treatment was nitrogen and urine returns of N would have interfered with the results. Thus, the increase in dead matter was likely the result of an inability to clean-up graze the pastures.
6 GENERAL DISCUSSION AND CONCLUSIONS

6.1 General discussion

Dryland farmers in Canterbury are often faced with the issue of managing winter feed deficits while maintaining subterranean clover in their pastures. The aim of this study was to explain the physiological basis for pasture responses to autumn nitrogen application and offer practical guidelines for nitrogen use to dryland farmers.

6.1.1 DM production

The data obtained from the experiments emphasise the ability of autumn N fertiliser to increase autumn and winter feed supply. N applied in late February at rates of 200 and 400 kg N/ha resulted in pasture production responses until the end of the experiment in mid-August. Cocksfoot DM production from autumn to early spring was increased by 197% with the addition of 50 kg N/ha and by 310% through the application of 100 kg N/ha. Perennial ryegrass DM production over the same 160 day period was not increased with the addition of 50 kg N/ha, but the application of 100 kg N/ha resulted in a 69% increase. The effects of applications of 50 and 100 kg N/ha on DM production were, however, fairly short-lived, and resulted in no winter DM response in cocksfoot or perennial ryegrass. DM responses to the applications of 200 and 400 kg N/ha carried over into winter. In cocksfoot, winter DM production was 274% higher than the control when 200 kg N/ha was applied, and 770% higher with the application of 400 kg N/ha. In perennial ryegrass, winter DM production was increased by 105% with the application of 200 kg N/ha and by 441% with 400 kg N/ha.

Low DM responses over winter and N analyses from May soil samples in the 50 and 100 kg N/ha treatments suggest that soil N levels were low over winter. This is important from an environmental perspective as N leaching losses are reduced under lower soil N (NO$_3^-$) content. Applications of 50 to 100 kg N/ha in autumn may therefore be a more environmentally “friendly” option than applying N at rates ≥ 200 kg/ha. However, the use of DCD nitrification inhibitors (such as ‘eco-n’) during winter and early spring when N leaching is at its highest has potential to reduce leaching losses even at N applications of 200 kg/ha to 400 kg/ha. Vogeler et al. (2010) found that N leaching losses were reduced by around 50% with the application of DCD. The application of DCD would, however,
add an additional cost, which may therefore result in farmers moving away from this option.

DM production is dependent on available soil moisture, and N fertilisation is therefore unlikely to give economic DM responses in drought conditions. However, the use of N fertiliser in this experiment resulted in increased WUE. The use of N in dryland conditions therefore has the potential to improve the efficiency at which the limited supply of available moisture is utilised by pastures. In the present study, the application of N was timed to occur immediately prior to a rainfall event. In dryland Canterbury, mean rainfall tends to increase from February to June, and adequate rainfall may not always occur in early autumn. Therefore, applications of N later in autumn (late March to April) may be more effective than when applied in February.

6.1.2 Herbage quality
Pasture regrowth in winter was limited by temperature and possibly short daylengths which resulted in slower leaf appearance rates (Section 5.2). Winter grazing similarly reduces the leaf area index of pastures as green herbage is removed. The result is a reduction in pasture quality as plants are reliant on stored sugars rather than photosynthates for growth. Resultant spring pasture ME content can therefore be compromised by grazing pastures hard during winter as shown in Figures 4.12 and 4.13. Nitrogen application had minimal effect on pasture ME content and was unable to overcome the effects of mowing (grazing). Pasture ME was, however, still high enough to support twin-bearing ewes of 65 kg liveweight, but larger ewes will not perform well on such low ME pasture.

6.1.3 The economics
The economic analysis showed that it would be more expensive to produce additional DM at increasing rates of N application. Considering the importance of DM production in autumn, winter and early spring, and the costs of purchasing conserved feeds (hay and/or silage) to fill the feed deficit period, applications of N at rates $\geq 200$ kg/ha remains a potential option.

6.1.4 Maintaining sub clover
Pasture management in the present study aimed at maximising DM production rather than maintaining the associated sub clover population. The sub clover content of N fertilised pastures was subsequently reduced. This emphasises the importance of frequent grazing to
reduce competition between grasses and clovers for light to maintain a productive sub clover population. In this experiment pasture were mowed after the 200 and 400 kg N/ha treatments had already lodged to allow lower N treatments to produce a reasonable amount of DM as well. By the time pastures were mown, many treatments had reached five to six leaves in the first rotation. However, grazing these pastures at about the three-leaf stage would likely have resulted in reduced competition for light between the sub clover and grass, therefore allowing the sub clover to persist and have a higher DM production. From leaf appearance data in Figure 4.9 the phyllochron of cocksfoot during Rotation 1 was calculated as 69 °Cd and perennial ryegrass as 95 °Cd. The three-leaf stage and therefore grazing time in Rotation 1 should therefore have been around 20 March for cocksfoot (when the first destructive harvest was performed) and 27 March for perennial ryegrass.

6.1.5 Recommendations to dryland farming systems

- Improving pasture DM production in autumn and winter is important to dryland farmers. This can be achieved through the application of N at rates ≥ 200 kg N/ha in early autumn (February/March) to cocksfoot and perennial ryegrass pastures. However, split applications of 50-100 kg N/ha throughout autumn and early winter are likely to give a similar response in DM production while reducing potential leaching losses.

- Increased DM production should be managed by regular grazing intervals of 207 °Cd for cocksfoot and 285 °Cd for perennial ryegrass to maintain a persistent and productive sub clover (or other clover) component. This amounts to about 21 to 28 day rotations in autumn. As the days get cooler towards winter, the rotation lengths should be extended as leaf appearance is limited by temperature. Hard grazing is required in summer and autumn to enable sub clover to successfully establish.

- To maintain spring pasture quality, hard grazing during winter should be avoided to ensure that these pastures have adequate leaf area for photosynthesis, and are not reliant on stored sugars for growth.
6.2 Conclusions

Based on the research presented in this dissertation, the following conclusions can be drawn:

- Increases in production of up to 4.8 t DM/ha in cocksfoot and 4.0 t DM/ha in perennial ryegrass with increasing N application rate to 400 kg N/ha were largely the result of increases in leaf extension. In cocksfoot leaves were up to 100% larger and in perennial ryegrass up to 108% over two Rotations, which enabled pastures to intercept a larger proportion of incoming radiation.

- Mowing or grazing of pastures in winter resulted in reduced pasture growth rates even when temperature effects were accounted for using thermal time. This resulted in reduced pasture quality (ME) as stored sugar in leaves was removed and new leaves had to grow under low temperature conditions with low light interception. Pasture ME in cocksfoot was reduced from 11.6 MJ/kg DM in winter to 10.4 MJ/kg DM in spring and perennial ryegrass from 12.4 MJ/kg DM in winter to 10.2 MJ/kg DM in spring.

- N application allowed pastures to utilise limited available moisture more efficiently than N deficient pastures. Cocksfoot used moisture at 3.7 kg DM/ha/mm PET without N application and at 25.5 kg DM/ha/mm PET with the addition of 400 kg N/ha. The WUE of perennial ryegrass was 8.0 kg DM/ha/mm PET with the addition of 0-50 kg N/ha and 24.7 with the application of 400 kg N/ha.

- Increased grass growth as a result of increased N application rates results in decreased sub clover content and DM production if pastures are not managed to minimise competition for light. Hard grazing before autumn rains opens the sward allowing light to reach germinating clover seedlings. Autumn grazing intervals are therefore recommended at around 21-28 days to prevent the grass from supressing young clover seedlings.
ACKNOWLEDGEMENTS

On completion of this dissertation I would like to thank the following people for their support throughout the year:

• Firstly, to my supervisor, Professor Derrick Moot. Thank you for your time, patience, guidance and willingness to offer advice throughout the year. I would not have been able to get this far without your support.

• Dr. Anna Mills for your guidance and advice with setting up the experiment, running the experiment and my statistical analyses. Your help was vital to the completion of this dissertation.

• Malcolm Smith for providing the necessary equipment for harvests, for your advice and for helping with the flexinets. Your dedication to us as honours students, and willingness to offer advice and assistance were greatly appreciated.

• Keith Pollock for providing weather data and equipment.

• Fellow honours students at the FSC, and my office mates, Dave and Travis. Thanks for always managing to cheer me up, and making this year one of the most enjoyable I’ve had. You guys are awesome!

• Lastly, I would like to say a special thanks to my parents, Daan and Elmarie, and my brother, Gerrit, for the love, support and encouragement you provided not only this year, but during the four years I’ve spent at Lincoln University.
REFERENCES


Ates, S., Tongel, M. O. and Moot, D. J. 2010. Annual herbage production increased 40% when subterranean clover was over-drilled into grass dominant dryland pasture. *Proceedings of the New Zealand Grassland Association*, 72, 3-10.


Vogeler, I., Cichota, R., Snow, V. and Shepherd, M. 2010. Modelling the role of DCD in mitigating nitrogen losses under grazed pastures. Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world, Brisbane, Australia,


Appendix 6.1 Treatment layout of cocksfoot treatments including five rates of N application (0, 50, 100, 200 and 400 kg N/ha) and dimensions of the blocks and plots.
Appendix 6.2 Treatment layout of perennial ryegrass treatments including five rates of N application (0, 50, 100, 200 and 400 kg N/ha) and the dimensions of the blocks and plots.
Appendix 6.3 Soil moisture content (%) of cocksfoot treatments (0, 50, 100, 200 and 400kg N/ha) from 16 May 2012 to 10 July 2012. Error bars represent LSD values at each measurement date.
Appendix 6.4 Soil moisture content (%) of perennial ryegrass treatments (0, 50, 100, 200 and 400 kg N/ha) from 16 May 2012 to 10 July 2012. Error bars represent LSD values at each measurement date.

Appendix 6.5 Cocksfoot pasture yield accumulation curve parameters and regressions. Accumulated yield = A + B * R^x.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>R</th>
<th>s.e.</th>
<th>B</th>
<th>s.e.</th>
<th>A</th>
<th>s.e.</th>
<th>R2</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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Appendix 6.6 Perennial ryegrass pasture yield accumulation curve parameters and regressions. Accumulated yield = A + B * R^x.

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<th>Treatment (kg N/ha)</th>
<th>R</th>
<th>s.e.</th>
<th>B</th>
<th>s.e.</th>
<th>A</th>
<th>s.e.</th>
<th>R2</th>
<th>n</th>
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Appendix 6.7 Regressions and standard errors of the slopes for DM production against thermal time are presented with the $R^2$ for cocksfoot pastures at 0, 50, 100, 200 and 400 kg N/ha.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>Slope</th>
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<th>R2</th>
</tr>
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<td>400</td>
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<td>0.18</td>
<td>0.99</td>
</tr>
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Appendix 6.8 Regressions and standard errors of the slopes for DM production against thermal time are presented with the $R^2$ for perennial ryegrass pastures at 0, 50, 100, 200 and 400 kg N/ha.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
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<th>R2</th>
</tr>
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Appendix 6.9 Cocksfoot leaf extension curve parameters and regressions for Rotations 1 and 2. Accumulated leaf extension = $A + B \times R^x$.  

<table>
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<th>Treatment (kg N/ha)</th>
<th>R</th>
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<th>B</th>
<th>s.e.</th>
<th>A</th>
<th>s.e.</th>
<th>R2</th>
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<table>
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<th>B</th>
<th>s.e.</th>
<th>A</th>
<th>s.e.</th>
<th>R^2</th>
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Appendix 6.11 Regressions and standard errors of the slopes for leaf appearance rates against thermal time for Rotation 1 are presented with the R^2 for cocksfoot pastures at 0, 50, 100, 200 and 400 kg N/ha.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>Slope</th>
<th>s.e.</th>
<th>Constant</th>
<th>s.e.</th>
<th>R^2</th>
</tr>
</thead>
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<td>0.127</td>
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Appendix 6.12 Regressions and standard errors of the slopes for leaf appearance rates against thermal time for Rotation 1 are presented with the R^2 for perennial ryegrass pastures at 0, 50, 100, 200 and 400 kg N/ha.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>Slope</th>
<th>s.e.</th>
<th>Constant</th>
<th>s.e.</th>
<th>R^2</th>
</tr>
</thead>
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<td>0.009</td>
<td>0.0007</td>
<td>0.33</td>
<td>0.120</td>
<td>0.95</td>
</tr>
<tr>
<td>400</td>
<td>0.011</td>
<td>0.0008</td>
<td>0.30</td>
<td>0.134</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Appendix 6.13 Regressions and standard errors of the slopes for leaf appearance rates against thermal time for Rotation 2 are presented with the $R^2$ for cocksfoot pastures at 0, 50, 100, 200 and 400 kg N/ha.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>Slope</th>
<th>s.e.</th>
<th>Constant</th>
<th>s.e.</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.005</td>
<td>0.0003</td>
<td>-0.05</td>
<td>0.050</td>
<td>0.96</td>
</tr>
<tr>
<td>50</td>
<td>0.004</td>
<td>0.0002</td>
<td>-0.08</td>
<td>0.037</td>
<td>0.97</td>
</tr>
<tr>
<td>100</td>
<td>0.004</td>
<td>0.0003</td>
<td>-0.06</td>
<td>0.044</td>
<td>0.96</td>
</tr>
<tr>
<td>200</td>
<td>0.005</td>
<td>0.0004</td>
<td>-0.03</td>
<td>0.058</td>
<td>0.96</td>
</tr>
<tr>
<td>400</td>
<td>0.005</td>
<td>0.0007</td>
<td>-0.07</td>
<td>0.100</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Appendix 6.14 Regressions and standard errors of the slopes for leaf appearance rates against thermal time for Rotation 2 are presented with the $R^2$ for perennial ryegrass pastures at 0, 50, 100, 200 and 400 kg N/ha.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>Slope</th>
<th>s.e.</th>
<th>Constant</th>
<th>s.e.</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.006</td>
<td>0.0006</td>
<td>0.13</td>
<td>0.091</td>
<td>0.92</td>
</tr>
<tr>
<td>50</td>
<td>0.005</td>
<td>0.0004</td>
<td>0.01</td>
<td>0.058</td>
<td>0.95</td>
</tr>
<tr>
<td>100</td>
<td>0.005</td>
<td>0.0005</td>
<td>-0.02</td>
<td>0.080</td>
<td>0.92</td>
</tr>
<tr>
<td>200</td>
<td>0.005</td>
<td>0.0002</td>
<td>-0.05</td>
<td>0.035</td>
<td>0.98</td>
</tr>
<tr>
<td>400</td>
<td>0.005</td>
<td>0.0007</td>
<td>0.06</td>
<td>0.103</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Appendix 6.15 Cocksfoot N accumulation curve parameters and regressions. Accumulated N yield = $A + B \times R^\alpha$.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>R</th>
<th>s.e.</th>
<th>A</th>
<th>s.e.</th>
<th>$R^2$</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.99</td>
<td>0.002</td>
<td>94</td>
<td>25.8</td>
<td>0.99</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>0.98</td>
<td>0.004</td>
<td>104</td>
<td>9.4</td>
<td>0.97</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>0.98</td>
<td>0.005</td>
<td>131</td>
<td>9.3</td>
<td>0.97</td>
<td>5</td>
</tr>
<tr>
<td>200</td>
<td>0.98</td>
<td>0.003</td>
<td>177</td>
<td>13.3</td>
<td>0.99</td>
<td>5</td>
</tr>
<tr>
<td>400</td>
<td>0.99</td>
<td>0.003</td>
<td>245</td>
<td>22.1</td>
<td>0.99</td>
<td>5</td>
</tr>
</tbody>
</table>

Appendix 6.16 Perennial ryegrass N accumulation curve parameters and regressions. Accumulated N yield = $A + B \times R^\alpha$.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>R</th>
<th>s.e.</th>
<th>B</th>
<th>s.e.</th>
<th>A</th>
<th>s.e.</th>
<th>$R^2$</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
<td>0.002</td>
<td>58.5</td>
<td>47.2</td>
<td>-57</td>
<td>48.5</td>
<td>0.99</td>
<td>6</td>
</tr>
<tr>
<td>50</td>
<td>0.99</td>
<td>0.003</td>
<td>-84.8</td>
<td>11.0</td>
<td>86</td>
<td>11.8</td>
<td>0.96</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>0.99</td>
<td>0.005</td>
<td>-101.4</td>
<td>21.4</td>
<td>107</td>
<td>23.2</td>
<td>0.92</td>
<td>6</td>
</tr>
<tr>
<td>200</td>
<td>0.99</td>
<td>0.002</td>
<td>-149</td>
<td>10.1</td>
<td>151</td>
<td>10.4</td>
<td>0.99</td>
<td>6</td>
</tr>
<tr>
<td>400</td>
<td>0.99</td>
<td>0.003</td>
<td>-251.4</td>
<td>27.4</td>
<td>253</td>
<td>29.7</td>
<td>0.98</td>
<td>6</td>
</tr>
</tbody>
</table>
Appendix 6.17 Regressions and standard errors of the slopes for leaf appearance rates against thermal time for Rotation 1 are presented with the $R^2$ for perennial ryegrass pastures at 0, 50, 100, 200 and 400 kg N/ha after the exclusion of the last two data points.

<table>
<thead>
<tr>
<th>Treatment (kg N/ha)</th>
<th>Slope</th>
<th>s.e.</th>
<th>Constant</th>
<th>s.e.</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.009</td>
<td>0.0002</td>
<td>0.05</td>
<td>0.031</td>
<td>0.99</td>
</tr>
<tr>
<td>50</td>
<td>0.010</td>
<td>0.0007</td>
<td>0.19</td>
<td>0.083</td>
<td>0.98</td>
</tr>
<tr>
<td>100</td>
<td>0.009</td>
<td>0.0005</td>
<td>-0.01</td>
<td>0.066</td>
<td>0.98</td>
</tr>
<tr>
<td>200</td>
<td>0.010</td>
<td>0.0011</td>
<td>0.27</td>
<td>0.135</td>
<td>0.93</td>
</tr>
<tr>
<td>400</td>
<td>0.012</td>
<td>0.0006</td>
<td>0.17</td>
<td>0.075</td>
<td>0.99</td>
</tr>
</tbody>
</table>