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Physiological and environmental constraints to winter forage crops production

A thesis
submitted in partial fulfilment
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by
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A study was conducted on three forage species; faba bean, oats and Italian ryegrass, sown and harvested at different dates during the 2008 and 2009 growing seasons with the main objective being to maximize dry matter (DM) production. The general aim was to produce a total of 45 t DM ha\(^{-1}\) yr\(^{-1}\). The crops were sown on 4\(^{th}\) March, 28\(^{th}\) March, 21\(^{st}\) April, 12\(^{th}\) May and 3\(^{rd}\) June in 2008 on a Templeton soil and on 16\(^{th}\) March, 16\(^{th}\) April and 15\(^{th}\) May 2009 on a Wakanui silt-loam soil.

Maximum total DM yield (TDM) of forage crops was higher in 2009 (from 15,995 to 23,055 kg ha\(^{-1}\)) compared with 2008 (from 6,360 to 13,490 kg ha\(^{-1}\)). This was essentially due to disease, bird damage, lodging, frost damage and snow fall in 2008 and a longer growing duration in 2009. Oats produced the highest maximum TDM yield in the 2008 (12,010 kg ha\(^{-1}\)) and 2009 (23,055 kg ha\(^{-1}\)) growing seasons. This was followed by Italian ryegrass (8,720 kg ha\(^{-1}\)) and faba bean (7,580 kg ha\(^{-1}\)) in 2008 and faba bean-oat intercrop (21,155 kg ha\(^{-1}\)), faba bean (19,645 kg ha\(^{-1}\)) and Italian ryegrass (15,995 kg ha\(^{-1}\)) in 2009.

In 2008, the weighted mean absolute growth rate (WMAGR) at earlier sowing dates was lower than at later sowing dates as was the maximum crop growth rate (C\(_{\text{max}}\)). In contrast, the duration of crop growth (DUR) was longer for the earlier sowing dates than for the later sowings. This indicated that although the earlier sowing dates had lower WMAGR it occurred over a longer duration, thus the earlier sowing dates still produced a greater maximum TDM yield. However, the differences in maximum TDM in 2009 were influenced by the favourable growing conditions and there were no differences in the WMAGR and C\(_{\text{max}}\) in this year. However, the linear growth phase of Italian ryegrass was longer than for the two other crops and an intercrop.
Based on these results, oats was the best crop to sow for the lactation of dairy cows as it attained a herbage ME of 11.5 MJ kg\(^{-1}\) DM and produced the greatest total ME per ha when sown in early March and harvested at the end of August. Oats were also suitable to sow for liveweight gain for sheep and cattle when harvested in mid October and they reached 10 MJ kg\(^{-1}\) DM of ME. Italian ryegrass was the other alternative forage crop for farmers to sow. Faba bean was the best crop to choose for lactating dairy cows as it reached a required herbage N of 2.4% (15% CP). Similarly, Italian ryegrass (sown in early to mid March) was another option as it attained a N content of 2.4% (15% CP) when harvested in mid October. In summary, total DM yield can be maximized by sowing oats and Italian ryegrass in early or in the middle of March and sowing faba bean in the middle of March. The harvest dates of these forage crops should be in the end of August to the end of November depending on the choice of crop and desirable target.

In relation to crop development, the findings of the present study indicate that using soil temperature taken at 20 mm depth was appropriate for calculating thermal time (Tt) requirements for emergence for all species. However, the use of air temperature for faba bean and oats and soil temperature for Italian ryegrass was most appropriate for calculating the Tt requirement at the leaf appearance stage. In addition, using air temperature was found to be appropriate at flowering/anthesis and pod filling stages. Based on the present study, the prediction of the following phenological phases; emergence, leaf appearance, flowering/anthesis and pod filling using Tt provides useful information to be extrapolated to other sites and seasons to determine the most suitable sowing and harvest dates as well as forage crop species to be sown.

Total intercepted PAR in 2008 (398 to 589 MJ m\(^{-2}\)) was lower than in 2009 (788 to 982 MJ m\(^{-2}\)). This was mostly due to the shorter growth duration in 2008 which was associated with a shorter duration of LAI development and allowed a lower PAR to be intercepted. In addition, the lower incident solar radiation received, the occurrence of snow, disease and frost damage in 2008 compared with 2009 also influenced the amount of total intercepted PAR. Further, faba bean sown on the last three sowing dates did not reach canopy closure, nor did oats sown on the last two sowing dates. This meant that these crops captured less incident radiation than they could have. All of these causes could explain the variation in maximum TDM produced in both years. Higher RUE in the earlier sowing dates specifically for faba bean and Italian ryegrass was related to the higher temperature in the earlier sowings than in later sowings when the temperature was lower. However, for oats temperature did not
affect RUE. In both study seasons, oats had a higher RUE (2.4-2.5 g DM MJ$^{-1}$) than faba bean (1.7-2.1 g DM MJ$^{-1}$), Italian ryegrass (1.8-2.1 g DM MJ$^{-1}$) and the faba bean-oat intercrop (2.3 g DM MJ$^{-1}$).

To maximize total annual DM production the choice of a summer crop is also important. As shown in the present study, oats yielded 15 t DM ha$^{-1}$ when sown in early March (4th March) and harvested at the end of September. If this was followed by a summer crop of maize sown in October, it would give an approximate potential yield of 43 t DM ha$^{-1}$ yr$^{-1}$ which is close to the industry target of 45 t DM ha$^{-1}$ yr$^{-1}$. This was the best crop sequence found in the present study.

**Keywords:** faba bean (*Vicia faba*), oats (*Avena sativa*), Italian ryegrass (*Lolium multiflorum*), faba bean-oat intercrop, DM yield, nutritive value, thermal time, temperature, light interception, radiation use efficiency
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTM</td>
<td>Long term mean</td>
<td>-</td>
</tr>
<tr>
<td>a.s.l</td>
<td>Altitude (above sea level)</td>
<td>m</td>
</tr>
<tr>
<td>NIR</td>
<td>Near infrared-spectroscopy</td>
<td>-</td>
</tr>
<tr>
<td>Y</td>
<td>Yield</td>
<td>kg ha(^{-1}) or t ha(^{-1})</td>
</tr>
<tr>
<td>ME</td>
<td>Metabolisable energy</td>
<td>MJ kg(^{-1}) DM or GJ ha(^{-1}) yr(^{-1})</td>
</tr>
<tr>
<td>CP</td>
<td>Crude protein</td>
<td>%</td>
</tr>
<tr>
<td>DOMD</td>
<td>Digestible organic matter in dry matter</td>
<td>%</td>
</tr>
<tr>
<td>DMD</td>
<td>Dry matter digestability</td>
<td>%</td>
</tr>
<tr>
<td>WMAGR</td>
<td>Weighted mean absolute growth rate</td>
<td>kg DM ha(^{-1}) d(^{-1})</td>
</tr>
<tr>
<td>DUR</td>
<td>Duration of growth</td>
<td>days</td>
</tr>
<tr>
<td>C(_{\text{max}})</td>
<td>Maximum crop growth rate</td>
<td>kg DM ha(^{-1}) d(^{-1})</td>
</tr>
<tr>
<td>LSD</td>
<td>Least significant difference</td>
<td>-</td>
</tr>
<tr>
<td>R(^2)</td>
<td>Coefficient of determination</td>
<td>-</td>
</tr>
<tr>
<td>b(_{o})</td>
<td>Intercepted used to calculate the base temperature</td>
<td>-</td>
</tr>
<tr>
<td>b(_{1})</td>
<td>Slope used to calculate the thermal time requirement</td>
<td>-</td>
</tr>
<tr>
<td>T(_{b})</td>
<td>Base temperature</td>
<td>°C</td>
</tr>
<tr>
<td>T(_{t})</td>
<td>Thermal time</td>
<td>°C d</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf area index</td>
<td>dimensionless</td>
</tr>
<tr>
<td>LAI(_{\text{crit}})</td>
<td>Critical leaf area index (95% interception)</td>
<td>dimensionless</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically active radiation</td>
<td>MJ m(^{-2})</td>
</tr>
<tr>
<td>Fi</td>
<td>Fraction of radiation intercepted</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>Radiation below the canopy</td>
<td>-</td>
</tr>
<tr>
<td>I(_{o})</td>
<td>Radiation above the canopy</td>
<td>-</td>
</tr>
<tr>
<td>S(_{a})</td>
<td>Intercepted photosynthetically active radiation</td>
<td>MJ m(^{-2})</td>
</tr>
<tr>
<td>k</td>
<td>Extinction coefficient</td>
<td>-</td>
</tr>
<tr>
<td>RUE</td>
<td>Radiation use efficiency</td>
<td>g dry matter MJ(^{-1})</td>
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Chapter 1
General introduction

1.1 Background

The pastoral industry is an important component of the New Zealand economy. The production of agricultural commodities such as milk, meat and wool depend on the availability of feed from pastures which are the most important element of the pastoral industry (Caradus, 2006; Clark and Woodward, 2007). Farmers are seeking to improve the production of their livestock systems by adopting technologies that improve the growth and consumption of pasture (Caradus, 2008). Improvement in the yield and feeding value of pasture and fodder crops would contribute greatly to the profitability of the pastoral industry. Continued reliance on pasture, and cultivated crops, must also be cost-effective for New Zealand agricultural and food products to remain competitive on world markets.

Agricultural products comprising of dairy products, meat and wool are the biggest earners in the agricultural sector, contributing about 48% of New Zealand’s export earnings. In the years from 1990 to 2010, the dairy industry increased its land use by 59%, whereas the area used for sheep, beef and deer production dropped by 27% (MAF, 2011). Significant increases in dairy cattle and wool revenue increased the gross agricultural revenue by 10% by the end of March 2011. In the year ending June 2011, the dairy industry contributed NZ$13 billion of the total merchandised export value and had 4.68 million dairy cows and heifers. Beef cattle numbers declined from 4.1 million in 2010 to 3.95 million at 30 June 2011. The sheep number was 32.5 million and there were 1.2 million deer mainly in Canterbury, Otago and Southland (MAF, 2011).

The Strategic Framework for New Zealand’s Future Dairy Farming and Industry has declared specific production targets for the period 2005 – 2015 (Caradus, 2006; DairyNZ, 2010). The dairy industry aims to achieve a 50% total productivity gain (4% year\(^{-1}\)) and a 35% total yield increase in milk solids (3% year\(^{-1}\)). Their main feed based objectives are; i) to increase the metabolisable energy (ME) utilised by 50% per hectare, ii) improve the quality of feed and iii) increase the quantity of supplementary feed on dairy farms by developing and applying appropriate production systems. For the meat and wool sectors, the target is a 35% gain in total productivity (3% year\(^{-1}\)) with a major focus being on cost effectiveness and sustainability.
with the aim of increasing the metabolisable energy available from grazed pasture by 35% (Caradus, 2006; DairyNZ, 2010). These goals aim to increase farmers’ profits over the next 10 years and thus directly increase New Zealand’s agricultural output.

An adequate supply of forage throughout the year is needed to meet all of these targets since livestock performance or production is the end result of feed intake. New Zealand’s temperate climate has fewer sunlight hours and lower temperatures in the winter than in the summer which limit the yield, and quality, of winter forage crops. A study by Baars and Waller (1979) identified rainfall and temperature as the main climatic variables which affect pasture production, with temperature being crucial for pasture growth especially in winter and early spring.

Reduced incident solar radiation receipts in winter means less radiation is available to be intercepted by the crop canopy in the winter. Low temperatures can reduce the conversion of intercepted radiation to dry matter (DM) or the radiation use efficiency (RUE) hence there is reduced biomass production (Watiki et al., 1993; Kooman et al., 1996; Loss et al., 1997). In addition, low temperatures have been shown to slow leaf appearance and expansion, thus canopy closure takes longer (Kirby et al., 1982; Firman et al., 1995). These factors cause seasonal variation in pasture supply which complicates management of the pastoral systems (Diaz-Solis et al., 2006). Temperature could also affect the phenological development of crops described in terms of thermal time (Tt) or growing degree day (°Cd) (Kirby et al., 1982; Saarikko and Carter, 1996; Olivier and Annandale, 1998). This is an important aspect of increasing the accuracy in predicting crop development to determine optimum sowing and harvest dates.

Dry matter yield harvested from perennial ryegrass (Lolium perenne), white clover (Trifolium repens) and many other forage species vary throughout New Zealand (Clark et al., 2007; Valentine and Kemp, 2007). Cultivation of supplementary forage crops such as annual ryegrasses (Lolium multiflorum), oats (Avena sativa) and faba bean (Vicia faba) could provide additional feed when growth of perennial pastures or other feed sources are insufficient to meet livestock requirements. There are many approaches to ensure these forage crops attain their yield potential. These include different sowing dates, intercropping, crop rotation, or as a break crop within a pasture renewal phase to increase forage yield and quality (Reddy et al., 2003). The importance of sowing date as a crop management factor has been recognised in increasing crop yield (Grenz et al., 2005; Schwarte et al., 2005; Yau, 2007).
Several potential benefits from integrating appropriate break crops into the pasture renewal phase as well as crop rotation include increasing the quality and quantity of feed, to minimise occupied land, an opportunity to break the perennial weed cycle and break insect pest cycles. It also offers the opportunity for forward planning, to address soils of declining fertility and the N benefits of legume break crops may offer an environmental benefit to reduce N fertilizer use (Evans et al., 2001; Moot et al., 2007).

A combination of optimal sowing time and appropriate harvest time are the key to maximizing total annual production and forage quality from a given land area. For example, Husain (1984), reported that total DM yield of faba bean ranged from 5.0 to 11.5 t ha$^{-1}$ for autumn and 4.6 to 10.4 t ha$^{-1}$ for spring sown crops in two growing seasons. Faba bean sown in autumn gave about 20% more yield than spring sown crops. This was supported by Dahlke et al. (1993) who reported that high yielding small grain crops could be produced by sowing earlier. Further, intercropping studies of cereal-legume crop mixtures have suggested a potentially higher grain yield (Haymes and Lee, 1999). There is also the potential to maximize DM yield by harvesting the forage crop at different harvest dates as reviewed by (Turk et al., 2009) who reported that DM yield increased with later harvest dates beginning at flowering, full flowering and the seed filling stages. Besides identifying forage crops with high DM yield, it is imperative that a concomitant improvement in forage quality, especially in terms of their feeding value is also considered. In addition, the potential of following summer crops is also a key to maximize annual DM yield.

This research was conducted to identify suitable sowing and harvest dates for forage crops to fit into a crop sequence that results in maximum DM production and forage quality in an effort to accomplish all of the specific feed objectives under the dairy industry target. Differences in growth and development of forage crops over winter will be explained by the critical role of solar radiation and temperature when water supply and nutrients were not limiting.
1.2 Aims and research objectives

The aim of the study was to evaluate biophysical constraints that affect yield of forage crops and to determine the influence of various agronomic practices on different forage crops. The specific objectives of the experiments were:

1) To determine the most suitable sowing and harvest dates of annual forage crops to maximise their yield and quality.
2) To assess the potential production of intercropping of annual species with different canopy architecture in comparison with monocultures.
3) To quantify the phenological development of winter forage crops in relation to environmental factors over the growing season.
4) To quantify the physiological aspects, specifically canopy light interception and radiation use efficiency of winter forages.

This thesis is presented in 7 chapters derived from two main field experiments in 2008 and 2009. Chapter 1 is a general introduction for the justification of the research that was conducted. Chapter 2 presents the literature review and Chapter 3 describes the materials and methods of experimentation and analyses. Chapter 4 describes agronomic results including DM yield and nutritive value. Chapter 5 explains crop development by quantifying the relationship between temperature and crop phenological phases and Chapter 6 reports on the physiology of winter forages through canopy light interception and RUE. Chapter 7 presents the general discussion, recommendations for future research and general conclusions.
Chapter 2
Literature review

This literature review primarily covers factors which control forage yield. In particular, the effect of environmental factors on the growth and development of forages is described. The review focuses on the effects of temperature and light interception on yield formation of forage crops. It discusses crop management (sowing date, intercropping and crop rotation) strategies to increase forage yield and quality.

2.1 Forage species and annual crops options in New Zealand

Perennial ryegrass and white clover are the two predominant pasture forage species grown in New Zealand (Kemp et al., 1999; Valentine and Kemp, 2007). Environmental variation in New Zealand means some regions, primarily on the East Coast, develop soil moisture deficits in summer or low temperatures in winter which contribute to the variation in seasonal growth rates of the main pasture species throughout the year. This results in low yields in summer and winter and a shortage of feed for animals. Thus, annual plant species, often categorized as supplementary forage crops, are grown to provide an adequate seasonal supply of forage to meet livestock requirements (Kemp et al., 1999).

In New Zealand, around 30 supplementary forage crops have been identified and these can be grouped into two generic types; (i) grazed forages which include legumes, herbs, forage cereals and brassicas and (ii) conserved forages comprising of pasture, lucerne hay or silage, maize silage and cereal straw. Annual forage brassica crops include kale (Brassica oleracea), rape (Brassica napus spp. biennis) and leaf turnips (Brassica rapa). Cereals include; oat, triticale (Secale cereale x triticum durum), barley (Hordeum vulgare), maize (Zea mays) and sorghum (Sorghum bicolor) (Clark et al., 2007). In addition, annual grasses such as Italian ryegrass and its hybrids and crop legumes, such as faba bean can be utilized as supplementary forage crops. In this study, three forage species were evaluated; faba bean, oats and Italian ryegrass. ‘Old New Zealand’ faba bean was used because it has high protein content and it commonly grows well at low temperatures. Additionally, ‘Milton’ oats was selected because it can provide high DM yields with autumn sowing and is well adapted to most of the soils and the climate in New Zealand. It is also resistant to crown rust (Puccinia coronata). ‘Feast II’ Italian ryegrass was utilized as it has the potential to produce high DM yields in winter.
2.1.1 Faba bean (*Vicia faba*)

Faba bean also known as broad bean, horse bean or Windsor bean, has erect stems, large leaflets, large pods, and large flattened seeds (Duc, 1997; Martin *et al*., 2006). It is the world’s seventh most important grain legume (Rees *et al*., 2000) with China being the main producer (Duc, 1997). It is a major source of protein, starch, cellulose and minerals from its mature seed therefore making it an important grain legume for human diets and animal feed. Faba bean is used widely as an animal feed in Europe (Turpin *et al*., 2003). Its seeds contain 27 to 34% protein with a high lysine content and are free from tannins (Duc, 1997). Another major feature of the faba bean is its symbiotic nitrogen (N) fixing capability, enabling it to produce substantial yields without the addition of N fertiliser, thus making it an attractive break-crop in an arable rotation (Rochester *et al*., 1998; Schwenke *et al*., 1998).

Faba beans grow in climates ranging from temperate to semi-arid, using different cultivars and crop management practices (López-Bellido *et al*., 2005). They are generally sown in the spring in northern latitudes, in the winter in warm-temperate and subtropical areas with specific cultivars for each region (Duc, 1997). There are grown predominately in areas with more than 400 mm average annual rainfall but in drier regions, they are commonly irrigated (Agung and McDonald, 1998). They are sensitive to water stress, and irrigation is needed to improve yield and yield stability (Husain, 1984; Husain *et al*., 1988). Where water is not limiting, temperature has a major effect on germination and initial growth of faba bean.

As a legume, it has a higher feed quality than grasses and is preferred by livestock (Charlton and Stewart, 2006). Average seed yield in Europe was about 3.5 t ha\(^{-1}\) and experimental yields have reached up to 7.0 t ha\(^{-1}\) at high plant populations (Langer and Hill, 1982) and 5.0 t ha\(^{-1}\) in France (Duc, 1997). Total dry matter yields over 10.0 t ha\(^{-1}\) have been reported in New Zealand (Husain, 1984), Scotland (Thompson and Taylor, 1982), England (Fascheun and Dennett, 1982) and Holland (Dantuma and Klein Hulze, 1979). In Spain, DM yield of faba bean ranged from 0.9 to 9.0 t ha\(^{-1}\) and depended on weather conditions, harvest date, location and season (Iglesias and Lloveras, 1998). It is categorized as an annual cool season legume that could fit into a double cropping system in New Zealand, France and Spain (Taylor, 1980; Thom, 1980; Lloveras-Vilamanya, 1987b).
2.1.2 Oats (*Avena sativa*)

Oat is an annual cereal grain crop belonging to the family *Gramineae* (Langer and Hill, 1982). It grows well in cool, moist conditions (Forsberg and Reeves, 1995). It is frost tolerant in the seedling and tiller stages (White et al., 1999). Oats complete their life cycle from sowing/germination to harvest/maturity in 6 to 11 months (White, 1995). It is used for both animal and human consumption. It can also be used to overcome seasonal feed shortages and is convenient in crop rotations (Forsberg and Reeves, 1995). Greater plant height in oats crops increases the susceptibility to lodging and has contributed to severe yield losses (Brouwer and Flood, 1995).

Ground or chopped oats are fed to breeding or young dairy cattle and ground oats are fed to poultry (Cuddeford, 1995). Oats can also be used for whole crop silage (Oltjen and Bolsen, 1980) or grazed *in situ* (McDonald and Wilson, 1980) for ruminants. Oats were much more favoured by the growers compared with other small grains, as a forage crop, because of its finer stem and higher palatability (Miller, 1984). Oats have a high crude fibre content compared with barley and wheat but a lower protein content of 11 to 14% (Cuddeford, 1995; Church and Richard, 2002).

Oats can have mean daily growth rates of 50 to 60 kg DM ha\(^{-1}\) d\(^{-1}\) over winter from autumn sowing (de Ruiter et al., 2002). Oats can be classified as a winter/spring green feed and can achieve growth rates of 80-100 kg DM ha\(^{-1}\) d\(^{-1}\) in the summer decreasing to 20-45 kg DM ha\(^{-1}\) d\(^{-1}\) in late autumn before increasing again (over 100 kg DM ha\(^{-1}\) d\(^{-1}\)) in spring.

2.1.3 Italian ryegrass (*Lolium multiflorum*)

Italian ryegrass usually acts as a winter annual but it can be a short-lived perennial under favourable conditions (Casler and Kallenbach, 2007). In New Zealand, Italian ryegrass is regularly sown in late summer or early autumn, and grows considerably more than perennial ryegrass in winter/early spring (Charlton and Stewart, 2006). This allows dairy farmers to overcome feed shortages in early lactation, around mid July to September (Thom and Bryant, 1996). However, by sowing earlier, production can be boosted for the first autumn grazing (Charlton and Stewart, 2006). Dry matter yields of 6-12 t ha\(^{-1}\) yr\(^{-1}\) can be produced for up to three years in New Zealand (Mooso et al., 1990; Cuomo et al., 1999).
There are two main types of cultivars of Italian ryegrass: diploid and tetraploid. Tetraploid ryegrasses are larger plants that require high fertility, moist conditions and can sustain longer rotations (Charlton and Stewart, 2006). The tetraploid cultivars have a higher feed quality than diploids because of larger cells with a lower cell wall:cell content ratio. They have a highly branched root system with multiple fibrous, adventitious roots (Casler and Kallenbach, 2007).

It is typically grown in a monoculture but can be mixed with annual legumes to decrease N fertilizer requirements (Morris et al., 1986). Grazing animals tend to prefer tetraploid plants and this can increase feed intake and improve animal performance (Charlton and Stewart, 2006). A post-grazing residual of a 7 to 10 cm of Italian ryegrass gives the greatest productivity over time (Casler and Kallenbach, 2007).

2.2 Dry matter production and seasonal yield

Pasture production is variable throughout New Zealand with temperature and rainfall being the two most important environmental factors affecting pasture growth and their variability creates inconsistency in feed supply (Baars and Waller, 1979). For instance, pasture production in Central Otago is about 5.0 t DM ha\(^{-1}\) yr\(^{-1}\) compared with 18.0 t DM ha\(^{-1}\) yr\(^{-1}\) for Northland and the Waikato (Matthews et al., 1999). Annual pasture production is mostly affected by low temperature in winter and soil moisture content in summer. Soil fertility also has a major effect on productivity. However, a key driver of annual productivity for perennial pastures is radiation interception (Valentine and Kemp, 2007). These environmental variations show how difficult it can be to balance feed supply and demand of forage for animals.

Annual herbage yields were 11.7 t DM ha\(^{-1}\) yr\(^{-1}\) in the Waikato, 10.9 t DM ha\(^{-1}\) yr\(^{-1}\) in the Wairarapa, 5.9 and 10.2 t DM ha\(^{-1}\) yr\(^{-1}\) for dryland and under irrigation in Canterbury, respectively, 12.0 t DM ha\(^{-1}\) yr\(^{-1}\) in Southland and 2.8 t DM ha\(^{-1}\) yr\(^{-1}\) in Central Otago (Valentine and Kemp, 2007). Clark et al. (2007) reported a mix of perennial ryegrass and white clover yielded 16.9 t DM ha\(^{-1}\) yr\(^{-1}\) at the Dargaville research station. A yield of new pasture of 17.6 t DM ha\(^{-1}\) yr\(^{-1}\) was reported from Lincoln and 14.4 t DM ha\(^{-1}\) yr\(^{-1}\) from the Woodlands research stations.

There is variability in pasture growth within years (seasonal variation) and between years (interannual variation) in all dairy regions in New Zealand. In the Manawatu, on average, the
percentage of annual pasture production for each season was; winter 14%, spring 32%, summer 33% and autumn 21% (Valentine and Kemp, 2007). Whereas for perennial ryegrass, seasonal production was 12% in winter, 40% in spring and 33% and 15% for summer and autumn, respectively. When environmental conditions limit production of perennial pasture species, annual crops can be used effectively (Hall and Kephart, 1991).

2.3 Environmental factors affecting growth and development of crop production

Environmental factors such as solar radiation, temperature, soil water and nutrient supply influence the yield of crops by affecting their growth and development (Dennis, 2005). The timing and expansion of leaf area and senescence exert a major influence on growth and yield primarily through effects on radiation interception by the canopy (Biscoe and Gallagher, 1977; Monteith, 1977).

2.3.1 Effects of temperature

Several studies have quantified the importance of temperature on plant growth (Van Delden et al., 2000; Turner et al., 2001; Thakura et al., 2010). It has been concluded that temperature is one of the most important factors controlling plant growth and development when water and nutrients are non-limiting (Monteith, 1977; Iannucci et al., 2008). However, other factors such as water availability, vernalisation, light availability and photoperiod may modify its effects (Tom, 1991; Porter and Megan, 1999). Moreover, temperature has a great influence on development of phenological phases of crops (Porter and Delecolle, 1988) such as emergence (Angus et al., 1981), rate of leaf appearance or phyllochron (Baker et al., 1986; Kirby and Perry, 1987; Cao and Moss, 1989), leaf and canopy expansion (Peacock, 1975; Thomas, 1975; Gastal et al., 1992), tiller appearance (Thomas and Norris, 1981), root extension (McKenzie et al., 1999), flowering (Iannucci et al., 2008) and physiological maturity (López-Castañeda and Richards, 1994). However species or cultivars may react differentially to temperature (Tom, 1991).

Higher temperatures encourage rapid growth, and lead to a faster development rate and a shorter overall growth period (Sinclair, 1994). This can decrease grain weight after anthesis for oats and sorghum (Eagles et al., 1978) and rice and barley (Chowdhury and Wardlaw, 1978). In oats, a change from high to low temperature delayed physiological maturity but increased the stem proportion whereas a change from low to high temperature promoted
earlier anthesis (Forsberg and Reeves, 1995). The influence of weather on pasture growth rates has been studied by Baars and Waller (1979). They reported that regrowth of ryegrass pasture following defoliation was dependent on temperature and management. They showed that a change of 1°C in daily maximum air temperature could cause a 7-12 kg DM ha⁻¹ d⁻¹ difference in the growth rate of pasture in the Waikato from August to October.

The rate of photosynthesis, respiration and plant nutrient uptake are also temperature dependent. Temperature affects on growth and photosynthesis are usually highly related within a species, indicating a close relationship between source (photosynthesis) and sink (growth) activities (Fageria et al., 2006). Growth responses are generally more sensitive to low temperature than photosynthesis, allowing excess photosynthate to accumulate in storage organs when growth slows.

A temperature range from 10-30 °C is suited for most crop species. Most temperate crop plants have their maximum development rate between 16 and 32 °C (Eastin and Sullivan, 1984) and a range of 20-25 °C is optimum for plant growth (McKenzie et al., 1999). However, at temperatures of less than 5 to 10 °C the physiological activity of many plant species is slowed (Sinclair, 1994) and temperatures above 43 °C damage many plants. Most cool-season crop plants cease growth at temperatures of 32 to 38 °C, while many annual crops are killed by temperatures below 0 °C.

During autumn, as temperatures decrease the quality of cool season forage grasses changes more slowly resulting in a slow decrease in stem growth and an accumulation of non-structural carbohydrates in the leaves (Volenc and Nelson, 2003). However, at high temperatures, most cool season grasses and legumes produce smaller cells with thicker cell walls, have a lower leaf:stem ratio, store less non-structural carbohydrate and produce herbage of lower digestibility.

2.3.1.1 Phenological development responses to thermal time

The development stages of a plant are characterised by the formation of various organs and their time of appearance. The most important phenological change is from vegetative to reproductive growth and this is strongly influenced by the environment (Horie, 1994). Various models have been proposed to relate environmental factors to crop development (Weir et al., 1984; Summerfield et al., 1991). One model that explains this in a consistent and predictable manner is thermal time (Tₜ) which is used to describe temperature effects on plant
development rather than expressing them in calendar days. Thermal time or growing degree days (temperature unit day\(^{-1}\), °Cd), have been utilized in numerous studies to predict crop phenological events (López-Castañeda and Richards, 1994; Jamieson et al., 1995; Olivier and Annandale, 1998; Sharratt, 1999; Moot et al., 2000; Baker and Reddy, 2001). Thermal time is defined as the cumulative temperature above a critical base temperature (T\(_b\)). The base temperature is the temperature at which development ceases.

In Australia, development and anthesis of oats, was quantified by López-Castañeda and Richards, (1994) who observed that ‘Echidna’ and ‘Hakea’ oats required 838 and 881 °Cd, respectively from sowing to reach terminal spikelet at a T\(_b\) of 0 °C. Both cultivars required a mean of 1298 °Cd to reach anthesis. For Italian ryegrass, Moot et al. (2000) reported that based on soil temperature at 20 mm, the T\(_t\) requirement for field emergence was 125 °Cd with a T\(_b\) of 1.9 °C compared with white clover at 152 °Cd with a T\(_b\) of 0 °C. They concluded that the T\(_b\) ranged from 0-4 °C for temperate grass and the dicotyledonous herbage species evaluated. Most species with a low seed weight required a low T\(_t\) for germination but a higher T\(_t\) for emergence.

McDonald et al. (1994) reported that on average 208 °Cd were required for faba bean emergence with a T\(_b\) of 0 °C for all varieties evaluated. Delayed sowing increased the time (days) to establish but the Tt accumulated from sowing to emergence did not differ. Ellis et al. (1990) pointed out that about 1000 °Cd were required for faba bean to flower above a T\(_b\) of 0 °C for six different genotypes. Whereas, Boote et al. (2002) proposed a T\(_b\) of 0 °C for reproductive development in their crop model to simulate faba bean growth and yield. Accurate predictions of phenological events for each phase of the crop cycle are necessary to choose suitable species, sowing and harvest dates to attain maximum yields within an environment. The Tt requirements for each phenological stage of faba bean, oats and Italian ryegrass will be quantified in Chapter 5.
2.3.2 Radiation interception by crop canopies

Incident solar radiation, its interception and utilization are the determinants of plant growth and crop yield as DM production is a function of the amount of intercepted photosynthetically active radiation (PAR) intercepted by the crop canopy (Williams et al., 1965; Biscoe and Gallagher, 1977; Monteith, 1977). Photosynthetically active radiation is the quantum flux density in the active wavebands of 0.4 – 0.7 µm (Hipps et al., 1983). The incident quantum flux intercepted by a crop canopy determines the rate of photosynthesis until the canopy is light saturated.

The intensity of incident radiation is reduced in temperate regions such as northern Europe due to low light angles, short days and excess rainfall during the winter (Charlton and Stewart, 2006). It has been established that DM production is linearly related with intercepted PAR (Monteith, 1977; Sivakumar and Virmani, 1984; Kiniry et al., 1989).

In the presence of an adequate supply of water and nutrients, optimal temperature and effective weed and disease control, crops only grow at their maximum potential rate when they are intercepting all available incident PAR. Interception of PAR and conversion of intercepted radiation into DM are both factors that drive DM production and seed yield (Stutzel and Aufhammer, 1992).

Sowing forage crops on different dates will affect the amount of light intercepted by the crop canopy. For example, Confalone et al. (2010) planted ‘Alameda’ faba bean on five different dates from mid-autumn to mid-spring at Lugo, Spain. The cumulative intercepted PAR was the greatest for the early sowings and ranged from 742 to 930 MJ m⁻². The last two sowing dates, which were spring sown, intercepted the lowest amount of PAR with a mean of 682 MJ m⁻² as the growth duration was shorter than that of the autumn sowing. At Merredin, Western Australia, a cumulative intercepted PAR of 367 and 583 MJ m⁻² was measured from two seasons by Thomson and Siddique (1997). Whereas, Muurinen and Peltonen-Sainio (2006) reported that accumulated intercepted radiation of oats was close to 500 MJ m⁻² for a 90 kg N ha⁻¹ treatment in Jokioinen, Finland.

2.3.2.1 Leaf area index

The leaf area index (LAI) is an important parameter to determine light interception and transpiration in field crops. Increased LAI depends on temperature (day and night), N, water
Availibility and plant density (Fageria et al., 2006). Biscoe and Gallagher (1977) emphasized that various climatic factors which restrict leaf growth can lead to decreased crop DM production.

An increase in LAI is the result of leaf area expansion which may be divided into tiller number per unit ground area, leaf appearance, leaf extension and leaf senescence per tiller (Davies, 1981). Canopy light interception and photosynthesis are closely related to LAI. The critical LAI (LAI_{crit}), defined as the LAI which is required for interception of 95% of the incident radiation (Pearce et al., 1965) and it determines when the crop will reach its maximum potential growth rate. To maximize productivity it is important that the canopy achieves LAI_{crit} as soon as possible after sowing. As the LAI increases, light interception also increases and for many cereal crops LAI_{crit} is about 4. However, Biscoe and Gallagher (1977) reported over 80% interception of incident PAR by the leaf canopy of cereals when the LAI was between 4 and 5. Specifically for oats, Peltonen-Sainio (1999) reported that oats reached canopy closure at an optimum LAI from 3 to 5 depending on leaf orientation.

Values of LAI increase until maximum values are attained at or around flowering, and they then subsequently decrease as leaves senesce. An increase in LAI up to LAI_{crit} resulted in more intercepted radiation and higher DM production. Early canopy closure enhances total energy interception, and in the absence of stress will enhance total DM production (Lawn, 1989). However, production remained constant with a further increase of LAI above LAI_{crit} (Shibles and Weber, 1965). This was because the relationship between % PAR interception and LAI plateaus above 95% interception.

2.3.2.2 Leaf appearance

The rate of leaf appearance in crop plants depends on the temperature of the expanding leaves (Hay and Porter, 2006; Valentine and Kemp, 2007), while the effects of other environmental factors such as solar radiation, water supply or nutrients status and cultural practices are somewhat controversial and minor. Several studies have shown that water and nutrient stress have little impact on the leaf appearance rate of wheat (Triticum aestivum) (Bauer et al., 1984; Hotsonyame and Hunt, 1997). Other workers reported that water and N stress could either increase or decrease the leaf appearance rate (Cutforth et al., 1992; Abeledo et al., 2004). These reports agreed with McMaster et al. (2003) who found temperature was the primary environmental factor controlling the phyllochron, or rate of leaf appearance in wheat. These results suggest that the soil temperature at crown depth would affect the leaf appearance rate.
of wheat more than the above canopy air temperature. This was supported by Jamieson et al. (1995) who stated that the rate of leaf appearance in wheat could be predicted based only on the near-surface soil temperature before stem extension commences, a point at which canopy temperature is used for further predictions.

Kirby (1982) concluded that leaf appearance tended to differ with different temperatures. He reported that leaf appearance of barley, in Britain, practically stopped in the coldest period from December to January. In a controlled environment, leaf appearance on the main stems of winter barley was faster with rising temperature until an optimum temperature of 22.5 °C was reached. This indicated that the appearance of new leaves was a linear function of temperature (Tamaki et al., 2002).

### 2.3.2.3 Leaf expansion

Bull (1968) showed that the rate of increase in leaf area plant\(^{-1}\) of field bean was influenced mainly by the maximum air temperature either on a daily or weekly basis compared with other environmental variables. The importance of temperature on leaf expansion was emphasized by Biscoe and Gallagher (1977). However, final leaf size depended on the rate and duration of expansion (Hay and Porter, 2006).

According to Hay and Kirby (1991), the duration of leaf expansion was a vital part of plant development. The other two crop management factors which have a large influence on leaf area are N and water stress. Low levels of N and limitations of soil moisture resulted in smaller leaves, a lower LAI and less radiation interception consequently giving lower biomass and grain yields.

### 2.3.2.4 Canopy architecture

The amount of light intercepted by a canopy depends on the LAI and leaf angle of the canopy architecture. The leaf angle determines the penetration of PAR into the crop canopy. Other factors that affect light interception include leaf thickness, leaf surface, leaf size, shape and the degree of dissection, phyllotaxis and the vertical stratification of leaf area (Hay and Walker, 1989). The leaf angle, as characterized by the extinction coefficient \((k)\), determines how quickly light is extinguished as it moves through the crop canopy. A low \(k\) indicates erect leaves which allow light deep into the canopy. Erect leaves require a high LAI, usually > 6 to intercept all light (Hay and Walker, 1989). A high \(k\) means the canopy consists mostly of flat
leaves and will require only a LAI of 3-4 to intercept all radiation. Generally, crops that have upright leaves display $k$ values of 0.3 to 0.5 while, crops that display their leaves horizontally have $k$ values of 0.7 to 1.0.

Solar radiation penetration (into a crop canopy) can be related to LAI as (Brown, 1984):

$$k = -\log\left(\frac{I}{I_0}\right)_{\text{LAI}}$$  

Equation 2.1

where $I$ is the irradiance under the crop canopy, $I_0$, the irradiance above the crop canopy and $k$ is the extinction coefficient which is the fraction of light intercepted per unit LAI. The $k$ of the canopy was calculated from Equation 2.1.

In a forage cropping system, canopy architecture may be important to maximise light capture in transitional periods in a pure sward of grasses or a mixture of grasses and other crops. While flat leaves catch more light than erect leaves they also become light saturated (for a C$_3$ species) at about half of full sunlight and this can reduce radiation use efficiency (RUE). Erect leaves do not become light saturated at angles of 60° or above and if LAI is sufficient to intercept all incident light the RUE will be higher and so will the crop growth rate (McKenzie et al., 1999).

For perennial ryegrass, a low LAI in the top strata of the canopy and the vertical disposition of the youngest leaves with $k = 0.5$ means that light penetrates deeply into the canopy and canopy photosynthesis can be spread over a large area of leaf (Hay and Porter, 2006). For wheat, Yunusa et al. (1993), reported that the $k$ of spring wheat differed among cultivars with an average of 0.76 for ‘Kulin’, 0.72 for ‘Gamenya’ and 0.63 for ‘Bencubbin’. The high $k$ for ‘Kulin’ was related to its large awned ears that were more effective than the leaves in intercepting light compared with the other cultivars. Confalone et al. (2010) reported a $k$ value of 0.83 for autumn-winter canopies of faba bean compared with 0.62 for spring sowings. They suggested solar elevation or canopy architecture (leaf angle or leaf thickness) caused the differences in $k$.

### 2.3.2.5 Radiation use efficiency (RUE) and dry matter yield

The RUE is defined as crop biomass produced per unit of total solar radiation or PAR intercepted by the canopy. This simple physiological approach can be used to estimate yield and analyse crop growth (Monteith, 1977). The performance of the crop photosynthetic
apparatus can be determined by its RUE which is the slope of the linear regression between cumulative DM production and cumulative radiation intercepted by the crop canopy (Muchow and Sinclair, 1994; Sinclair and Muchow, 1999). Pilbeam et al. (1991) showed differences in total DM yield of grain legumes were due to differences in their RUE and the amount of light intercepted by crops. Equation 2.2 summaries the relationship between incoming radiant energy on pasture or crop growth (Stockle and Kemanian, 2009):

\[
Y = \text{RUE}f_iS_t
\]

Where \( Y \) is biomass produced \( (g \ m^{-2}) \), RUE is the radiation use efficiency \( (g \ MJ^{-1}) \), \( f_i \) is the fraction of the incident solar radiation intercepted by the canopy and \( S_t \) is the total incoming solar radiation \( (MJ \ m^{-2}) \) in a given time interval.

Sinclair (1994) reported that in a diverse environment the relationship between accumulated DM and intercepted solar radiation was usually linear, indicating a constant RUE. This is in agreement with Muchow et al. (1993) who reported that RUE was stable across species and location throughout most of the growing period of the crops evaluated. Radiation use efficiency seems to be fairly stable across environments in optimal growing circumstance (Sinclair and Muchow, 1999). Baseline RUE values of some cereals are as follow; barley \((1.5-1.7 \ g \ DM \ MJ^{-1})\), wheat \((1.6-1.7 \ g \ DM \ MJ^{-1})\) (Kemanian et al., 2004) and oats \((1.2-1.7 \ g \ DM \ MJ^{-1})\) (Muurinen and Peltonen-Sainio, 2006). The reported RUE of faba bean was lower at \(1.03 \ g \ DM \ MJ^{-1}\) (Silim and Saxena, 1992) and \(1.45 \ g \ DM \ MJ^{-1}\) (Madeira et al., 1988). Generally legume crops have a lower RUE than other C\(_3\) crops (Sinclair and Muchow, 1999; Kemanian et al., 2004) due to their ability to fix atmospheric N which needs more energy than non legume crops.

In addition, different crop species have different photosynthetic capacities and different biochemical components. Thus, RUE differs among species. In fact, RUE can differ among cultivars (Stutzel et al., 1994). In Finland, Muurinen and Peltonen Sainio (2006) reported the RUE for three oats cultivars before heading ranged from 1.52 to 2.27 g MJ\(^{-1}\) at two different levels of N application (0 and 90 kg N ha\(^{-1}\)). In a study in Perth, Australia, Yunusa et al. (1993) showed the RUE for wheat was higher for a modern cultivar \((2.40 \ g \ DM \ MJ^{-1})\) compared with an old cultivar \((1.52 \ g \ DM \ MJ^{-1})\) for the pre-anthesis period. Similarly, Goyne et al. (1993) found that the RUE of ‘Gilbert’ barley was higher \((2.90 \ g \ DM \ MJ^{-1})\) than other cultivars \((2.60 \pm 0.04 \ g \ DM \ MJ^{-1})\). However, RUE was unaffected by sowing date.
Thomson and Siddique (1997) reported the RUE of faba bean was 1.99 g DM MJ\(^{-1}\) in the first season and 1.10 g DM MJ\(^{-1}\) in the second season. Their study compared the adaptation of a wide range of grain legume species to the low-rainfall Mediterranean-type environments of south western Australia. The low RUE in the second season was associated with the dry conditions in that year. Kiniry et al. (1989) also concluded that there was large variation in the RUE of species grown because of differences in environmental conditions between sites. The effect of temperature on photosynthetic activity of leaves has a high probability of influencing the RUE in crop species (Sinclair and Muchow, 1999). Brown et al. (2006) reported that the RUE\(_{total}\) of ‘Kaituna’ lucerne (\textit{Medicago sativa}) increased linearly from 0.60 to 1.60 g DM MJ\(^{-1}\) as the mean air temperature increased from 6 to 18 °C in Canterbury. Andrade et al. (1993) showed that the low RUE of maize was attributed to low temperature in Balcarce, Argentina.

Maximising DM production on an annual basis is only possible by matching appropriate crops to the given environment. The C\(_3\) crops like faba bean, oats and Italian ryegrass, have the potential to grow quickly during the cooler winter months because of their higher RUE’s under cool temperatures. In transitional times it is important to balance RUE with radiation interception to maximise interception and use of available solar radiation.

### 2.4 Crop management practices to maximise yield

#### 2.4.1 Sowing date

Sowing date has been identified as one of the agronomic practices that influences crop yield (Hay and Walker, 1989; Gomez-Macpherson and Richards, 1995; Adisarwanto and Knight, 1997). Sowing date is a critical management decision due to the wide variability in weather conditions throughout the growing season. Further, altering sowing date can substantially alter the duration of different crop developmental stages because the crop grows under different environment conditions (Hay and Walker, 1989) and long durations can produce high yields in small grain crops (Dahlke et al., 1993).

Adisarwanto and Knight (1997) found different sowing dates affected the emergence of faba bean seedlings. ‘Fiord’ seed sown on 24\(^{th}\) April and 14\(^{th}\) May took 14 days to emerge compared with 18 days for the plants sown on 26\(^{th}\) June in Australia. Under warmer conditions, it took fewer days to emerge compared with the colder conditions in June and July. However, if emergence was described in thermal time, it was unlikely to differ. Emergence is usually associated with soil temperature at the seed depth. Inadequate soil
moisture and soil temperature above 35 °C can retard germination of cool season species (Cardwell, 1984)

Annicchiarico and Iannucci (2007) observed that early sown faba bean produced 0.63 t ha⁻¹ grain yield less than the 3.03 t ha⁻¹ from the late sown faba bean in Lodi, northern Italy. Whereas at Foggia, in southern Italy, grain yield was lower with 1.53 t ha⁻¹ in early and 1.57 t ha⁻¹ in late sown crops. This yield variation resulted from greater mortality in early sown faba bean due to the occurrence of more frost injury and drought. In south-western Australia, Loss et al. (1997), observed that early sown faba bean produced superior seed yields because it flowered earlier, had a longer duration of flowering, produced more nodes, had a larger green area index (GAI), intercepted more PAR, had a greater peak and final biomass, more pods in the upper canopy, and a higher harvest index than late sown crops.

In Canterbury, New Zealand, Husain (1988), reported that autumn sowing of faba bean yielded more than spring sowing because they grew faster for a longer period and intercepted about 35% more PAR than the spring sown crops. This was associated with a longer duration of crop cover in the early sowings. The DM yield ranged from 5.0 - 11.5 t ha⁻¹ for autumn and 4.6 - 10.4 t ha⁻¹ for spring sown beans for the two seasons of the experiment.

Green et al. (1985) and Green and Ivins (1985) reported that grain yield of winter barley and total DM yield of wheat, respectively, sown on different sowing dates in United Kingdom declined as sowing dates were delayed. Delays in the time of sowing reduced the duration of growth and resulted in decreased numbers of grains associated with the fewer tillers produced. Total DM yield declined in later sowings compared to earlier sowings. The authors suggested this was because decreased duration of the growing season would reduce the radiation intercepted by the crop canopy and therefore compromise carbon assimilation.

**2.4.2 Intercropping**

Intercropping is the cultivation of two or more crop species simultaneously in the same area during a growing season (Ofori and Stern, 1987). It has been well documented as a crop production system which may produce greater yields than monocrops (Fukai, 1993). Other agronomic benefits include enhanced land use efficiency, greater use of light, greater water and nutrient utilization, control of pests and diseases and enhanced weed suppression (Vandermeer, 1989). It is mostly practiced in the tropics (Willey, 1979; Vandermeer, 1989; Fukai, 1993; Anil et al., 1998). Studies have confirmed the potential of increasing yield with
an intercrop compared with a sole crop especially in cereal-legume intercrops. This was reported by Willey and Osiru (1972) on a maize (Zea mays)/bean (Phaseolus vulgaris) intercrop, Rao and Singh (1990) on sorghum/pigeonpea (Cajanus cajan Millsp), groundnut (Arachis hypogaea)/pigeonpea, sorghum (Sorghum bicolor)/pearl millet (Pennisetum americanum Leeke) and on maize/soybean (Glycine max) by Russell and Caldwell (1989). In addition, Anil et al. (1998) stated that with less competition between each species, and utilising available resources from different ecological niches, intercrops could give higher yields than sole crops.

Ghanbari-Bonjar and Lee (2003) showed that the total DM production of monocropped wheat and faba bean intercrops was affected by harvest date. They reported that the mean DM yield of intercrops and sole crops of wheat and faba bean increased across harvest dates from 3.94 t ha\(^{-1}\) for the first harvest, 8.51 t ha\(^{-1}\) for the second harvest and 8.97 t ha\(^{-1}\) for the third harvest.

In Lacombe, Canada, Berkenkamp and Meeres (1987), showed that there was no yield advantage of a crop mixture over the monoculture since the DM yield of an oats-faba bean intercrop (12.0 t DM ha\(^{-1}\)) was not different from monocrop oats (12.9 t DM ha\(^{-1}\)) or monocrop faba bean (10.8 t DM ha\(^{-1}\)) over 3 growing seasons. They also indicated that the DM yield of an oat - pea intercrop was comparable with the oat - faba bean intercrop at 12.3 t DM ha\(^{-1}\). Anil et al. (1998) reviewed the performance of intercrops and concluded that intercropping was more beneficial for forage production than grain production in temperate climates.

Haymes and Lee (1999) showed that light intercepted by the crop canopy of a wheat/faba bean intercrop became an important factor in yield determination of both crops compared with their respective sole crop. They also indicated that competition between crop species in an intercrop suppressed weeds and improved nutrient uptake in soil and this could result in increased yields.

In another study, the potential yield and quality of intercropping with berseem clover (Trifolium alexandrinum) and oats, barley or triticale was influenced by the cereal species, seeding rate, seed emergence, time of harvest, soil fertility and environmental conditions (Shirley et al., 2004). Lauriault and Kirksey (2004) demonstrated that by growing barley - pea or oat - pea intercrops in the Southern High Plains of the USA, a higher forage yield and quality could be reached compared with the respective sole crops. In addition, Crews and
Peoples (2004), proposed that sowing of grain legumes in forage intercrops can provide a more sustainable source of N to cropping systems through biological N fixation.

Conversely, Sheri et al. (2008) reported that faba bean - barley and lupin - barley intercrops gave the same DM yield (12 t ha$^{-1}$) which was less than a pea - barley intercrop and a barley monoculture at 13.5 and 13.3 t ha$^{-1}$, respectively. The lower forage DM yield of the faba bean - barley and lupin - barley intercrop probably resulted from similar ecological niches of resources for both species in the combination. The high yield of a pea - barley intercrop could possibly be attributed to the enhanced compatibility of a pea - barley intercrop with regard to light utilization, nutrient uptake and water use.

### 2.4.3 Crop rotation

Crop rotations in a cropping system are used to increase forage production in many countries by adopting the best combination of crop sequences over a particular time period (Lloveras-Vilamanya, 1987a). Other advantages of crop rotations for forage production include improved weed control, pest and disease lifecycle breaks through changing hosts and their life cycles, restoration of soil fertility status by complementary use of depletive and restorative crops, providing adequate feed to meet seasonal animal needs, making use of idle land and improving nutrient use efficiencies and reducing N losses to surface and groundwater resources (Karlen and Sharpley, 1994; Moot et al., 2007).

In South Australia, most farms consist of integrated cereal/livestock systems based on a cereal/pasture rotation (Puckridge and French, 1983). The success of this system can mainly be ascribed to the use of pasture legumes for enriching the soil with N and organic matter for subsequent cereal crops and for high quality feed for livestock.

Crop sequences may include sowing winter forage crops such as oats, faba bean and Italian ryegrass followed by pasture or summer forages, for example by sowing maize, kale or turnips ($Brassica$ $rapa$). Kale can produce yields of 12-15 t ha$^{-1}$ in Canterbury and can be sown in the spring (October – December). Other crop sequences could involve sowing winter brassica options such as kale or winter green feeds (wheat, barley, Italian ryegrass) followed by summer kale. Others, such as swedes ($Brassica$ $napus$ spp. $napobrassica$) are sown by late November in Southland and West Otago regions to replace old grass. They are ready to be grazed off in winter followed by sowing of grass or cereals in October which can be harvested as silage in January or as grain in March (Moot et al., 2007).
Over two years of crop rotations, de Ruiter et al. (2010) found that a maize-wheat-maize-triticale rotation gave the highest total yield of 60.1 t ha\(^{-1}\) followed by maize-triticale + faba bean-kale-Italian ryegrass at 58.6 t ha\(^{-1}\) in Canterbury. The lowest DM yield was from the barley-forage rape-kale-oats + Italian ryegrass sequence at 46.8 t ha\(^{-1}\). High yields from crop sequences resulted from crops with high RUE and with short transitions between crops. The yield of 60.1 t ha\(^{-1}\) over two years was about 15 t ha\(^{-1}\) yr\(^{-1}\) less than the industry target of 45 t ha\(^{-1}\) yr\(^{-1}\). This production could be improved by enhanced crop management and selection of other potential crop species.

Recently, Fletcher et al. (2011) reported a yield of 33.5 t DM ha\(^{-1}\) might be possible based on a simulation model. This represented a 17.4 t DM ha\(^{-1}\) yield from a long-season maize hybrid sequence with 16.1 t DM ha\(^{-1}\) of cereal (oats, barley, wheat, triticale or ryecorn (Secale cereale)) phase. The simulation ran for 28 years (1974-2001) and the results indicated maize should be sown on 22\(^{nd}\) November in Canterbury. The simulated yield at optimum sowing date was lowest in Canterbury compared with Northland, Waikato and Taranaki due to cooler temperatures and decreased maize yield in Canterbury. Yield of a sequence could be modified by adjusting maize hybrid selection and sowing date.

**2.4.4 Crop quality**

The aim of maximizing yield in forage crops needs to be balanced with the quality of the forage produced because this has a direct effect on animals feeding and production. There are three main factors that affect the forage quality of sown crops; forage species, maturity and harvesting stage. The other factors are temperature, cultivar, soil moisture and nutrient level (Collins and Fritz, 2003), season, climate, leaf to stem ratio, whether the plants are annuals or perennial, grasses or legumes and the physiological and morphological characteristic of the crops (Turk et al., 2009). Nutritive quality of the crops will decline with physiological maturity (Miller, 1984).

Metabolisable energy (ME) and crude protein (CP) are among the important feed nutritive value indicators to consider in pasture selection and management, beside indicating forage quality and fibre proportions (Ulyatt et al., 1980; David, 2007; Waghorn, 2007). Metabolisable energy is the quantity of energy left or an approximation to the energy absorbed by animals after subtracting faecal, urine and methane energy losses that arised from digestion (Ulyatt et al., 1980). Crude protein which includes amino acid and non-protein N is calculated as percentage of N x 6.25 (Ulyatt et al., 1980; Waghorn, 2007). Thus, it could
represent directly the N content of the evaluated forage species. The percentage of CP differs among species and is influenced by several factors such as season, time of harvest and preservation techniques (David, 2007).

de Ruiter (2000) reported the crude protein (CP) content of ‘Hokonui’ oats declined from 29% at early harvest (1st May) to 17% (13th August) at late harvest. The progressive decline was accompanied by a decrease in ME. Turk et al. (2009) reported that forage quality of hairy vetch (*Vicia villosa* Roth) decreased over time although there was an increase in yield production. A similar trend was observed by Brink and Marten (1986) for barley and oats.

Carr *et al.* (2004) found that intercropping pea with barley or oat increased the CP concentration of forage compared with a sole crop of either cereal species under low-soil-N conditions in the Northern Great Plains, U.S.A. The results indicated that intercropping pea with oat may be preferred to a barley sole crop since forage DM yield is superior for the intercrop and CP concentration can be maintained.

Dordas and Lithourgidis (2011) reported that monocrop faba bean had the highest CP at 14.3% followed by intercrop faba bean – oat (12.8%) and monocrop oats (12.2%). In addition Ghanbari-Bonjar and Lee (2003) reported that the mean CP concentration of monocrop ‘Punch’ faba bean and a faba bean-wheat intercrop was higher than that of ‘Maris Widgeon’ wheat monocrop sown in autumn at Kent, in the United Kingdom. While, the CP of six faba bean cultivars reported by Clarke (1973), ranged from 13 - 19% in the United Kingdom.

### 2.5 Conclusions

From the literature reviewed the following conclusions can be made:

- Forage production is variable throughout New Zealand because of regional differences in temperature, solar radiation and precipitation.
- The amount of light intercepted by the crop canopy and its ability to convert it into DM is the primary determinant of crop growth and yield.
- Sowing date, intercropping and crop rotation are major considerations among agronomic practices which are capable of increasing DM yield.
- Evaluation of nutritive value of forage crops is an important aspect of crop selection, especially the determination of metabolisable energy and crude protein content as indicators of pasture quality.
• An appropriate combination of winter forage crops with the summer crops in a crop rotation system based on the environmental conditions is crucial for maximizing forage production.

This study investigated the effects of two main environmental factors; temperature and light interception on the growth and development of faba bean, oats and Italian ryegrass and an intercrop. Yield formation was quantified to explain the effects of different sowing and harvest dates on the total biomass produced by each of the three winter annual forages. The results are interpreted in relation to crop sequences that may precede or follow these winter crops in an annual rotation to meet a specific target of 45 t DM ha\(^{-1}\) yr\(^{-1}\) set by the New Zealand Dairy industry.
Chapter 3
Materials and methods

3.1 Introduction

This chapter describes the site of the experiments, soil characteristics, agronomic management and meteorological information for the two experimental years. This is followed by the measurements that were taken and the statistical analysis of the data. Specific descriptions of materials and methods used in each of the experiments are presented in Chapters 4, 5 and 6.

3.2 Meteorological conditions

3.2.1 Long term meteorological conditions

Meteorological data were obtained from Broadfields Meteorological Station, located about 1 km from Block H14 and 2 km north of Iversen 8. The long term monthly data presented were means from 1975-2007 (Figure 3.1). Air temperature data were recorded on site (Section 3.6.1) from March to October in 2008 and from March to December in 2009 (Figure 3.1a and b). The rest of the other months were taken from Broadfields Meteorological Station.

3.2.2 Mean air temperature, rainfall and solar radiation

The maximum of mean monthly air temperature was 22.7 °C and 24.4 °C recorded in January 2008 and 2009, respectively and both were higher than the long term mean of 22.1 °C in January (Figure 3.1a). The minimum of mean monthly air temperature was recorded at 0.2 °C in June 2008 and 1.0 °C in August 2009, correspondingly lower than the long term mean of 1.4 °C in July (Figure 3.1a). The annual rainfall was 721 mm in 2008 and 611 mm in 2009 (Figure 3.1b). The long term average annual rainfall was 626 mm. In 2008, the first growing season, rainfall exceeded the long term means in February, May, June, July, August, and December. In January, March, April, September, October and November all months received less than 40 mm of rain. In 2009, rainfall exceeded the long term means in February, April, May and October and the other months received less than 52 mm. In both years January received the highest solar radiation with 725 MJ m⁻² for 2008 and 723 MJ m⁻² for 2009 (Figure 3.1c). Solar radiation of 126 MJ m⁻² and 137 MJ m⁻² in June 2008 and 2009 were lower than the long term mean.
Figure 3.1: Meteorological data for maximum and minimum mean monthly air temperatures (a), rainfall (b), and total solar radiation (c) for 2008 (■) and 2009 (□) and the long term mean (1975-2007) (—) at Lincoln University, Canterbury, New Zealand.
3.3 Plant materials

In both experiments three different crops were used. They were:

(1) ‘Old New Zealand’ faba bean
(2) ‘Milton’ oats and
(3) ‘Feast II’ Italian ryegrass

Seed was provided by Plant and Food Research, Ltd Canterbury, New Zealand. Germination tests were used to calculate the seeding rate plot\(^{-1}\). Faba bean seeds were treated with the fungicide WAKIL\(^\circledR\) XL (metalaxy-M a.i. 175 g kg\(^{-1}\), fludioxonil a.i. 50 g kg\(^{-1}\), cymoxanil a.i 100 g kg\(^{-1}\)) while oats and Italian ryegrass seeds were not treated with any fungicide.

3.4 Experiment 1

3.4.1 Experimental site

The study was conducted on Block H14, Horticultural Research Area, Lincoln University, Canterbury, New Zealand (43° 38’ S, 172° 28’ E, 11 m a.s.l.). The experiment site had been used for barley trials in 2007.

3.4.2 Soil characteristics

The soil type is a Templeton silt loam interface. It is classified as Udic Ustochrept fine silty, mixed, mesic by the U.S Soil Taxonomy (Watt and Burgham, 1992) and as an ‘Immature Pallic Soil’ by New Zealand Soil Classification (Hewitt, 1998). Insufficient and excess soil water is common in this soil in summer and winter or spring, respectively (Hewitt, 1998). A Ministry of Agriculture and Fisheries (MAF) soil quick test was done before the start of the experiment and the soil test results are presented in Table 3.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>pH</th>
<th>Olsen-P (µg ml(^{-1}))</th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Na</th>
<th>Sulphate (µg g(^{-1}))</th>
<th>Anaerobic Mineralisable N (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>5.9</td>
<td>23</td>
<td>6.2</td>
<td>0.85</td>
<td>0.33</td>
<td>0.15</td>
<td>2</td>
<td>42</td>
</tr>
</tbody>
</table>
3.4.3 Treatments

There were five sowing dates and three crop species, combined factorially to give 15 treatments:

i) Sowing date (main plots):
   1. 4th March 2008 (S1)
   2. 28th March 2008 (S2)
   3. 21st April 2008 (S3)
   4. 12th May 2008 (S4)
   5. 3rd June 2008 (S5)

ii) Crop species (sub plots):
   1. ‘Old New Zealand’ faba bean (C1)
   2. ‘Milton’ oats (C2)
   3. ‘Feast II’ Italian ryegrass (C3)

These treatments were chosen to examine the combination of sowing dates and crop species to maximize crop yields during the autumn and spring transitional periods.

3.4.4 Experimental design

The experimental design was a split plot randomized complete block with sowing dates as main plots and the three crop species as sub-plots. There were four replicates. In total there were 60 plots with each sub-plot measuring 2.1 x 14 m. Each plot contained 14 rows of faba bean, oats or Italian ryegrass and was 14 m long.

3.4.5 Crop agronomy

3.4.5.1 Site preparation and sowing

Block H14 was ploughed on 18th February 2008; Dutch harrowed and rolled on 19th and 29th February 2008 to give a fine, firm seedbed. Faba bean, oats and Italian ryegrass seeds were sown with an Øyjord cone seeder. Seeds were sown at a target depth of 40 mm for faba bean and oats and at 10 mm for Italian ryegrass.

3.4.5.2 Planting density

The faba bean and oats were sown to achieve target populations of 60 plants m⁻² and 240 plants m⁻², respectively. The Italian ryegrass was sown at 25 kg ha⁻¹.
3.4.5.3 Fertilizer application

Sulphur superphosphate was applied on 2nd March 2008 at 200 kg ha\(^{-1}\) for the whole plot area. All plots except faba bean plots received 500 kg N ha\(^{-1}\) in 10 split applications of 50 kg N ha\(^{-1}\), as urea, during the growing season from 4th March to 31st October 2008.

3.4.5.4 Water management

Irrigation was applied when the soil moisture content was 20% below field capacity as measured by a Hydrosense probe to a depth of 0.3 m. Soil moisture content was monitored about every 7 to 10 days to avoid water stress and ensure that water was evenly provided during the growing season. Irrigation was by hand shift sprinklers. Irrigation was applied on 27th March 2008 (15 mm) and on 16th September 2008 (25 mm).

3.4.5.5 Pest and disease control

Pirimor 50 insecticide (a.i 500 g kg\(^{-1}\) pirimicarb) was applied for control of aphids, as vectors of Barley Yellow Dwarf Virus (BYDV), at 250 g ha\(^{-1}\) on 8th April, 29th May and 28th August 2008. Topsin\(^{\text{®}}\) M-4A (a.i 400 g l\(^{-1}\) thiophanate-methyl) at 2.5 l ha\(^{-1}\) was used to control *botrytis* on faba bean. This was applied on 8th April 2008. Chlorotex\(^{\text{®}}\) (a.i 500 g l\(^{-1}\) chlorothalonil) was also used to control *botrytis* and rust on faba bean and was applied on 5th and 29th May and 27th June 2008. Bravo\(^{\text{®}}\) was also used to control *botrytis* at 720 g l\(^{-1}\) chlorothalonil) and was sprayed on 14th July and on 14th August 2008. To combat rabbits netting was erected on 19th March 2008 around the whole experimental area. Bird netting was raised on 6th June 2008 for all plots in the 12th May sowing. Mesurol\(^{\text{®}}\) FS (a.i 500 g l\(^{-1}\) methiocarb) was applied on 11th June 2008 to the 12th May sowing plots to repel birds in the faba bean and oats plots.

3.4.5.6 Weed control

Glyphosate 450 (a.i 450 g l\(^{-1}\) glyphosate as the isoproplamine) was sprayed on 3rd March 2008 at 2 l ha\(^{-1}\) before the first sowing. Basagran\(^{\text{®}}\), (a.i 480 g l\(^{-1}\) bentazone) was sprayed at 2 l ha\(^{-1}\) on 3rd April 2008 to the plots where crops were sown. Weeds were also hand weeded from all plots throughout the growing season.
3.5 Experiment 2

3.5.1 Experimental site

The field experiment was carried out in Block 8 of ‘Iversen’ Field, Lincoln University, Canterbury, New Zealand (43° 38’S, 172° 28’ E, 11 m a.s.l.). The experimental site had previously been in lucerne in 2007, followed by barley in 2008.

3.5.2 Soil characteristics

The soil at this site is a Wakanui deep silt loam (U.S. Soil Taxonomy: Aquic Ustochrept fine sity, mixed, mesic) (Watt and Burgham, 1992). It is classified as an ‘Immature Pallic Soil’ by the New Zealand Soil Classification (Hewitt, 1998). Pallic soils have water deficits in summer and soil water surpluses in winter or spring with an average annual deficit of about 90-200 mm yr\(^{-1}\). A soil test was done prior to the experiment and the soil test results are in Table 3.2. The soil P content, at this site, was low compared with the site used in year one.

<table>
<thead>
<tr>
<th>Table 3.2: Soil test results (0-150 mm) at Iversen 8, Lincoln University, Canterbury, New Zealand.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>2009</td>
</tr>
</tbody>
</table>

3.5.3 Treatments

Three different sowing dates (chosen from the best of year 1) and three crop species and an intercrop of faba bean and oats were combined factorially to give 12 treatments:

i) Sowing date (main plots):
   1. 16\(^{th}\) March 2009 (S1)
   2. 16\(^{th}\) April 2009 (S2)
   3. 15\(^{th}\) May 2009 (S3)

ii) Crop species (sub-plots):
   1. ‘Old New Zealand’ faba bean (C1)
   2. ‘Milton’ oats (C2)
   3. ‘Feast II’ Italian ryegrass (C3)
   4. Combination of ‘Old New Zealand’ faba bean and ‘Milton’ oats (C4)
3.5.4 Experimental design

In the second experiment, the treatments were also in a split plot randomized complete block design with the sowing dates as the main plots and the four crop combinations as sub-plots. There were four replicates with 48 sub-plots each measured 6.3 x 10 m.

3.5.5 Crop agronomy

3.5.5.1 Planting density

The faba beans and the oats were sown to meet target population of 60 and 240 plants m\(^{-2}\), respectively. Italian ryegrass was again sown at 25 kg ha\(^{-1}\). For the intercrop, target population was 30 plants m\(^{-2}\) for faba bean and 120 plant m\(^{-2}\) for oats.

3.5.5.2 Site preparation

In the second experiment the plots were out of barley on 26\(^{th}\) February 2009. The soil was ploughed on 27\(^{th}\) February 2009; Dutch harrowed and rolled on 28\(^{th}\) February 2009 and 12\(^{th}\) March 2009.

3.5.5.3 Fertilizer application

A single application of 150 kg ha\(^{-1}\) of superphosphate was applied on 10\(^{th}\) March 2009 for the whole plot. Subsequent fertilizer applications were another 150 kg of diamonium phosphate (DAP) ha\(^{-1}\) and 33 kg N ha\(^{-1}\) in the form of urea.

3.5.5.4 Water management

All plots were irrigated using a hand shift sprinkler system to provide adequate water to the crops during the growing season. The plots were irrigated on 16\(^{th}\) November 2009 with 30 mm of water. Irrigation was applied when the soil moisture content was 20% below field capacity as measured by a Hydrosense probe inserted to a depth of 0.3 m.

3.5.5.5 Pest and disease control

The fungicide, Bravo\(^{®}\) (a.i 720 g l\(^{-1}\) chlorothalonil) was applied on 22\(^{nd}\) April 2009, 29\(^{th}\) September 2009 and 9\(^{th}\) November 2009 to control botrytis on the faba bean crops. Pirimor 50 insecticide (a.i 500 g kg\(^{-1}\) pirimicarb) was applied for aphid control at 250 g ha\(^{-1}\) on 5\(^{th}\) May 2009 as vectors of Barley Yellow Dwarf Virus (BYDV) on oats and faba bean plots.
3.5.5.6 Weed control

Roundup® (Transorb a.i 540 g l⁻¹ glyphosate) at 2 l ha⁻¹ was applied on 23rd February 2009 for weed control prior to cultivation of the whole plot area. A second application of the same herbicide was applied on 12th May 2009, prior to the third sowing. Weeds were also removed manually throughout the growing season.

3.6 Data collection

The following measurements, described in this section, were performed for both seasons of the first and second experiments.

3.6.1 Soil and air temperature

A temperature sensor (Thermistor KTY-110) was installed on each site after the first sowing of crops (5th March 2008 and 17th March 2009). Two data log temperature sensors were placed 20 mm under the soil surface to monitor soil temperature. There was one sensor above ground to measure air temperature at 1.4 m height. Temperatures were recorded and logged every 30 minutes. Data were downloaded using a hobo shuttle data logger (Onset Computer Corporation) at two-week intervals.

3.6.2 Emergence

Emergence was defined as when the coleoptile had clearly emerged through the soil surface for oats and Italian ryegrass and when the plumule started to open and emerge clearly on the soil surface for the faba bean. The number of emerged plants was determined from a marked area of 4 x 0.1 m² quadrats per plot. Counting was done daily in the autumn sowing period and at two-day intervals in winter. Counting was discontinued when plant numbers remained constant within the marked area for at least four consecutive days.

3.6.3 Above ground biomass

Above ground biomass was measured from two random samples taken from each plot using a 0.1 m² quadrat from the six central rows. Sampling commenced about 25 days after sowing and then at 2 to 3 week intervals in both experiments. For the final harvest 2 x 0.5 m² quadrats were used for sampling. Harvested plants were dried at 60 °C to constant weight. For Italian ryegrass the whole plot was mown when it lodged.
3.6.4 Leaf appearance

Leaf appearance was defined as when the leaf ligule appeared for oats and Italian ryegrass and when the leaf opened to more than 45° for faba bean. The number of fully expanded leaves was counted twice a week in the autumn and spring and once a week in the winter. Data are presented in the results section every seven days in autumn and spring and every 14 days in winter for clarity. Measurements were taken on 10 marked plants plot\(^1\) in the middle 2-3 rows. The number of days from sowing to the appearance of each leaf was counted for all species and sowing dates in both experiments. Italian ryegrass was harvested using a mower when it lodged and so leaf emergence counts ceased at that point.

3.6.5 Flowering/anthesis

The number of days to flowering was quantified from sowing date to the day when 50% of the marked plants showed the first sign of a flower. For faba bean, this was when the petal showed a purple colour. For oats, the emergence of the panicle and inflorescence of spikelet had fully emerged (Stage 10.5 based on the ‘Feekes’ scale) (Large, 1954). This was determined for all sowing dates in 2008 and 2009 for faba bean. For oats, only 4\(^{th}\) March and 28\(^{th}\) March sowing dates in 2008 were used because the last three sowing dates did not reach anthesis stage but all three sowing dates were used in 2009. Italian ryegrass did not show any visible signs of flowering and thus this phase could not be quantified.

3.6.6 Pod filling

The pod filling stage was determined from pod DM data, beginning at the first flower to final harvest but only for the 2009 season. There was no pod DM data in 2008.

3.6.7 Leaf area index

The leaf area index (LAI) was measured using a plant canopy analyser LAI-2000 (LI-COR Inc., Lincoln, Nebraska, USA) in the first experiment. This was measured weekly in March, April and May, once every three weeks in June, July and August and then weekly again in September and October. In the second experiment, the Sunscan canopy analysis system (type SS1) (Delta-T, Devices Cambridge, England) was used at the beginning of the experiment (only for three measurements) followed by use of Decagon’s AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, Inc, Pullman, WA). This was because the Sunscan was not working and needed to be fixed. The frequency of measurements was the same as in
the first experiment. Measurements of LAI for Italian ryegrass were continuously taken after mowing until it lodged in both seasons.

### 3.6.8 Light interception

In the first experiment, a plant canopy analyser LAI-2000 (LI-COR Inc., Lincoln, Nebraska, USA) was used and the fraction of radiation transmitted \((I/I_o)\) was measured. The measurement was done by taking one reading above and five readings below the canopy in each plot. The fraction of photosynthetically active radiation (PAR) intercepted by the canopy was then determined by Equation 3.1. The AccuPAR model LP-80 PAR/LAI Ceptometer was used in Experiment 2 to determine the fraction of PAR intercepted by the canopy by measuring incident PAR above and below the canopy. In each plot, three measurements were taken in quick succession. A session of measurements represented five random measurements above the canopy, five below the canopy and five more above the canopy between 11:00 to 14:00 NZST h during bright sunlight. The sensor was placed approximately 0.5 m above the crop canopy and then beneath the canopy near the soil surface. Measurements were taken until at least 90\% of the light was being intercepted by the crop canopy. The fraction of radiation intercepted \((F_i)\) by the canopy was determined by Equation 3.1 (Gallagher and Biscoe, 1978):

\[
F_i = 1.0 - \left( \frac{I}{I_o} \right)
\]

where, \(I\) is radiation under the canopy and \(I_o\) is radiation above the canopy.

Daily incident solar radiation from the Broadfield Meteorological Station (2 km north of the site) was used to determine total incident PAR and 50\% of the incident solar radiation received was taken as PAR (Monteith, 1972). The amount of intercepted PAR by the crop \((S_a)\) was calculated from (Szeicz, 1974):

\[
S_a = F_i \times S_i
\]

in which \(S_i\) is the total amount of incident PAR.

Total intercepted PAR was calculated as the sum of daily intercepted PAR for the duration of the three crop species over the growing season. Differences in the amount of daily intercepted PAR are a function of LAI, the extinction coefficient \((k)\) and the incident radiation. Solar
radiation penetration into a crop canopy can be related to LAI, $I$ and $I_o$, as shown in Equation 2.1.

### 3.6.9 Radiation use efficiency (RUE)

The RUE was calculated as the slope of the linear relationship between accumulated crop biomass and accumulated intercepted PAR. The regression line was forced through the origin based on the assumption that when accumulated intercepted PAR was zero, no DM was produced.

### 3.6.10 Nutritive value analysis

Analyses of forage quality were performed on the oats, intercrop (oats) and Italian ryegrass from DM yield samples for selected harvest dates for both experimental periods in 2008 and 2009. Samples were ground by a centrifugal grinder (Retsh ZM 200) to pass through a 1 mm stainless steel sieve for chemical analysis. The ground samples were then analysed by near infrared-spectroscopy (NIR) using a NIRS-Foss NIR systems 5000 Rapid Content at the Analytical Service Laboratory Lincoln University. Samples were analysed for nitrogen content (%), and digestible organic matter in dry matter (DOMD%). Calibration equations developed from NIRS spectra explained 90 to 99% of sample variation in analysing nutritive value of crops (Collins and Fritz, 2003). Crude protein (CP) and metabolisable energy (ME) were calculated based on Equations 3.3 and 3.4 (Nicol, 1989).

\[
CP = \text{N}\% \times 6.25 \quad \text{Equation 3.3}
\]

\[
ME = \text{DOMD} \times 0.16 \quad \text{Equation 3.4}
\]

The ME was presented as herbage ME (MJ kg$^{-1}$ DM) and calculated as total ME in Gigajoule ha$^{-1}$ (GJ ha$^{-1}$), herbage N (%) and total N were also calculated on a per hectare basis. Faba bean was unable to be analysed by NIR since there were no calibration in the current NIR software. These samples were analysed by wet chemistry for nitrogen (N) and DM digestibility (DMD) at the Lincoln University Analytical Service. For ME analyses a value above 11.5 MJ kg$^{-1}$ DM is considered adequate to support lactating dairy cows while less than 10 MJ kg$^{-1}$ DM is adequate for live weight gain of sheep and cattle (Fulkerson et al., 2007). For N, values above 2.4% are adequate for lactating dairy cows while the lower value of 1.6% is for live weight gain of sheep and cattle (Ulyatt et al., 1980).
3.6.11 Functional growth analysis (Dry matter)

Accumulated biomass was analysed using a standard curve option in Genstat version 12.2. The curve that was used was the Generalised logistic curve (Equation 3.5) (Gallagher and Robson, 1984).

\[ Y = \frac{C}{(1 + T e^{-b(x-m)})^{1/T}} \]  
Equation 3.5

where, C was the final (maximum) above ground dry matter and \( T, b \) and \( m \) were constants. The values of C, \( T, b \) and \( m \) were used to calculate the weighted mean absolute growth rate (WMAGR), duration of growth (DUR) and the maximum crop growth rate (\( C_{\text{max}} \)) based on the given equations (3.6-3.8). Generalised logistic curves:

\[ \text{WMAGR} = \frac{b + C}{2(T+2)} \]  
Equation 3.6

\[ \text{DUR} = \frac{2(T+2)}{b} \]  
Equation 3.7

\[ \text{\( C_{\text{max}} \)} = \frac{b + C}{(T+1)^{2+1/T}} \]  
Equation 3.8

3.7 Statistical analysis

Statistical analyses were carried out using the Genstat package (Version 12.2). A full split plot analysis of variance was used with sowing dates as main plots and species as sub-plots and four replicates in both of the experiments conducted in 2008 and 2009. Other statistics calculated were the standard errors of the mean (S.E.M), the coefficient of variation (CV as a %), the correlation coefficient, the percent variance accounted for (R\(^2\)) and the coefficients of linear regression. Significant main effects and interactions were separated by the Least Significant Difference (LSD) test at the 5% level. Details of the data analysed are given in each respective chapter.
Chapter 4
Dry matter yield and nutritive value of faba bean, oats and Italian ryegrass

4.1 Introduction

It is expected that early-sown crops require a longer period to mature and that later harvest dates can therefore maximize yields. Husain (1984), reported dry matter (DM) yield of faba bean was higher when it was sown in autumn compared with spring in Canterbury, New Zealand. His study concluded that crops sown on different dates gave different yields because of differences in the climatic conditions between seasons and variation in crop duration (Section 2.4.1). Furthermore, intercropping could possibly increase DM yield through more effective utilisation of the available resources, particularly light, by crops with complementary canopy architecture (Section 2.4.2).

At the other end of growing season, the time of harvest would also influence the nutritive value of crops. In general, as DM increased the crop quality drops and usually the feed quality of a crop declines with delays in the harvest date (Section 2.4.4). For instance, Khorasani et al. (1997) reported that greater DM yields of cereal forages were obtained however the nutritive value was decreased by the delayed harvest.

In this chapter the first objective was to quantify DM yield of three forage crops sown and harvested on different dates and compare these with yields from an intercrop of faba bean and oats. The second objective was to describe the quantity-quality trade-off of the crops grown over a long duration as they progress from vegetative to reproductive development. In the first season plots were harvested at an early stage of crop development to mimic on farm requirements to prepare for a following crop. The assumption was that a greater DM yield could be achieved with the early sowing of a following summer crop, such as maize or kale. In the second season, crops were grown over a longer duration to evaluate the impact of different times of sowing and harvest on the relationship between DM yield and quality of these forages crops.
4.2 Materials and Methods

This chapter reports on the DM yield and growth rates for two growing seasons of experiments in 2008 and 2009. A detailed description of the sites, crops sown, environmental conditions, experimental design and crop management was presented in Chapter 3. In the first season of the experiment, the crops were sown on 4\textsuperscript{th} March, 28\textsuperscript{th} March, 21\textsuperscript{st} April, 12\textsuperscript{th} May and 3\textsuperscript{rd} June of 2008 and in the second season on 16\textsuperscript{th} March, 16\textsuperscript{th} April and 15\textsuperscript{th} May of 2009.

In 2008, the crops were harvested at different times for each particular sowing date but with an aim of harvesting before the end of October. In 2009 the crops were harvested sequentially for all sowing dates until a final harvest date when crops were more mature than in the previous season. Therefore, the final harvest for the first season was also at a different time and stage of crop development for each sowing date. Specifically, harvests were on 13\textsuperscript{th} October for the 4\textsuperscript{th} March sowing date, 11\textsuperscript{th} October for the 28\textsuperscript{th} March sowing date and 25\textsuperscript{th} October for the 21\textsuperscript{st} April sowing date. For the 12\textsuperscript{th} May and 3\textsuperscript{rd} June sowing dates, the final harvest was taken on 30\textsuperscript{th} October 2008. In contrast in 2009, crops were sequentially harvested through October and November before a final harvest was taken on the 4\textsuperscript{th} December 2009, for all 3 sowing dates.

4.3 Measurements

The main measurements and a detailed description of the measurements taken in this Chapter were presented in Chapter 3. The measurements were above ground biomass (Section 3.6.3), nutritive value (Section 3.6.10) and functional growth analysis (Section 3.6.11).

4.4 Statistical analysis

4.4.1 Above ground biomass and functional growth analysis

Analyses of variance (ANOVA) using Genstat 12.2 were used to determine main effects and significant interactions. Means were separated by least significant difference tests at the 5\% significance level. Both the experiments, in 2008 and 2009, were analysed as split plot designs with sowing dates as main plots and species as sub-plots with four replicates. The maximum TDM production for individual plots was identified and analysed by ANOVA. The ‘maximum TDM’ refers to the highest yield from the whole growing season for each sowing date for both seasons of the experiments, and may have occurred at or before the final harvest.
A generalised logistic function was fitted for DM yield data (Section 3.6.11). However, in 2008, for sowing date 1 (4\textsuperscript{th} March 2008) the calculation for the weighted mean absolute growth rate (WMAGR), duration of exponential growth (DUR), and the maximum crop growth rate ($C_{\text{max}}$) were determined manually from the relationship between accumulated DM and time over the range of days from 5 to 95% of maximum DM for all species. This was because of a poor dataset associated with atypical crop growth due to unfavourable environmental conditions (snow, frost damage, disease infestation, and lodging). The functions were derived from the means of treatments and ANOVAs were conducted on growth variates calculated from parameters of curves fitted to each plot for functional analysis.

4.4.2 Nutritive value

The herbage ME, total ME, herbage N and total N data were fully replicated and subjected to analyses of variance (ANOVA) using Genstat 12.2 and the standard error of mean (S.E.M) for sowing date effect, species effect and the interaction of sowing date and species effect are presented.


4.5 Results

4.5.1 Experiment 1 (2008)

4.5.1.1 Maximum total dry matter (TDM)

In 2008 the greatest maximum TDM yield was obtained from the 4\textsuperscript{th} March sowing (13,490 kg ha\textsuperscript{-1}) while the last two sowings gave the lowest yields as presented in Table 4.1. There was no difference in the maximum TDM production between the 28\textsuperscript{th} March and 21\textsuperscript{st} April sowings or between the 12\textsuperscript{th} May and 3\textsuperscript{rd} June sowings. There was a significant species effect with oats yielding 4,430 kg ha\textsuperscript{-1} more than the faba bean and 3,290 kg ha\textsuperscript{-1} more than the Italian ryegrass. There was no significant interaction between sowing date and species for maximum TDM yield.

Table 4.1: Maximum total dry matter (TDM) yield during the growing season of three different species sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Maximum TDM (kg ha\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4\textsuperscript{th} March</td>
<td>13,490\textsuperscript{a}</td>
</tr>
<tr>
<td>28\textsuperscript{th} March</td>
<td>10,350\textsuperscript{b}</td>
</tr>
<tr>
<td>21\textsuperscript{st} April</td>
<td>9,900\textsuperscript{b}</td>
</tr>
<tr>
<td>12\textsuperscript{th} May</td>
<td>7,070\textsuperscript{c}</td>
</tr>
<tr>
<td>3\textsuperscript{rd} June</td>
<td>6,360\textsuperscript{c}</td>
</tr>
<tr>
<td>S.E.M</td>
<td>379.4</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
</tr>
</tbody>
</table>

Species (S)

<table>
<thead>
<tr>
<th>Species</th>
<th>Maximum TDM (kg ha\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oats</td>
<td>12,010\textsuperscript{a}</td>
</tr>
<tr>
<td>Faba bean</td>
<td>7,580\textsuperscript{c}</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>8,720\textsuperscript{b}</td>
</tr>
<tr>
<td>S.E.M</td>
<td>253.3</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
</tr>
</tbody>
</table>

Interaction (SD x S) NS

Sowing date and species followed by the same letter are not significantly different, *** = P <0.001, NS = Not significant
4.5.1.2 Total dry matter accumulation over time

The pattern of total DM accumulated over time for faba bean, oats and Italian ryegrass is shown in Figures 4.1a-e for the five sowing dates in 2008. In most cases, the curve fitting approximates the increase in DM yields. However, the final harvest occurred before most crops reached a final asymptotic phase, particularly for the later sowings. In all cases, a distinct lag phase was apparent before the rapid accumulation of DM in the linear phase. Based on these curves functional growth analysis provides a summary of these patterns. However, the results should be interpreted with caution due to the lack of an asymptotic final growth phase in some treatments. The lack of a distinct plateau or ceiling yield was one reason why harvests were extended in the second season.
Figure 4.1: Total dry matter (DM) yield of faba bean (●), oats (○) and Italian ryegrass (▼) over time when sown on 4\textsuperscript{th} March (a), 28\textsuperscript{th} March (b), 21\textsuperscript{st} April (c) 12\textsuperscript{th} May (d) and 3\textsuperscript{rd} June 2008 (e) at Lincoln University, Canterbury, New Zealand. Error bars are standard error of mean (S.E.M) of maximum total DM. Lines are the fitted generalized logistic curves. Coefficients are given in Appendix 1.
4.5.1.3 Functional Growth Analysis

Weighted mean absolute growth rate (WMAGR)

The interaction in WMAGR between sowing date and species is shown in Figure 4.2. This was caused by the highest WMAGR for faba bean and oats occurring from the 12\textsuperscript{th} May sowing with a decline when sown on 3\textsuperscript{rd} June. However, for Italian ryegrass, the highest WMAGR was from the 3\textsuperscript{rd} June sowing. There was no significant difference in the WMAGR of the last three sowing dates for oats (mean of 167 ± 13.1 kg DM ha\textsuperscript{-1} d\textsuperscript{-1}) with the 12\textsuperscript{th} May sowing of faba bean (147 kg DM ha\textsuperscript{-1} d\textsuperscript{-1}). However, the WMAGR of oats sown on 12\textsuperscript{th} May and 3\textsuperscript{rd} June was significantly different from all other sowing dates and species. The main effect of sowing date and species on the WMAGR is presented in Appendix 2.

Figure 4.2: Weighted mean absolute growth rate (kg DM ha\textsuperscript{-1} d\textsuperscript{-1}) of faba bean (■), oats (■) and Italian ryegrass (■) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bar represents least significant differences (LSD) at 5\% level.
Duration of the exponential phase of growth (DUR)

There was a significant (P<0.01) sowing date by species interaction for the DUR of the exponential phase as shown in Figure 4.3. Duration of the exponential phase showed a general trend of a shorter time period with later sowings in oats and Italian ryegrass. Both oats and Italian ryegrass had their longest DUR in the 4th March sowing date and their shortest DUR in the 3rd June sowing date. However, in faba bean the shortest duration of exponential growth occurred for the crop sown on 12th May 2008. The main effect of sowing date and species on DUR is presented on Appendix 2.

Figure 4.3: Duration of the exponential phase (days) of growth of faba bean (■), oats (■) and Italian ryegrass (■) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bar represents least significant differences (LSD) at 5% level.
Maximum crop growth rate ($C_{\text{max}}$)

Figure 4.4 illustrates the interaction between sowing date and species on $C_{\text{max}}$. There was a similar trend of increased $C_{\text{max}}$ in oats and faba bean but their $C_{\text{max}}$ values were higher in the 12th May sowing date than in the early sowing (4th March) and in the last sowing date (3rd June). In contrast, the highest $C_{\text{max}}$ for Italian ryegrass occurred in 3rd June sowing date. The effect of sowing date and species on $C_{\text{max}}$ is presented in Appendix 2.

**Figure 4.4:** Maximum crop growth rate (kg DM ha$^{-1}$ d$^{-1}$) of faba bean (■), oats (■) and Italian ryegrass (■) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bar represents least significant differences (LSD) at 5% level.
4.5.1.4 Nutritive value of winter forages

Herbage metabolisable energy (ME)

Italian ryegrass showed a higher maximum herbage ME than faba bean and oats from the 4th March, 21st April, 12th May and 3rd June sowing dates (P<0.001) (Figure 4.5).

All of the species produced DM that contained at least 11.5 MJ kg⁻¹ DM. This value is considered adequate to support lactation in dairy cows. However, this occurred at different times. Faba bean DM reached 11.5 MJ kg⁻¹ from 106-186 DAS. For oats and Italian ryegrass this occurred from 145 - 178 DAS and 150 - 203 DAS respectively. For the last two sowing dates, all of the species reached a herbage ME of 11.5 MJ kg⁻¹ DM at the same time which was in late October (141 to 171 DAS).

For all the crops the ME declined from 11.5 to 10 MJ kg⁻¹ DM over a 30 to 40 days period. Despite this decline, only the oats from 21st April sowing date had an ME which was significantly below 10 MJ kg⁻¹ DM at final harvest.
Figure 4.5: Herbage metabolisable energy (ME) of faba bean (●), oats (○) and Italian ryegrass (▼) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for species effect. Sowing dates of crops are given in the top left corner. Dotted line (∙∙∙) for herbage ME at 10 MJ kg\(^{-1}\) DM and dashed line (---) for herbage ME at 11.5 MJ kg\(^{-1}\) DM.
Total metabolisable energy (ME)

Combining the yield and quality values allows total crop ME to be calculated. Oats tended to produce a higher total ME ha\(^{-1}\) than Italian ryegrass and faba bean for all sowing dates in 2008 as presented in Figure 4.6. The highest total ME was 163 GJ ha\(^{-1}\) (203 DAS) for oats sown on 4\(^{th}\) March. This was greater (P<0.001) than the total ME from Italian ryegrass (130 GJ ha\(^{-1}\)) and faba bean (54 GJ ha\(^{-1}\)), when crops were harvested at late of September (203 DAS).

Similarly, from the 28\(^{th}\) March sowing date, oats produced the highest total ME of 139 GJ ha\(^{-1}\) (184 DAS) when this crop was harvested at the end of September. This yield was higher (P<0.001) than those of Italian ryegrass (90 GJ ha\(^{-1}\)) and faba bean (38 GJ ha\(^{-1}\)).

For the last three sowing dates, oats maintained the highest total ME which ranged from 97 to 129 GJ ha\(^{-1}\) followed by Italian ryegrass (68 to 92 GJ ha\(^{-1}\)) and faba bean (27 to 45 GJ ha\(^{-1}\)). All of crops in these sowing dates reached their highest total ME at the middle to the end of October (145 to 187 DAS).
Figure 4.6: Total metabolisable energy (ME) of faba bean (●), oats (○) and Italian ryegrass (▼) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for species effect. Sowing dates of crops are given in the top left corner.
**Herbage N (%)**

At all sowing dates, only faba bean always produced a N content of at least 2.4% (15% CP) (Figure 4.7). Herbage N for the first four sowing dates ranged from 3.2 to 3.8% (20 to 24% CP) from crops harvested at the end of September to the end of October. For oats, a herbage N of 2.4% was reached 86 DAS by the 4th March sowing date, 165 DAS for the 28th March and 153 DAS for the 21st April sowing dates. For the last two sowing dates, oats achieved 2.4% N at 131 DAS (12th May sowing) and 123 DAS (3rd June sowing), respectively. For Italian ryegrass, all of the sowing dates attained a herbage N of 2.4% when harvested in early to late October. The exception was for cut carried out for the 4th March sowing date (reached at the middle of June, 102 DAS) and in 12th May sowing (reached at the end of September, 140 DAS).

Faba bean herbage N was more than 1.6% (10% CP) on all sampling dates. This suggests that harvesting could be delayed until after October and this was a reason for the increased crop duration in the second year of the experiment. Oats reached a herbage N of 1.6% in August (166 DAS) for the 4th March sowing date, while the other sowing dates attained 1.6% N in early to the end of October. This pattern was similar for Italian ryegrass. However, for the 21st April and 12th May sowing dates, Italian ryegrass continued to maintain a higher herbage N of 2.0% (187 DAS) and 2.2% (171 DAS), respectively. Herbage N declined as crop maturity advanced with later harvests.
Figure 4.7: Herbage nitrogen (N) of faba bean (●), oats (○) and Italian ryegrass (▼) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for maximum herbage N for species effect in 2008 season. Sowing dates of crops given in the top left corner. Dotted line (⋯) for herbage N at 1.6% (10% CP) and dashed line (---) for herbage N at 2.4% (15% CP).
Total N

The combination of yield and herbage N% was also used to calculate total crop N harvested. As shown in Figure 4.8 for the 4\textsuperscript{th} March sowing date, faba bean had a higher total N (115 kg N ha\textsuperscript{-1}) compared with oats (81 kg N ha\textsuperscript{-1}) and Italian ryegrass (69 kg N ha\textsuperscript{-1}) (P<0.05) when harvested in early May (62 DAS). However, when harvested later at 86 and 166 DAS, there was no significant difference among species. Similarly, at the last three harvested dates, there was no significant difference between faba bean and Italian ryegrass. For oats, crop N remained below 200 kg ha\textsuperscript{-1} even at the end of the season. For the 28\textsuperscript{th} March sowing, the total N of all crops was similar and reached 272 kg N ha\textsuperscript{-1} by the end of September (184 DAS). For the last three sowing dates, the maximum total N was less than 200 kg ha\textsuperscript{-1} except for one harvest of faba beans in the 21\textsuperscript{st} April sowing date.
Figure 4.8: Total nitrogen (N) of faba bean (●), oats (○) and Italian ryegrass (▼) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for species effects. Sowing dates of crops given in the top left corner.
4.5.2 Experiment 2 (2009)

4.5.2.1 Maximum total dry matter (TDM)

The significant interaction between sowing date and species for maximum TDM yield is shown in Figure 4.9. This illustrates that with faba bean, oats and Italian ryegrass the maximum TDM decreased with later sowing dates. However, for the faba bean-oat intercrop yield declined in the 16\textsuperscript{th} April sowing date and increased again in the 15\textsuperscript{th} May sowing date. The maximum TDM yield of oats from the March sowing was higher (P<0.01) than from the other species and sowing dates except for the faba bean-oats intercrop sown on 16\textsuperscript{th} March. There was no significant difference in faba bean sown in the 15\textsuperscript{th} May sowing with Italian ryegrass sown on 16\textsuperscript{th} April and 15\textsuperscript{th} May 2009. The main effects of sowing date and species on maximum TDM are presented in Appendix 3.

**Figure 4.9:** Maximum total dry matter yield (TDM) of faba bean (■), oats (■), Italian ryegrass (■) and faba bean-oat intercrop (■) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Error bar represents least significant differences (LSD) at 5% level.
4.5.2.2 Total dry matter accumulation over time

Figure 4.10 shows the TDM accumulated over time. Functional growth analysis for 2009 indicated a different trend in the growth rates of species sown compared with 2008 (Table 4.2). Sowing date had no effect on any growth rate (P<0.07) but as expected the duration of the linear phase declined (P<0.001) as sowing was delayed (Appendix 5).
Figure 4.10: Total dry matter (DM) yield of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean-oat intercrop (Δ) over days when sown on 16th March (a), 16th April (b) and 15th May 2009 (c) at Lincoln University, Canterbury, New Zealand. Error bar represents standard error of mean (S.E.M) of maximum total DM. Lines are fitted generalized logistic curves. Coefficients are given in Appendix 4.
4.5.2.3 Functional Growth Analysis

Weighted mean absolute growth rate (WMAGR)

There was no sowing date by species interaction (P<0.07) for the WMAGR in 2009. Table 4.2 shows that there was no significant difference in the WMAGR for oats and the faba bean-oat intercrop but these were higher than in Italian ryegrass (P<0.001). Oats growth rates were 17.5% higher than in faba bean. There was also no difference between faba bean and the faba bean-oat intercrop with an average of 176 ± 7.53 kg DM ha$^{-1}$ d$^{-1}$.

Table 4.2: The effect of sowing date and species on the weighted mean absolute growth rate (WMAGR) and maximum crop growth rate ($C_{\text{max}}$) of three different species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>WMAGR (kg DM ha$^{-1}$ d$^{-1}$)</th>
<th>$C_{\text{max}}$ (kg DM ha$^{-1}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16$^{\text{th}}$ March</td>
<td>150</td>
<td>264</td>
</tr>
<tr>
<td>16$^{\text{th}}$ April</td>
<td>164</td>
<td>262</td>
</tr>
<tr>
<td>15$^{\text{th}}$ May</td>
<td>171</td>
<td>270</td>
</tr>
<tr>
<td>S.E.M</td>
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<td>8.37</td>
</tr>
<tr>
<td>Significance</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Species (S)

<table>
<thead>
<tr>
<th>Species</th>
<th>WMAGR (kg DM ha$^{-1}$ d$^{-1}$)</th>
<th>$C_{\text{max}}$ (kg DM ha$^{-1}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oats</td>
<td>201$^\text{a}$</td>
<td>329$^\text{a}$</td>
</tr>
<tr>
<td>Faba bean</td>
<td>171$^\text{b}$</td>
<td>290$^\text{a}$</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>96$^\text{c}$</td>
<td>143$^\text{b}$</td>
</tr>
<tr>
<td>Faba bean-oat intercrop</td>
<td>181$^\text{ab}$</td>
<td>299$^\text{a}$</td>
</tr>
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<td>S.E.M</td>
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<td>14.34</td>
</tr>
<tr>
<td>Significance</td>
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<tr>
<td>Interaction (SD x S)</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Sowing date and species followed by the same letter are not significantly different, ***P=<0.001, NS= Not significant

Duration of the exponential phase of growth (DUR)

There was an interaction (P<0.001) between sowing date and species for crop DUR as shown in Figure 4.11. The DUR of Italian ryegrass, sown on 16$^{\text{th}}$ March, was significantly longer at 261 days compared with a mean of 144 ± 10 days for the other crops. Duration of the exponential phase of Italian ryegrass from the 16$^{\text{th}}$ April sowing date was also longer than from the other sowing dates and species. Essentially the longer DUR appeared to compensate for the lower WMAGR (Table 4.2). The main effects of sowing date and species on DUR are presented in Appendix 5.
Figure 4.11: Duration of the exponential phase (days) of growth of faba bean (■), oats (■), Italian ryegrass (■) and faba bean-oat intercrop (■) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Bar represents least significant differences (LSD) at 5% level.

**Maximum crop growth rate ($C_{\text{max}}$)**

The species effect ($P<0.001$) for $C_{\text{max}}$ indicated no difference between oats, faba bean and the faba bean-oat intercrop with an average of 306 kg DM ha$^{-1}$ d$^{-1}$ but these were higher than in Italian ryegrass at 143 kg DM ha$^{-1}$ d$^{-1}$ (Table 4.2).
4.5.2.4 Nutritive value

Herbage metabolisable energy (ME)

In 2009, from all three sowing dates, Italian ryegrass sown on 15\textsuperscript{th} May had the highest (P<0.001) herbage ME (13.1 MJ kg DM\textsuperscript{-1}) compared with faba bean, oats and the faba bean-oat intercrop. This maximum value was achieved in early September (113 DAS) as shown in Figure 4.12. Across sowing dates, herbage ME ranged from 9.3 to 13.1 MJ kg DM\textsuperscript{-1} for Italian ryegrass, 7.0 to 12.8 MJ kg DM\textsuperscript{-1} for oats, 9.8 to 12.1 MJ kg DM\textsuperscript{-1} for faba bean and 9.2 to 12.4 MJ kg DM\textsuperscript{-1} for the faba bean-oat intercrop. In all cases the early season vegetative ME was above 11.5 MJ kg DM\textsuperscript{-1} except for the 16\textsuperscript{th} March sowing and once ME began to decline there was an almost linear decrease to the minimum value at final harvest. Specifically, Italian ryegrass had herbage ME of at least 11.5 MJ kg DM\textsuperscript{-1} from sowing until when it was harvested around early October to the end of November (163 to 259 DAS). For faba bean and oats, an ME ≥ 11.5 MJ kg DM\textsuperscript{-1} was obtained from early August to late September (113 to 128 DAS for faba bean and 137 to 148 DAS for oats). As expected, for the faba bean-oat intercrop changes in the herbage followed an intermediate pattern between the two monocultures. An ME at 10 MJ kg DM\textsuperscript{-1}, occurred in Italian ryegrass from 203 to 228 DAS, at 182 to 203 DAS for the faba bean, 166 to 180 DAS for oats and 169 to 180 DAS for the faba bean-oat intercrop. As in the previous year, herbage ME declined as the harvest was delayed and the crop matured.
Figure 4.12: Herbage metabolisable energy (ME) of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean-oat intercrop (Δ) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for herbage ME of sowing date effects (SD) (a) species effects (S) (b) and SD*S interactions (c). Sowing dates of crops are given in the top left corner. Dotted line (…) for herbage ME at 10 MJ kg⁻¹ DM and dashed line (---) for herbage ME at 11.5 MJ kg⁻¹ DM.
Total metabolisable energy (ME)

Accumulated total ME ha\(^{-1}\) showed an increasing trend as the harvest date was delayed (Figure 4.13). Oats showed a consistently higher total ME than the other forage crops for the 16\(^{th}\) March and 15\(^{th}\) May sowing dates, while it was higher than in faba beans and the intercrop from the 16\(^{th}\) April sowing. The maximum ME from the three sowing dates was 220 GJ ha\(^{-1}\) for oats, 176 GJ ha\(^{-1}\) for Italian ryegrass, 81 GJ ha\(^{-1}\) for faba bean and 9.2 to 166 GJ ha\(^{-1}\) for the faba bean-oat intercrop. Faba bean had the lowest total ME on most harvest dates for all sowing dates.
Figure 4.13: Total metabolisable energy (ME) of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean-oat intercrop (∆) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for total ME of sowing date effects (SD) (a) species effects (S) (b) and SD*S interactions (c). Sowing dates of crops are given in the top left corner.
Herbage N (%)

As expected, herbage N content was highest at the initial vegetative stage of crop growth and declined as maturity advanced as shown in Figure 4.14. Faba bean had a higher herbage N which was above 2.4% (15% CP) far longer for all sowing dates. For example, the herbage N was still above 2.6% at harvests at late November and early December, 250 DAS on the 16\textsuperscript{th} March sowing, 218 DAS on the 16\textsuperscript{th} April and 202 DAS on the 15\textsuperscript{th} May sowing. The oats maintained ≥ 2.4% N when they were harvested from early September (170 DAS) to late of October (160 DAS) from each sowing date. While for Italian ryegrass, a suitable time to harvest and achieve at least 2.4% N was from the middle of October (213 DAS) to the end of November (196 DAS). The herbage N of Italian ryegrass ranged from 1.4 to 4.4% for the 16\textsuperscript{th} March sowing date, 1.3 to 5.4% for the 16\textsuperscript{th} April sowing date and 2.1 to 4.2% for the 15\textsuperscript{th} May sowing date. All the crops achieved highest percentage herbage N when they were harvested in the end of autumn (May) to early spring (September) before declining in the middle of spring towards early summer (December). Additionally for the faba bean-oat intercrop only, crops harvested from the end of October (224 DAS) to the middle of November (186 DAS) had a herbage N at ≥ 2.4%. From all sowing dates, herbage N dropped to 1.6% (10% CP), for oats harvested at the end of October (198 DAS) to the middle of November (184 DAS). In contrast, Italian ryegrass was ≥ 1.6% N up to early December (229 DAS). The faba bean-oat intercrop, harvested later than the middle of November still had a herbage N over 1.6% at 203 DAS in the 15\textsuperscript{th} May sowing date.
Figure 4.14: Herbage nitrogen (N) of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean- oat intercrop (Δ) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Error bars represent standard error of mean (S.E.M) for maximum herbage N for sowing date effects (SD) (a) species effects (S) (b) and SD*S interactions (c) in 2009 season. Sowing dates of crops are given in the top left corner. Dotted line (∙∙∙) for herbage N at 1.6% (10% CP) and dashed line (---) for herbage N at 2.4% (15% CP).
Total N

The accumulation of total N ha\(^{-1}\) of the forage species in 2009 showed a similar pattern to 2008, with a low total N during the early growth stage and a high total N as the crop yield increased as shown in Figure 4.15. For most harvest dates, the faba bean produced a greater total N than the oats, the Italian ryegrass and the faba bean-oat intercrop for the 16\(^{th}\) March and 16\(^{th}\) April sowing dates. The total N in faba bean reached a maximum of 539 kg ha\(^{-1}\) for all evaluated sowing dates. Maximum total N was 401 kg N ha\(^{-1}\) (239 DAS) for oats, 412 kg N ha\(^{-1}\) (218 DAS) for Italian ryegrass and 445 kg N ha\(^{-1}\) (213 DAS) for the faba bean-oat intercrop. Oats produced the lowest total N yield in most of harvest dates in all sowing dates. The minimum total N of oats in the 16\(^{th}\) March sowing was 67 kg N ha\(^{-1}\) which was 66 DAS, 48 kg N ha\(^{-1}\) (98 DAS) for the 16\(^{th}\) May sowing date and 58 kg N ha\(^{-1}\) (113 DAS) for the 15\(^{th}\) May sowing date.
Figure 4.15: Total nitrogen (N) of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean-oat intercrop (Δ) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Error bars represent maximum standard error of mean (S.E.M) for sowing date effects (SD) (a) species effects (S) (b) and SD*S interactions (c). Sowing dates of crops are given in the top left corner.
4.6 Discussion

4.6.1 Maximum total dry matter (TDM)

From the results presented above, there were no significant interactions between sowing date and species in 2008 for maximum TDM (Table 4.1). However, there was an interaction in 2009 (Figure 4.9). The pattern of maximum TDM production showed higher DM yield of forage crops from earlier sowing dates and a decline in DM yield as the sowing was delayed in both seasons. Across the species sown, oats consistently gave the highest maximum TDM in both growing seasons of 2008 and 2009 (Table 4.1 and Figure 4.9). These yields were consistent with the results of McDondald and Stephen (1979) who also reported oats gave the most consistent and high DM yields, over a 4 year study period in Mosgiel, New Zealand, ranging from 3,000 to 17,000 kg ha\(^{-1}\).

Overall, maximum TDM in 2009 (Figure 4.9) was greater than in 2008 (Table 4.1). This could be attributed to the later final harvest in 2009. However, there was some variation in yield that showed a window of sowing dates was available to produce similar yields. For instance, oats sown on 4\(^{th}\) March produced 15,016 kg ha\(^{-1}\) by the end of September which was 203 DAS (Figure 4.1). Similarly, in 2009, by this particular harvest date, the TDM of oats sown on 16\(^{th}\) March was only 652 kg ha\(^{-1}\) less at 14,364 kg ha\(^{-1}\) (191 DAS) (Figure 4.10). For oats sown later on 28\(^{th}\) March in 2008, 12,636 kg ha\(^{-1}\) was grown by the end of September (184 DAS) (Figure 4.1), while oats sown on 16\(^{th}\) March in 2009, yielded 15,331 kg ha\(^{-1}\) (196 DAS) at a similar harvest date (Figure 4.10). However, after the 28\(^{th}\) March sowing (21\(^{st}\) April, 12\(^{th}\) May and 3\(^{rd}\) June in 2008 and 16\(^{th}\) April and 15\(^{th}\) May in 2009) there was a consistent decrease in the DM yield compared with sowing in March, specifically due to the shorter growing period.

In summary, these results suggest oats can be sown early, or in the middle of March, but not later to produce yields of at least 14 t ha\(^{-1}\) by the end of September. Oats sown on 4\(^{th}\) March 2008 still produced a maximum TDM about 4.5% higher than when sown on 16\(^{th}\) March 2009 when harvested on the same date, despite a severe attack of barley yellow dwarf virus (BYDV) and lodging in the 2008 crop. Delaying the first sowing until the middle of March in 2009 possibly protected the crop from the peak autumn flight of the virus vectors and therefore BYDV was not detected in 2009. Barley yellow dwarf virus has been identified as a serious cause of yield reduction in cereals in New Zealand, the United States and the United Kingdom and often leads to economic loss (Smith, 1963). In Lincoln, Canterbury, Farrell and
Stufkens (1992) reported that six aphid species were detected as vectors of BYDV, mostly by the bird cherry-oat aphid (*Rhopalosiphum padi*).

For faba beans, the maximum TDM of crops sown on 4\textsuperscript{th} March 2008 was 11,410 kg ha\textsuperscript{-1} (223 DAS) (Figure 4.1) compared with 14,290 kg ha\textsuperscript{-1} for crops sown on 16\textsuperscript{th} March 2009 (211 DAS) (Figure 4.10) when both crops were harvested in the middle of October. When the sowing date was delayed to 28\textsuperscript{th} March in 2008, the maximum TDM decreased to 7,460 kg ha\textsuperscript{-1} when harvested in the end of September (184 DAS) compared with 12,870 kg ha\textsuperscript{-1} for the crop sown on 16\textsuperscript{th} March in 2009 and harvested at 196 DAS (Figure 4.10). Moreover, faba bean sown later on 21\textsuperscript{st} April 2008 and harvested in the middle of October (179 DAS) produced a maximum TDM of 7,930 kg ha\textsuperscript{-1} (Figure 4.1) compared with 13,212 kg ha\textsuperscript{-1} harvested at 184 DAS for the crops sown on 16\textsuperscript{th} April in 2009 (Figure 4.10). These results show the 2008 season consistently had lower yields than in 2009 from crops sown and harvested on similar calendar dates.

As an overview, faba bean should be sown before end of March to ensure a high DM production. The differences in maximum TDM yield in 2008 compared with 2009 were related to an infestation of chocolate spot (*Botrytis fabae*), and Ascochyta blight (*Ascochyta fabae*). This started in April 2008 and a severe outbreak of rust (*Uromyces viciae-fabae*) occurred which was most serious in 4\textsuperscript{th} March 2008 sowing. Furthermore, in the 21\textsuperscript{st} April 2008 sowing date, some plots were affected by a wilt caused by *Fusarium oxysporum*. Further, snow falls in early June and July 2008 caused some lodging and frost damage which affected plant growth especially when the main stems were broken and most of the regrowth was recovered by growth of branches from the base of the main stem. Overall, the experience in 2008 indicated faba beans were an agronomically more challenging crop to grow than oats and Italian ryegrass, particularly in a difficult growing season.

For Italian ryegrass, the crops sown on 4\textsuperscript{th} March 2008 had a maximum TDM of 12,730 kg ha\textsuperscript{-1} (223 DAS) (Figure 4.1) which was 392 kg ha\textsuperscript{-1} lower than that sown on 16\textsuperscript{th} March 2009 (Figure 4.10) when both crops were harvested in the middle of October. The crop sown later on 28\textsuperscript{th} March 2008 produced 10,040 kg ha\textsuperscript{-1} (Figure 4.1) when harvested in the middle of October (197 DAS) compared with 12,904 kg ha\textsuperscript{-1} (209 DAS) when sown on 16\textsuperscript{th} March in 2009 (Figure 4.10). For crops sown later than mid March, Italian ryegrass yields were significantly lower than for oats (Figure 4.1). Thus, sowing Italian ryegrass either early
or in the middle of March would be advisable to attain a higher DM yield. The higher DM yield appears difficult to obtain if it is sown later than the middle of March.

For the faba bean-oat intercrop, the maximum TDM was 14,200 kg ha\(^{-1}\) when it was harvested at the end of September (191 DAS) for the crops sown on 16\(^{th}\) March 2009 (Figure 4.10). The crops yielded 6,020 kg ha\(^{-1}\) less when sowing was delayed to 16\(^{th}\) April 2009 and harvested at the end of September (160 DAS). Thus, the faba bean-oat intercrop is appropriate for sowing in the middle of March. Yield will be reduced if the sowing date is delayed later than this period.

In 2009, the maximum TDM of monocrop faba bean was 2 t ha\(^{-1}\) less than the intercrop (Figure 4.9). In contrast, Faulkner (1985) reported that faba bean mixed with barley gave a yield of 8,000 kg ha\(^{-1}\) compared with 10,000 kg ha\(^{-1}\) from faba bean as a sole crop at Loughgall, in the United Kingdom. The finding that the monoculture of oats gave a greater DM yield than faba bean, Italian ryegrass or the intercrop for the March sowing dates in both growing seasons (Table 4.1 and Figure 4.9) suggests that, if yield is the sole aim of crop production oats should be sown as a monoculture.

In relation to functional growth analysis the findings in this study showed that all of the crops followed a similar pattern of DM accumulation over a particular growing period. This is commonly described as slow increase in early growth (lag phase) followed by a linear growth phase before the crops attained their maximum yield (Figure 4.1 and 4.10). From the growth analysis results of 2008, there were significant interactions between sowing date and species on the WMAGR (Figure 4.2), DUR (Figure 4.3) and \(C_{\text{max}}\) (Figure 4.4). These significant interactions were an artefact of the poor crop growth in the 12\(^{th}\) May 2008 sowing which suffered from bad bird damage in the oat and faba bean plots. This resulted in poor crop emergence and directly reduced the plant density.

In most cases the WMAGRs of earlier sown forage species were lower than those which were sown later. The WMAGR was highest in the last three sowing dates in 2008 and ranged from 118 to 139 kg DM ha\(^{-1}\) d\(^{-1}\) compared with the two early sowing at 67 and 73 kg DM ha\(^{-1}\) d\(^{-1}\) (Figure 4.2). Overall, there was a compensatory change in WMAGR and DUR for crops. As a consequence, the \(C_{\text{max}}\) was also lower for the earlier sowing dates. In contrast, early sown crops had a longer DUR (Figure 4.3). Thus, early sowings produced greater maximum TDM yields (Table 4.1) due to their extended DUR rather than differences in their growth rates.
In 2009, the smaller range of sowing dates meant that there were no differences in the WMAGR and $C_{\text{max}}$ among the sowing dates (Table 4.2). The differences in maximum TDM production (Figure 4.9) in 2009 were solely due to differences in DUR (Figure 4.11). Agronomically, higher maximum TDMs and WMAGR’s were achieved in 2009 due to the narrower spread of sowing dates under favourable growing conditions with relatively warmer temperatures, adequate rainfall in the early growing period (Figure 3.1), minimal bird damage, absence of severe disease infestation and snow on the ground compared with 2008.

Based solely on these analyses of TDM yield can be maximized by 1) sowing oats in early or in the middle of March 2) sowing faba bean in the middle of March, and 3) sowing Italian ryegrass in early or the middle of March. No yield advantage was apparent from the intercrop. However, for these forage crops yield and quality must be considered together and the end use for lactation or growth feed considered.

4.6.2 Nutritive value of winter forages

4.6.2.1 Herbage metabolisable energy (ME) and total ME

Figures 4.5, 4.6, 4.12 and 4.13 indicate oats could be the best choice of farmers who tend to sow forage crop for the lactation of dairy cows since it attained at herbage ME of 11.5 MJ kg$^{-1}$ DM and at the same time gave the greatest total ME ha$^{-1}$. Oats sown in early March gave a higher total ME at 136 GJ ha$^{-1}$ when harvested at the end of August, 178 DAS. This harvest date was at the anthesis stage of oat development. When oats are harvested at the end of August there is adequate time to prepare the land for spring sowing of pasture or subsequent summer crops. The harvest of oats sown in early March could also be delayed until late September to maximize total ME. However, the mean ME declined to 10 MJ kg$^{-1}$ DM which is still adequate for growth of sheep and cattle. This latter harvest in September would still allow adequate land preparation time for later sown maize (October) or kale (November) crops to follow.

An alternative approach to ensure maximum DM yield as well as high quality is to sow Italian ryegrass from early March to mid April and harvest any time before the end of November. Italian ryegrass maintained a herbage ME of $\geq$ 11.5 MJ kg$^{-1}$ DM longer than other species (Figure 4.12) and had a high total ME at 169 GJ ha$^{-1}$ (sown on 16th April 2009) because it was cut at regular intervals (140 and 182 DAS). As a consequence the regrowth remained vegetative with a high nutritive value and digestibility. By harvesting Italian ryegrass in November, the last regrowth could be ensiled before summer forage crops such as kale could
be sown in the middle of December. Equally, from similar sowing dates, the last Italian ryegrass could be delayed until the end of November (228 DAS) when quality was still sufficient for the liveweight gain requirement of 10 MJ kg\(^{-1}\) DM for sheep and cattle. Thus Italian ryegrass offers flexibility for harvest while maintaining quality because it remains vegetative throughout the winter spring period. The summary of the recommended highest total ME at 11.5 MJ kg\(^{-1}\) and 10 MJ kg\(^{-1}\) was presented in Figure 4.16.

![Figure 4.16: Summary of recommended highest total metabolisable energy (ME) at 11.5 MJ kg\(^{-1}\) DM (—) and 10 MJ kg\(^{-1}\) DM (—∙—) of oats (○) and Italian ryegrass (▼) to continue with optional summer crop (□) with period of land preparation (---).](image)

The pattern of herbage ME of all crops showed a decline with advancing maturity (Figure 4.5 and 4.12). This occurred because the highly digestible leaf was reduced and less digestible reproductive fractions increased in the oats and faba beans. This results in an increased proportion of structural cell wall carbohydrate (lignin, cellulose and hemicelluloses) and declining digestibility contributing to a decline in herbage ME of the whole plant (Waghorn and Barry, 1987). In summary, crops must be harvested at optimum growth stage to capture their highest feeding value, but when that is depends on the end use of the crop.

As an example, from the results in this study, the herbage ME showed a huge difference in the rate of decline specifically in the 12\(^{th}\) May and 3\(^{rd}\) June 2008 sowing dates (Figure 4.5) and in the 15\(^{th}\) May 2009 sowing date (Figure 4.12) compared with the earlier sowing dates. This coincided with rapid stem elongation and the shorter duration of growth particularly in spring for the later sown crops, 12\(^{th}\) May and 3\(^{rd}\) June in 2008 and 15\(^{th}\) May in 2009. For all of these sowing dates, faba bean had reached flowering and only oats sown on 15\(^{th}\) May 2009 had reached anthesis. In contrast, the first three sowing dates in 2008 and the first two sowing dates in 2009 had a longer vegetative stage before stem elongation. At any point during this
vegetative period all crops could be harvested and provided high quality ($\geq 11.5$ MJ ME kg$^{-1}$ DM) feed if that was the desired target.

### 4.6.2.2 Herbage N and total N

Figures 4.7, 4.8, 4.14 and 4.15, showed faba bean as the best choice of forage crop if the main aim is to maximize N yield and maintain a requirement of herbage N of 2.4% (15% CP) for lactation of dairy cows. Whether this protein is an acceptable form for dairy cows needs to be determined (Ulyatt *et al.*, 1980). For faba bean to perform optimally, it should be sown in early March until mid April and harvested at the end of November with a yield of N up to 539 kg ha$^{-1}$. The late harvest in November suggests some restriction in the following crop but does provide sufficient time for land preparation for a summer crop such as kale or rape in December. In addition, faba bean maintained a high quality ($\geq 2.4\%$) of herbage N towards crops maturity. Towards the end of the season, faba bean still had the higher herbage N of over 1.6% (10% CP) when harvested at the end of November.

As well as a high ME, Italian ryegrass also maintained a N content of 2.4% when sown in early to mid March and harvested in mid October. However, the 317 kg N ha$^{-1}$ harvested required 72 kg urea ha$^{-1}$ and 150 kg DAP ha$^{-1}$ of applied N suggesting a further 60 kg ha$^{-1}$ from soil N. As indicated previously, the more consistent quality, and prolonged vegetative growth of Italian ryegrass, means it offers flexibility for the following crop. A faba bean-oat intercrop could be sown in mid March and harvested in mid October to produce 445 kg N ha$^{-1}$ at herbage N of 2.4% and the second week of November to produce 433 kg N ha$^{-1}$ at a minimum requirement of herbage N (1.6%) for growth of sheep and cattle. A summary of the recommended highest total N percentage at 2.4% and 1.6% is presented in Figure 4.17.
The trends for herbage N were similar to herbage ME in both growing seasons. Both Figures 4.7 and 4.14, show a difference in the rate decline for forages sown in March and April sowing dates compared with May and June. The rate of decline for the first three dates in 2008 and two dates in 2009 was relatively slow. Again this occurred due to longer duration of young vegetative growth before stem extension and reproductive development. The general trend was that herbage N (% CP) declined with advancing maturity. As reported by de Ruiter (2000), the CP content of ‘Stampede’ oat ranged from 10.4 - 28.3% from the first harvest (1st May) to the third harvest (3rd August) for an autumn sown crop. Crude protein was initially higher but declined as the crops matured.

In this study, oats showed a trend of having a lower herbage N (% CP) in both seasons of experiments compared with the other two forage species. Nevertheless, oats when mixed with faba bean showed a slightly greater herbage N (% CP) at most harvest dates in 2009 than the monoculture. As reported by Lauriault and Kirksey (2004), a CP of 14.8% in an oat monocrop was lower than in oats intercrops with hairy vetch or winter pea with 17% and 19.9%, respectively. Similarly, Robinson (1960) reported that intercropping pea with oat enhanced forage CP concentration compared with an oat sole crop in Minnesota.
4.7 Conclusions

- Oats yielded a greater maximum TDM compared with faba bean, Italian ryegrass or a faba bean-oat intercrop.

- Oats and Italian ryegrass should be sown in early to mid March, while faba bean could be sown in the middle of March to maximize DM yield.

- There was no yield advantage of the faba bean-oat intercrop over the oat monocrop.

- Oats sown in early March and harvested at the end of August to late September gave an adequate requirement of herbage ME at 11.5 MJ kg\(^{-1}\) DM to meet demand for lactation of dairy cows and at the same time produced highest total ME.

- Italian ryegrass sown from early March to mid April and harvested before the end of November provide sufficient herbage ME for lactating dairy cows as well as maximize total ME/ha and delayed harvesting until the end of November still provide sufficient herbage ME for growth of sheep and cattle.

- Faba bean could be used by farmers who require a high protein diet. It gave a high herbage N (2.4%) (15% CP) and the highest total N yield. Crops could be sown in early March until mid April and harvested at the end of November.
Chapter 5
Phenological development of winter forage crops

5.1 Introduction

This chapter focuses on the descriptive aspects of phenological development of the crops used in this study in relation to environmental factors. Temperature is important in controlling the rate of plant developmental processes under conditions of non-limiting water and nutrients (Section 2.3.1). Temperature sensitivity can vary during each stage of plant development and there is no phase during which temperature does not modify development (Slafer and Rawson, 1994).

Accurate prediction of phenological events for each phase of the crop cycle is necessary to choose suitable species, sowing and harvest dates to attain maximum yields. It is also useful base information in the development of crop simulation models and decision support systems (Hans, 1992; Jamieson et al., 1995; Xue et al., 2004; Ravi et al., 2009). Quantifying phenological development requires definition of the most appropriate base, optimum and maximum temperatures and choice of air or soil monitoring as the appropriate driver. Flowering is a crucial stage in crop development because environmental conditions during the reproductive phase have a large impact on final yield. The commencement of flowering also determines crop duration and its prediction is a key driver of decision support systems.

Thus, the objective of this chapter is use data from the two years of experiments to quantify the Tt requirements of crop phenophases. For all crops, sowing to emergence and the interval between successive main stem leaves (phyllochron) could be determined. However, not all crops reached flowering or physiological maturity during the two years of experimentation so those phases are less well defined. The precision of Tt requirements, based on soil and air temperature measurements, will also be evaluated to determine which was most suitable.
5.2 Materials and Methods

Information regarding the sites, experimental design and management details for both experimental seasons is presented in Chapter 3.

5.2.1 Measurements

Specific measurements and details of the measurements done in relation to this chapter are described in Chapter 3 as emergence (Section 3.6.2), leaf appearance (Section 3.6.4), flowering (Section 3.6.5) and pod filling (Section 3.6.6).

5.2.2 Calculations and data analysis

5.2.2.1 Determination of base temperature and thermal time calculations for emergence, leaf appearance, flowering and pod filling

Base temperature ($T_b$, °C) and thermal time ($T_t$, °Cd) requirements for field emergence can be determined using a linear regression analysis (Moot et al., 2000). Data for each species; faba bean, oats and Italian ryegrass were determined for five sowing dates in 2008 and three sowing dates in 2009. These were plotted as the reciprocal of the duration (in days) to 75% emergence against the mean soil temperature. The inverse of duration (day$^{-1}$) represents the rate of development.

The same method was used for the leaf appearance. The rate for each species was defined from the reciprocal of the duration (in days) from the day after emergence (DAE) to reach a set number of leaves against mean air or soil temperature. The evaluated stage for the faba bean monocultures and faba bean in the intercrop was from emergence to 13 leaves, compared with 6 leaves for the monocultures and oats in the intercrop and 5 leaves for Italian ryegrass. The number of leaves stage for faba bean and oats was chosen because they were the highest common number amongst all treatments. For Italian ryegrass it was the highest number of leaves amongst treatment crops before they were cut.

For flowering, linear regression analysis of the rate of flowering (1/days) was determined as the inverse of the number of days from emergence to flowering against the mean air temperature.

At pod filling stage, $T_b$ was determined from the analysis of $T_t$ requirements from flowering to the start of pod filling for a range of values (0 to 10 °C) based on air temperature. The
lowest coefficient of variance (CV,%) among the treatments was chosen to calculate the Tt requirement from flowering to the start of pod filling.

The linear relationship found for all analyses indicates that the Tt concept was a valid approach. Least squares regression analysis was used for the positive linear portion of the line whereby:

\[
\text{Rate}(y) = b_0 + b_1 x
\]

The regression coefficients can then be used to calculate \( T_b \) and Tt (Angus et al., 1981; Moot et al., 2000) as:

\[
T_b = -\frac{b_0}{b_1} \quad \text{and} \quad Tt = \frac{1}{b_1}
\]

Thermal time was also calculated after the \( T_b \) was identified by using a modified sine curve method (Equation 5.1), which is fitted to mean daily air or soil temperature above \( T_b \) (Jones and Kiniry, 1986). Temperature was interpolated into 8 x 3 hour intervals to account for diurnal temperature fluctuations throughout a day.

\[
T_{t\text{daily}} = t_{\text{range-fract}} \times \text{diurnal range}
\]

\[
t_{\text{range-fract}} = 0.92 + 0.0114P - 0.07P^2 + 0.005P^3 \quad \text{Equation 5.1}
\]

\[
\text{diurnal range} = T_{\text{max}} - T_{\text{min}}
\]

where \( P \) is the period (1-8) for each interval during the day and the sum of \( P \) 1-8 gives daily Tt (Tt daily). These were then summed to determine the accumulated Tt for each species for any respective growth stage at any given sowing date. This approach was required because many of the daily temperature records were near or below \( T_b \) due to these being winter annual crops.
5.2.2.2 Maximum pod growth rate

The maximum (max) pod growth rate was also calculated from the relationship between pod DM and accumulated Tt for the steepest slope of the linear stage of pod DM.

5.2.2.3 Photoperiod

Analysis of flowering of faba bean and anthesis of oat crops was performed to determine any additional photoperiod (P) effect on flowering. Daylength was taken at emergence as the time in hours from civil twilight for Lincoln, Canterbury, New Zealand (43° 38’S, 172° 28’E). The Tt to flowering (°Cd) was plotted against photoperiod at emergence (hours) and the photoperiod from emergence to flowering (hours) for each sowing date and species for both years. For Tt calculations, Tₜ at 0.8 °C for faba bean and 0.7 for oats and also 0 °C were used for comparison.

5.2.3 Statistical analysis

The rate of leaf appearance or its inverse, the phyllochron, was estimated as the coefficient for the slope of the linear regression of mean leaf number on the main stem against either days after emergence or Tt, for each plot. Data were subjected to analysis of variance using Genstat (Version 12.2) to determine any difference in the phyllochron among species and sowing dates. Both experiments, carried out in the years 2008 and 2009, were analysed as split plot designs with sowing dates as main plots and species as sub-plots with four replicates. Least significant differences were calculated and means were compared at the 5% confidence level.
5.3 Results

5.3.1 Base temperature and thermal time requirements for emergence

In the two seasons of experiments, across the species sown, the number of days to 75% emergence ranged from 7 to 48 days over a mean soil temperature range of 6 to 16 °C (Figure 5.1a). The number of days to 75% emergence decreased exponentially as the temperature increased. As expected, the relationship between emergence rate and mean soil temperature indicated a linear response. This allowed $T_b$ and $T_t$ requirements to be defined (Figure 5.1b) from the regression equations (Appendix 6). In summary, faba bean had a $T_t$ requirement for emergence of 217 °Cd ($T_b$=1.2 °C), compared with 132 °Cd ($T_b$=1.6 °C) for oats and 132 °Cd ($T_b$=1.8 °C) for Italian ryegrass.
Figure 5.1: Number of days to 75% emergence (a) and emergence rate (b) against mean soil temperature (20 mm) for faba bean sole crop (●), faba bean in the intercrop (○), oats sole crop (▼), oats in the intercrop (Δ) and Italian ryegrass (■) sown on five sowing dates in 2008 and three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Lines are fitted by least squares regressions (b). Coefficients are given in Appendix 6.
5.3.2 Base temperature and leaf appearance on the main stem

There was variability in the relationship between the number of leaves on the main stem against DAE in both seasons (Figure 5.2a-c and 5.3a-e). Figure 5.4 shows the duration of leaf appearance to a defined number of leaves (days) declined as mean air or soil temperature increased. The inverse of duration, which is the rate of leaf appearance (RLA) against mean air (Figures 5.4b and d) or soil temperature (Figure 5.4f) was linear with $T_b$ estimated as 2.4 °C for faba bean, 3.0 °C for oats and 0.7 °C for Italian ryegrass (Appendix 7). Based on these analyses, either air or soil temperature could be used to determine the phyllochron for oats and Italian ryegrass. However, for faba bean the coefficient of determination ($R^2$) increased from 0.54 to 0.85 when using air rather than soil temperature (data not shown). Thus, for faba bean air temperature was a more accurate predictor of leaf appearance than soil temperature.
Figure 5.2: Number of leaves on the main stem of faba bean (a), oats (b) and Italian ryegrass (c) against days after emergence (DAE) sown on 3rd March (●), 28th March (○), 21st April (▼), 12th May (△) and 3rd June (■) 2008 at Lincoln University, Canterbury, New Zealand.
Figure 5.3: Number of leaves on the main stem of faba bean (a) faba bean in the intercrop (b) oats (c) oats in the intercrop (d) and Italian ryegrass (e) against days after emergence sown on 16th March (●), 16th April (○) and 15th May (▼) 2009 at Lincoln University, Canterbury, New Zealand.
Figure 5.4: Duration and rate of leaf appearance from days after emergence of faba bean sole crop (●) and faba bean in the intercrop (○) (0-13 leaves) (a-b), oats sole crop (●) and oats in the intercrop (○) (0-6 leaves) (c-d) against mean air temperature and mean 20 mm soil temperature for Italian ryegrass (0-5 leaves) (e-f) for five sowing dates in 2008 and three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Lines are fitted least squares regressions (b, d and f). Coefficients are given in Appendix 7.
From the relationship between rate of leaf appearance and mean air/soil temperature (Figures 5.4b, d and f) for the range of sowing dates used in years 2008 and 2009 the phyllochron was estimated to be 52 °Cd leaf\(^{-1}\) for faba bean, 100 °Cd leaf\(^{-1}\) for oats and 118 °Cd leaf\(^{-1}\) for Italian ryegrass. However, the low number of autumn sowing dates resulted in a limited temperature range so the phyllochron was also determined from the relationship between the number of leaves on the main stem and accumulated Tt.

When the rate of leaf appearance was plotted against Tt, the relationship was linear for each species. There was a significant interaction between sowing date and species (Table 5.1), for the rate of leaf appearance in the first season of the experiment. The mean phyllochron, was affected (P<0.001) by sowing date (Table 5.1). The phyllochron was also influenced by species (P<0.001) (Table 5.1). Faba bean had the lowest phyllochron with 68 °Cd leaf\(^{-1}\) followed by oats (123 °C leaf\(^{-1}\)) and Italian ryegrass (124 °Cd leaf\(^{-1}\)).

**Table 5.1:** The phyllochron (°Cd leaf\(^{-1}\)) of three different species sown on five different sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Species</th>
<th>Faba bean</th>
<th>Oats</th>
<th>Italian ryegrass</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>4(^{th}) March</td>
<td>63</td>
<td>112</td>
<td>108</td>
<td>94(^{c})</td>
<td></td>
</tr>
<tr>
<td>28(^{th}) March</td>
<td>69</td>
<td>130</td>
<td>120</td>
<td>106(^{ab})</td>
<td></td>
</tr>
<tr>
<td>21(^{st}) April</td>
<td>70</td>
<td>128</td>
<td>112</td>
<td>103(^{b})</td>
<td></td>
</tr>
<tr>
<td>12(^{th}) May</td>
<td>76</td>
<td>134</td>
<td>120</td>
<td>110(^{a})</td>
<td></td>
</tr>
<tr>
<td>3(^{rd}) June</td>
<td>61</td>
<td>114</td>
<td>161</td>
<td>112(^{a})</td>
<td></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>68(^{b})</strong></td>
<td><strong>123(^{a})</strong></td>
<td><strong>124(^{a})</strong></td>
<td><strong>112(^{a})</strong></td>
<td></td>
</tr>
<tr>
<td><strong>S.E.M</strong></td>
<td>1.30</td>
<td></td>
<td></td>
<td>1.87</td>
<td></td>
</tr>
</tbody>
</table>

Sowing dates and species followed by the same letter are not significantly different.
Similarly, in 2009, there were significant interactions (P<0.001) between sowing dates and species. However, the F value generated was too small thus the interaction was not considered and the results only focus on the main effect of sowing dates and species. Sowing date had a significant effect (P<0.05) on the phyllochron (Table 5.2). However, the difference among sowing dates was small with a mean of 97 ± 1.84 °Cd leaf⁻¹. The phyllochron was also influenced by species (P<0.001). The phyllochron for faba bean was 65 °Cd leaf⁻¹, 123 °Cd leaf⁻¹ for oats and a phyllochron 113 °Cd leaf⁻¹ for Italian ryegrass. Compared with the 2008 results, the phyllochron for oats was exactly the same at 123 °Cd leaf⁻¹. For faba bean the phyllochron was comparable with 68 °Cd leaf⁻¹ and for Italian ryegrass it was a little bit higher with a phyllochron of 124 °Cd⁻¹ leaf⁻¹.

Table 5.2: Phyllochron based on air temperature for faba bean and oats and soil temperature for Italian ryegrass sown on three different sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Phyllochron (°Cd leaf⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16th March</td>
<td>104ᵃ</td>
</tr>
<tr>
<td>16th April</td>
<td>94ᵇ</td>
</tr>
<tr>
<td>15th May</td>
<td>94ᵇ</td>
</tr>
<tr>
<td>S.E.M</td>
<td>1.84</td>
</tr>
<tr>
<td>Significance</td>
<td>*</td>
</tr>
</tbody>
</table>

Species (S)

<table>
<thead>
<tr>
<th></th>
<th>Phyllochron (°Cd leaf⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean</td>
<td>65ᶜ</td>
</tr>
<tr>
<td>Faba bean (intercrop)</td>
<td>65ᶜ</td>
</tr>
<tr>
<td>Oats</td>
<td>123ᵃ</td>
</tr>
<tr>
<td>Oats (intercrop)</td>
<td>123ᵃ</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>113ᵇ</td>
</tr>
<tr>
<td>S.E.M</td>
<td>1.93</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
</tr>
</tbody>
</table>

Sowing dates and species followed by the same letter are not significantly different, ***=P<0.001, *P=<0.05.

When the eight sowing dates from the two seasons of experiments were analysed together, the mean phyllochron for faba bean was found to be 66 ± 1.65 °Cd leaf⁻¹, 123 ± 3.90 °Cd leaf⁻¹ for oats and 120 ± 4.21 °Cd leaf⁻¹ for Italian ryegrass.
### 5.3.3 Base temperature and thermal time requirement for flowering/anthesis

Figure 5.5a-d shows the relationships between the duration to reach flowering/anthesis stage (days) and the rate of flowering/anthesis (1/days to reach flowering/anthesis stage) against mean air temperature for faba bean and oats. The greater range of data for faba bean showed the number of days to flowering after emergence declined as mean temperature increased (Figure 5.5a). Extrapolation of the regression for rate of flowering indicates the $T_b$ was 0.8 °C for faba bean (Figure 5.5b) (Appendix 8). Oats took 191 days after emergence to reach anthesis (Figure 5.5c) with an estimated $T_b$ of 0.7 °C (Figure 5.5d) (Appendix 8).

For both the faba bean and oats species, the interval from days after emergence to flowering/anthesis expressed as the inverse of duration was stronger with an $R^2$ of 0.87 for faba bean and 0.93 for oats with mean air temperature than soil temperature ($R^2$ of 0.63 for faba bean and 0.76 for oats) (data not shown).
Figure 5.5: Duration and rate of flowering/anthesis from days after emergence of faba bean sole crop (●) and faba bean in the intercrop (○) (a-b) for five sowing dates in 2008 and three sowing dates in 2009 and of oats sole crop (●) and oats in the intercrop (○) (c-d) against mean air temperature for two sowing dates in 2008 and three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Lines are fitted least square regression (b and d). Coefficients are given in Appendix 8.

Table 5.3 shows faba bean took 77 to 125 days to reach flowering from emergence. Oats took 170 to 190 days from emergence to panicle emergence. The thermal time requirement for flowering for faba bean was averaged at 880 ± 12.1 °Cd \( (T_b = 0.8 \, \degree C) \) with no systematic error amongst sowing dates. Similarly, the \( T_t \) requirement for oats was averaged as 1555 ± 3.92 °Cd \( (T_b = 0.7 \, \degree C) \) across years.
Table 5.3: Number of days after emergence (DAE) and thermal time (Tt) requirement for flowering/anthesis stage of two different species sown on five different sowing dates in 2008 and three different sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>(a) Year</th>
<th>Species</th>
<th>Sowing date</th>
<th>DAE (days)</th>
<th>Accumulated Tt (°Cd)</th>
<th>Tb 0°C</th>
<th>Tb 0.8 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Faba bean</td>
<td>4th March</td>
<td>77</td>
<td>901&lt;sup&gt;e&lt;/sup&gt;</td>
<td>808&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>28th March</td>
<td>124</td>
<td>1042&lt;sup&gt;b&lt;/sup&gt;</td>
<td>915&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>21st April</td>
<td>121</td>
<td>998&lt;sup&gt;c&lt;/sup&gt;</td>
<td>874&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15th May</td>
<td>108</td>
<td>929&lt;sup&gt;e&lt;/sup&gt;</td>
<td>814&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3rd June</td>
<td>96</td>
<td>960&lt;sup&gt;d&lt;/sup&gt;</td>
<td>847&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Faba bean</td>
<td>16th March</td>
<td>113</td>
<td>1051&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>928&lt;sup&gt;ab&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th April</td>
<td>125</td>
<td>1073&lt;sup&gt;a&lt;/sup&gt;</td>
<td>946&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15th May</td>
<td>98</td>
<td>926&lt;sup&gt;c&lt;/sup&gt;</td>
<td>821&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faba bean</td>
<td>16th March</td>
<td>115</td>
<td>1062&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>938&lt;sup&gt;ab&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th April</td>
<td>123</td>
<td>1063&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>937&lt;sup&gt;ab&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15th May</td>
<td>103</td>
<td>961&lt;sup&gt;d&lt;/sup&gt;</td>
<td>851&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(intercrop)</td>
<td>16th March</td>
<td>115</td>
<td>1062&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>938&lt;sup&gt;ab&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th April</td>
<td>123</td>
<td>1063&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>937&lt;sup&gt;ab&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15th May</td>
<td>103</td>
<td>961&lt;sup&gt;d&lt;/sup&gt;</td>
<td>851&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
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<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>109</td>
<td>997</td>
<td>880</td>
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</tr>
<tr>
<td></td>
<td>S.E.M</td>
<td></td>
<td></td>
<td>13.8</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td></td>
<td></td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
</tbody>
</table>

Sowing dates and species followed by the same letter are not significantly different, ***=P<0.001

<table>
<thead>
<tr>
<th>(b) Year</th>
<th>Species</th>
<th>Sowing date</th>
<th>DAE (days)</th>
<th>Accumulated Tt (°Cd)</th>
<th>Tb 0°C</th>
<th>Tb 0.7 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Oat</td>
<td>4th March</td>
<td>175</td>
<td>1715&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1520&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td></td>
<td></td>
<td>28th March</td>
<td>190</td>
<td>1784&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1578&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Oat</td>
<td>16th March</td>
<td>178</td>
<td>1759&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1563&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th April</td>
<td>190</td>
<td>1782&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1582&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15th May</td>
<td>171</td>
<td>1717&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1525&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oats (intercrop)</td>
<td>16th March</td>
<td>178</td>
<td>1759&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1563&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th April</td>
<td>190</td>
<td>1785&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1584&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15th May</td>
<td>170</td>
<td>1714&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1522&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
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<tr>
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<td>Mean</td>
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<td>180</td>
<td>1752</td>
<td>1555</td>
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</tr>
<tr>
<td></td>
<td>S.E.M</td>
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<td></td>
<td>4.28</td>
<td>3.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Significance</td>
<td></td>
<td></td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
</tbody>
</table>

Sowing dates and species followed by the same letter are not significantly different, ***=P<0.001

Further analysis was performed to determine any influence of photoperiod (P) on flowering/anthesis of both species. Appendix 9a-b shows Tt from emergence to flowering/anthesis was plotted against P at emergence and Appendix 10a-b present Tt from emergence to flowering/anthesis against P from emergence to flowering/anthesis at Tb 0°C and Appendices 11 and 12 at Tb 0.8 for faba bean and 0.7 for oats. Both for P at emergence or P from emergence to flowering/anthesis, there was no significant relationship among the
evaluated dependent and independent variables. From the trends shown, daylength did not appear to influence the start of flowering/anthesis in either species.

5.3.4 Base temperature and thermal time requirements from flowering to estimated start of pod filling

As described above, in Section 5.2.2.1, the lowest CV was found from the $T_b$ of 0 °C, thus 0 °C was used in Tt calculation from flowering to the start of pod filling and the final harvest (data not shown).

Figure 5.6 indicates the relationship between pod DM and accumulated Tt from flowering to the start of pod filling and until final harvest. Table 5.4 shows the accumulated Tt from flowering to the start of pod filling, final harvest and estimated maximum pod growth rate. For the start of pod filling, the Tt ranged from 413 to 1047 °Cd from 15th May to 16th March sowing. While for final harvest the Tt requirement ranged from 717 to 1501 °Cd for the same sowing dates as the start of pod filling until maximum pod DM. The estimate of maximum pod growth rate was $0.60 \pm 0.12 \text{ g DM} \text{ °Cd}^{-1}$ during the duration of pod filling.
Figure 5.6: Pod dry matter (DM) against accumulated thermal time (Tt) from flowering to start of pod filling until the final harvest of faba bean sole crop sown at 16\textsuperscript{th} March (●), 16\textsuperscript{th} April (▼) and 15\textsuperscript{th} May (■) 2009 and faba bean in the intercrop sown at 16\textsuperscript{th} March (○), 16\textsuperscript{th} April (△) and 15\textsuperscript{th} May (□) 2009 at Lincoln University, Canterbury, New Zealand. Bars represent the standard error of mean for the start of pod filling. (——) was the extrapolated data points. On each line, first point is the start of pod filling and the last point is the final harvest.
Table 5.4: Accumulated thermal time (Tt) (°Cd) from start of flowering to start of pod filling, from start of flowering to final harvest and the estimated of maximum (max) rate of pod filling for faba bean sown alone or intercropped at three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Start of pod filling (°Cd)</th>
<th>Final harvest (°Cd)</th>
<th>Estimated max rate of pod filling (g DM/°Cd)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16th March</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faba bean</td>
<td>899&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1501&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.41</td>
</tr>
<tr>
<td>Faba bean (intercrop)</td>
<td>1047&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1486&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.62</td>
</tr>
<tr>
<td>16th April</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faba bean</td>
<td>564&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1004&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.78</td>
</tr>
<tr>
<td>Faba bean (intercrop)</td>
<td>573&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1012&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.50</td>
</tr>
<tr>
<td>15th May</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faba bean</td>
<td>430&lt;sup&gt;d&lt;/sup&gt;</td>
<td>735&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.66</td>
</tr>
<tr>
<td>Faba bean (intercrop)</td>
<td>413&lt;sup&gt;d&lt;/sup&gt;</td>
<td>717&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.63</td>
</tr>
<tr>
<td>Mean</td>
<td>654</td>
<td>1076</td>
<td>0.60</td>
</tr>
<tr>
<td>S.E.M</td>
<td>9.18</td>
<td>9.18</td>
<td>0.12</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
<td>NS</td>
</tr>
</tbody>
</table>

Sowing dates and species followed by the same letter are not significantly different, ***=P<0.001, NS = Not significant.
5.4 Discussion

5.4.1 Base temperature and thermal time requirement for emergence

In this study, the T_b and Tt requirements for emergence, leaf appearance, flowering and start of pod filling were determined for faba bean, oats and Italian ryegrass. There was some indication of a difference in T_b and Tt across species and phenological phases. A T_b of 1.2 °C and Tt requirement of 217 °Cd of faba bean was calculated from sowing to 75% emergence based on 20 mm soil temperatures. The Tt requirement of faba bean in the present study was comparable with the ‘Fiord’ faba bean with mean Tt of 217 °Cd for emergence in the study reported by McDonald et al. (1994) with a T_b of 1.7 °C in Australia however, their T_b value was based on air temperature which requires more investigation given the seeds and therefore the growing points are in the soil.

Information on the T_b and Tt requirements for the emergence of oats is scarce. Thus most of the references were based on wheat or barley. The Tt requirement for oats in this study was 132 °Cd with a T_b of 1.6 °C. The present Tt value of 132 °Cd for oats was comparable with a Tt required for emergence of wheat in New South Wales, Australia reported by Addae and Pearson (1992) with a Tt of 139 °Cd and a T_b of 0.4 °C. In addition, Saarikko and Carter (1996) found a T_b requirement that ranged from -4.1 to -5.0 °C for three oat cultivars sown in Finland. These values were derived from a regression analysis of the mean rate of development from sowing to emergence against mean soil temperature. However, they interpreted these values as ‘apparent values’ because the values were below 0 °C which means no development process has occurred. Saarikko and Carter (1996) also demonstrated a linear relationship between the rate of development and mean soil temperature of other species at other developmental phases; emergence-heading, sowing-heading, heading-yellow ripening and sowing–yellow ripening of spring cereals (barley and wheat).

For Italian ryegrass, the T_b of 1.8 °C (based on soil temperature) was comparable with the findings of Moot et al. (2000) in Canterbury, New Zealand. They reported a T_b of 1.9 °C and 0 °C for the 50% field emergence of ‘Moata’ Italian ryegrass based on soil and air temperatures, respectively. A thermal time of 132 °Cd was required from sowing to 75% emergence in the present study which was not much different to the 125 °Cd reported by Moot et al. (2000). From the findings of this study, soil temperature was appropriate to use in the determination of T_b and Tt requirements at the emergence stage for all species evaluated.
5.4.2 Base temperature requirement for leaf appearance and flowering/anthesis

For leaf appearance, a $T_b$ of 2.4 °C was found for faba bean and 0.7 °C for Italian ryegrass. For oats, the $T_b$ of 3.0 °C, in the present study, was similar to the $T_b$ of wheat reported by Klepper et al. (1982). Whereas Sonego (2000) used a $T_b$ of 0 °C for his Tt calculation for RLA at Canterbury, New Zealand. Other studies reported a $T_b$ for leaf appearance of wheat as 2.4 °C (Davidson and Campbell, 1983) and 0 °C (Baker and Gallagher, 1983; Baker et al., 1986). The use of $T_b$ of 0 °C for calculating the Tt requirements for RLA of winter wheat in Nottingham, the United Kingdom was supported by Baker et al. (1980).

A $T_b$ of 0.8 °C was determined, in the present study, for the flowering of faba bean. This value was lower than the value reported by Husain (1984) with a $T_b$ of 2.7 °C for faba bean from emergence to flowering in his field study in Canterbury, New Zealand. However, Mwanamwenge et al. (1999) reported a $T_b$ of 0 °C in their Tt calculations for 50% flowering for ‘ACC286’, ‘Fiord’ and ‘Icarus’ faba beans as well-watered unstressed control treatments.

While for oats, the estimated $T_b$ from emergence to anthesis was 0.7 °C. There was no closest value of $T_b$ to compare at the same phenophase (emergence to anthesis). The closest example was the study of Saarikko and Carter (1996), who reported $T_{bs}$ for ‘Veli’, ‘Puhti’ and ‘Ryhti’ oats of -1.7, -2.4 and -3.3, respectively from sowing to heading and 5.3, 3.7 and 4.7, respectively from heading to yellow ripening.

5.4.3 Rate of leaf appearance (phyllochron)

In the 2008 season, interactions occurred in the phyllochron between sowing date and species. The phyllochron for faba bean was slower (76 °Cd leaf$^{-1}$) in the 12$^{th}$ May sowing date. For the 12$^{th}$ May sowing there was poor crop establishment due to severe bird damage and plants took longer to regenerate new leaves. Thus, the higher thermal units requirement was an artefact of this physical damage and a single value of 66 °Cd leaf$^{-1}$ from the analyses of the eight sowing dates of the two seasons of the experiments could be usefully incorporated into decision support systems for faba bean.

The rate of leaf appearance (RLA) of Italian ryegrass in the 3$^{rd}$ June sowing date was slowest and thus had a higher phyllochron (161 °Cd leaf$^{-1}$) compared to the other sowing dates. It is unclear why the phyllochron of Italian ryegrass in the 3$^{rd}$ June sowing date was so much longer than at the other dates. Nonetheless the variation in the phyllochron of Italian ryegrass
sown in autumn and winter in the 2008 season showed a similar tendency to that of Baker et al. (1980) on winter wheat in the United Kingdom which indicated that the phyllochron was lower in the spring (faster RLA) compared with wheat sown in the autumn (higher phyllochron and slower RLA).

In 2009, RLA or phyllochron were also significantly affected by sowing date. However, the difference of phyllochron among sowing dates was small and likely to have little biological meaning. Most of the significant effect came from species because faba bean had a faster RLA and the lowest thermal unit required for appearance of the successive leaves (65 °Cd leaf\(^{-1}\)) than either Italian ryegrass (113 °Cd leaf\(^{-1}\)) or oats (123 °Cd leaf\(^{-1}\)).

Differences in the phyllochron of ‘Otal’ barley between early and late sowing dates with an average of 75 °Cd leaf\(^{-1}\) were reported by Sharratt (1999) in his study in Alaska. Inconsistency of the phyllochron in their results appeared to be due to the effect of different daylengths at the time of seedling emergence and variation in the air temperature. The phyllochron for early sowings was 80 °Cd leaf\(^{-1}\) while it was 60 °Cd leaf\(^{-1}\) for late sowings. Another reason was the phyllochron might have been influenced by sowing date in the study through differences in the air temperature. Sonego (2000) found an inconsistent phyllochron between oat cultivars and sowing dates when related to calendar days and Tt. These differences could have been due to varying daylengths or a failure to keep the temperature probe at a fixed or appropriate depth below the soil surface.

The phyllochron of oats in this study was 123 °Cd leaf\(^{-1}\). This was identical to the phyllochron of ‘Drummond’ oats, based on air temperature when the oats were sown in May, in Canterbury, New Zealand (Sonego, 2000). This finding agreed with most of the research reports on wheat which generally shows that the Tt required to produce successive leaves on the main stems, was constant for the entire leaf growth period in most field environments. Based on a modelling study by Jamieson et al. (1995), it was concluded that the leaf appearance rate of wheat was only dependent on temperature and was not influenced by daylength or its rate of change. They concluded that the location of the correct monitoring of either air, soil or canopy temperature was the main factor in accuracy of the RLA without taking into account when the crops were sown.

As reported by Gallagher (1979) and Kirby et al. (1982), the number of leaves on the main stem and thus RLA has been shown to be much more strongly correlated with accumulated thermal units than with chronological time. Cao and Moss (1991) and Ball et al. (1995) also
reported a similar observation stating that the appearance of leaves on the main stem of wheat and barley was closely related to the cumulative thermal units from sowing or crop emergence.

In several studies, the number of leaves on the main stem of wheat plants was found to be a linear function of accumulated degree-days in either field or controlled environments (Gallagher, 1979; Hay and Tunnicliffe, 1982; Klepper et al., 1982) which means that the phyllochron was constant over the course of those studies.

5.4.4 Flowering/anthesis and start of pod filling

In the present study, the accumulated Tt for faba bean from emergence to flowering ranged from 808 to 946 °Cd (T_b=0.8 °C). These results were comparable with the results reported by Iannucci et al. (2008) which indicated that the minimum Tt requirements to reach the early and full flowering stage of faba bean were 833 °Cd (T_b=1.7 °C) and 823 °Cd (T_b=2.5 °C), respectively (based on air temperature). While, for ‘Fiord’ faba bean which represents an ‘average’ flowering genotype from sowing to flowering, Mwanamwenge et al. (1999) reported a Tt requirement of 887 °Cd in southern Australia. They also reported a Tt requirement of 657 °Cd for ‘ACC286’ faba bean (categorized as an ‘early’ flowering genotype) for the similar phenophases with the T_b of 0 °C based on air temperature. In addition, McDonald et al. (1994) reported that 887 °Cd (T_b=0 °C) based on air temperature was required for “Acc 758’ faba bean cultivar from emergence to initiation of the first flower in Strathalbyn, Australia. Indeed, air temperature is suitable to use in Tt calculation at the flowering stage compared with soil temperature and the requirement to flower is essentially cultivar dependent but is not affected by photoperiod. As in the current results a T_b of 0 °C, gave a mean value of 997 °Cd from emergence to flowering for eight evaluated sowing dates from a two year of experimental period. Thus, a T_b of 0 °C is probably acceptable to use in Tt calculation at the flowering stage.

For oats, based on a T_b of 0.7 °C, the Tt requirements from emergence to anthesis in the two seasons of experiments ranged from 1520 to 1584 °Cd with 10 leaves produced. The mean value of 1555 °Cd from emergence to anthesis from analyses of two sowing dates in 2008 and three sowing dates in 2009, provides useful information for computer simulation studies for oats itself or in searching for the most suitable species and sowing date for a particular region.
For the phenophase from flowering to the start of pod filling, in this study, a $T_b$ of 0 °C was found for faba bean and the average $T_t$ requirement was 654 °Cd for the three sowing dates in 2009. Table 5.4 shows differences in the $T_t$ requirements from the flowering to the start of pod filling for the 16th March sowing date compared with the 16th April and 15th May sowings. This was probably associated with abortion of the early flowers from the 16th March sowing. There was little abortion of flowers in the later sowing dates. For the estimated maximum rate of pod filling, there was no significant difference, at all sowing dates, except the maximum rate of pod filling for the monocrop faba bean in the 16th March sowing was the lowest of the other sowing dates. The average of 0.60 g DM °Cd$^{-1}$ was found for all three sowing dates from early autumn (March) to the end of autumn (May) in 2009.

5.4.5 The importance of using air or soil temperature for prediction of forage crop phenology

Determination of $T_b$ or $T_t$ requirement using either soil or air temperature is necessary to improve the prediction of crop phenology. In this study, soil temperature at 20 mm depth was used from days after sowing to 75% emergence for all species because it was most closely related to the emergence process. Moot et al. (2000) reported the $T_t$ requirement for 50% field emergence of ‘Moata’ Italian ryegrass based on the soil temperature. They concluded this to be more accurate due to smaller variance in the data compared with air temperature. In addition, Forcella et al. (2000) emphasized that soil temperature can be directly used as a predictor of seedling emergence and it is the most distinct and recognizable factor governing emergence. Awal and Ikeda (2002) reported that faster seedling emergence of peanut (Arachis hypogaea) occurred at higher soil temperature.

At the leaf appearance stage, this study has demonstrated that inclusion of air temperature in $T_t$ calculations for faba bean markedly improved the accuracy in the prediction of $T_b$ ($R^2=0.85$) and RLA or phyllochron. This was probably because the shoot apex or growing point of the faba bean is at the top of plant and is always above ground. Thus, it was evident that soil temperature was a poor predictor of RLA or phyllochron for faba bean.

For oats, air temperature gave a better prediction of defined $T_b$ ($R^2=0.97$) and a strong relationship between the number of leaves on the main stem with the accumulated $T_t$ in determination of RLA or phyllochron. Jamieson et al. (1995) reported that soil temperature at crown depth (location of the shoot apex) gave a greater accuracy in predicting the RLA of wheat than canopy temperature. However, after stem elongation canopy temperature is a
better predictor of RLA than the soil temperature. In contrast, McMaster and Wilhelm (1998) found that the use of soil temperature did not significantly improve the prediction of wheat phenology compared with the air temperature for a crop grown in the Central Great Plains of the USA.

By contrast, for Italian ryegrass, soil temperatures gave a slightly better prediction for \( T_b \) \((R^2=0.96)\) and RLA or phyllochron compared with air temperature \((R^2=0.94)\). This was because the shoot apex is always located under the ground and it is therefore reasonable to assume that development rate responds to soil temperature. However, if soil temperature was unavailable, air temperature could still be used to estimate \( T_t \). Air temperature data are more easily collected than soil temperature data and are readily available from meteorological stations worldwide. However, their use should be approached with caution when interpreting biological data. Knowledge of the anatomy of the test crop is important to interpret data based solely on air temperature if the growing point spends a significant period of the crop duration below ground.

In terms of time to flowering/anthesis and start of pod filling, air temperature gave a more precise calculation of \( T_t \) than soil temperature for both faba bean and oats.

### 5.5 Conclusions

Based on the results presented in this chapter the following conclusions can be made:

- The \( T_b \) to reach 75% emergence was 1.2 °C for faba bean, 1.6 °C for oats and 1.8 °C for Italian ryegrass based on soil temperature.
- The \( T_t \) requirement to reach 75% emergence was 217 °Cd for faba bean and 132 °Cd for oats and Italian ryegrass.
- The phyllochron was 66 °Cd leaf\(^{-1}\) for faba bean, 123 °Cd leaf\(^{-1}\) for oats and 120 °Cd leaf\(^{-1}\) for Italian ryegrass from the relationship between the number of leaves on the main stem against accumulated \( T_t \) for two seasons.
- Base temperature to flowering was 0.8 °C for faba bean and 0.7 °C for oats based on air temperature.
- There was no photoperiod effect on time to flowering of faba bean or anthesis of oats.
- Base temperature for start of pod filling of faba bean was 0°C based on air temperature.
- The estimated maximum rate of pod filling was found to be 0.60 g DM °Cd\(^{-1}\) for two seasons.
Chapter 6
Light interception and radiation use efficiency

6.1 Introduction

In Chapter 4 the total DM accumulation and nutritive value of winter forage crops sown on different dates were quantified. Differences in yield were explained in terms of functional growth analysis which showed that the duration and rate of growth differed amongst treatment combinations. A limitation of this approach is that it does not explain the physiological basis for the differences in yield.

Total DM yield of a crop is a function of the amount of light intercepted by the canopy and how effectively this intercepted light is turned into biomass. The relationship between crop DM production and the amount of light intercepted has been studied for many crops including winter forages (Section 2.3.2). In Chapter 5 crop development was explained for each species in terms of distinct phenophases and leaf appearance rates. These processes interact at the individual plant level to produce canopy leaves.

High DM production is associated with earliness of canopy development. A crop species which rapidly produces an abundant leaf area and reaches critical leaf area index ($\text{LAI}_{\text{crit}}$) is likely to be superior in yielding ability due to an increase in the quantity of captured light. Indeed, for crops grown under non-stressed conditions, DM production is strongly correlated with intercepted light over the growing season (Monteith, 1977; Gallagher and Biscoe, 1978). As presented in Chapter 4, oats were found to have the highest TDM yield compared with the other species used in both experimental seasons which may be explained by the amount of light intercepted or their radiation use efficiency (RUE).

In this chapter, the agronomic yield responses of faba bean, oats, Italian ryegrass and faba bean-oat intercrop sown on different sowing dates, will be explained in terms of their canopy development. This is quantified by the leaf area index (LAI) and the architecture of the canopy, as defined by the extinction coefficient ($k$), which combine to affect light interception and then the efficiency with which captured light is converted to DM, defined as the RUE.
6.2 Materials and Methods

The materials and methods, details of the sites, crops sown, meteorological conditions for the whole growing period, experimental design and other agronomic information regarding the crop management of these two experiments were presented in Chapter 3.

6.3 Measurements

The main measurements of leaf area index (LAI), light interception and methods for calculating the total intercepted PAR, k and RUE are described in Chapter 3 (Section 3.6.7 – 3.6.9).

6.4 Statistical analysis

Analyses of variance (ANOVA) using Genstat 12.2 were used to determine main effects and interactions. Means were separated by least significant differences (LSD) at a 5% probability level. Data were analysed as split plot designs with sowing dates as main plots and species as sub-plots with four replicates. Simple linear regressions were also performed using Genstat 12.2. The slopes of the relationship between Ln of radiation transmitted through the canopy against leaf area index of all species for 2008 and 2009 were tested using T-test.
6.5 Results

6.5.1 Intercepted radiation and extinction coefficient \((k)\) – 2008 & 2009

The relationship between the fraction of radiation intercepted and the LAI for each species is shown in Figure 6.1a, b, c and d for five sowing dates in 2008 and three sowing dates in 2009. From the exponential curve in Figure 6.1, the critical LAI \((\text{LAI}_{\text{crit}})\) at which 95% of intercepted PAR was calculated to be 3.48 for faba bean (Figure 6.1a), 3.45 for oats (Figure 6.1b), 4.19 for Italian ryegrass (Figure 6.1c) and 3.93 for the faba bean-oat intercrop (Figure 6.1d). Leaf area index above the LAI\(_{\text{crit}}\) gave negligible increases in radiation interception.

Figure 6.2a, b, c and d gives the extinction coefficient \((k)\) value from the slopes of the fitted regressions lines between the \(\ln(1-\text{Fi})\) and LAI for the 2008 and 2009 growing seasons since the slopes were significantly different \((P<0.05)\) between seasons. The pooled data of all five sowing dates in 2008, for each species indicate a \(k\) value of 1.06 for faba bean (Figure 6.2a), 0.96 for oats (Figure 6.2b) and 0.98 for Italian ryegrass (Figure 6.2c). While pooled data of all three sowing dates in 2009, show a \(k\) value of 0.67 for faba bean (Figure 6.2a), 0.77 for oats (Figure 6.2b), 0.72 for Italian ryegrass (Figure 6.2c) and 0.72 for faba bean-oat intercrop (Figure 6.2d).

Analyses of variance of the single plot measurements in 2008 showed that faba bean had the greatest \(k\) value \((P<0.002)\) of 1.05 while oats and Italian ryegrass were 0.96 and 0.93, respectively (Appendix 13). In 2009 however, there was no significant species differences and the overall mean was 0.72 (Appendix 14).
Figure 6.1: The relationship between the fraction of radiation intercepted against leaf area index of faba bean (a), oats (b), Italian ryegrass (c) and faba bean-oat intercrop (d) sown on five sowing dates in 2008 (●) and three sowing dates in 2009 (○) at Lincoln University, Canterbury, New Zealand. The solid line fitted exponential curve, $y=0.98(1-e^{-0.97x})$ ($R^2=0.96$) (a), $y=0.99(1-e^{-0.96x})$ ($R^2=0.97$) (b), $y=0.98(1-e^{-0.87x})$ ($R^2=0.95$) (c) and $y=0.99(1-e^{-0.80x})$ ($R^2=0.97$) (d). The dashed line represents the 95% photosynthetically active radiation (PAR) intercepted and the critical leaf area index, respectively.
Figure 6.2: The relationship between Ln of radiation transmitted through the canopy against leaf area index of faba bean (a), oats (b), Italian ryegrass (c) and faba bean-oat intercrop (d) sown on five sowing dates in 2008 (●) and three sowing dates in 2009 (○) at Lincoln University, Canterbury, New Zealand. In 2008, \( y = 0.05 - 1.06x \) (\( R^2 = 0.99 \)) (a), \( y = -0.06 - 0.96x \) (\( R^2 = 0.99 \)) (b), \( y = 0.12 - 0.98x \) (\( R^2 = 0.88 \)) (c) and in 2009 \( y = -0.32 - 0.67x \) (\( R^2 = 0.91 \)) (a), \( y = -0.04 - 0.77x \) (\( R^2 = 0.95 \)) (b), \( y = -0.06 - 0.72x \) (\( R^2 = 0.87 \)) (c) and \( y = -0.17 - 0.72x \) (\( R^2 = 0.93 \)) (d).
6.5.2 Leaf area index

6.5.2.1 Experiment 1 (2008)

Leaf area index (LAI) of faba bean, oats and Italian ryegrass for five sowing dates is shown in Figure 6.3. Leaf area index increased, over time, from days after sowing and reached a maximum LAI (LAI_max) at different accumulated Tt for the different species and sowing dates. The range in LAI_max was 1.9 to 4.1 for faba bean, 3.4 to 5.1 for oats and 4.3 to 5.5 for Italian ryegrass. As shown in Figure 6.3 the accumulated Tt required to reach the critical leaf area index (LAI_crit) could be determined based on the value of LAI_crit stated in Section 6.5.1. The faba bean from the 4th March sowing date reached the LAI_crit in early September at 1297 °Cd. While, 867 °Cd was required for 28th March sowing and this was attained in late August. However, for the last three sowing dates, faba bean did not reach LAI_crit.

Oats sown on 4th March reached LAI_crit at 1006 °Cd which was in the 3rd week of July. For the 28th March and 21st April sowing dates, they required 706 and 711 °Cd, respectively to reach the LAI_crit. These were attained in late July for the 28th March sowing and in early September for the 21st April sowing. Oats sown on 12th May and 3rd June did not reach the LAI_crit.

Italian ryegrass reached the LAI_crit in mid June for the 4th March sowing at 1015 °Cd. Italian ryegrass sown on 28th March required 970 °Cd which was reached in early August and 827 °Cd, in early September, for the 21st April sowing. As for the 12th May and 3rd June sowing dates, they attained the LAI_crit in the late September (752 °Cd) and early October (712 °Cd), respectively.
Figure 6.3: The leaf area index of faba bean (●), oats (○) and Italian ryegrass (▼) against accumulated thermal time (Tt) sown on 4th March (a), 28th March (b), 21st April (c), 12th May (d) and 3rd June (e) 2008 at Lincoln University, Canterbury, New Zealand. Error bar represents standard error of mean (S.E.M) of maximum leaf area index. (↑) indicate time of defoliation of the Italian ryegrass. Lines are a fitted sigmoid curve. Coefficients are given in Appendix 15.
6.5.2.2 Experiment 2 (2009)

In 2009 LAI development was again closely related to thermal time (Figure 6.4). The maximum LAI ranged from 5.7 to 7.0 for faba bean, 6.8 to 7.4 for oats, 6.4 to 7.1 for Italian ryegrass and 6.8 to 7.4 for the faba bean-oat intercrop. Faba bean sown on 16\textsuperscript{th} March reached LAI\textsubscript{crit} in the end of autumn (May) with 562 °Cd. While the others crop species sown on 16\textsuperscript{th} March sowing date reached LAI\textsubscript{crit} in the early winter (June) with 602 °Cd for oats, 700 °Cd for Italian ryegrass (first growth) and 538 °Cd for the faba bean-oat intercrop.

Whereas, for the crops sown on 16\textsuperscript{th} April, reached their LAI\textsubscript{crit} at the end of winter (August). The faba bean-oat intercrop accumulated the least thermal unit at 603 °Cd, followed by faba bean with 652 °Cd, oats with 687 °Cd and Italian ryegrass with 730 °Cd (first growth).

For the last sowing date (15\textsuperscript{th} May), the LAI\textsubscript{crit} was attained in early spring (mid September) for all crop species. The accumulated Tt required to reach their LAI\textsubscript{crit} were 570 °Cd for faba bean, 635 °Cd for oats, 612 °Cd for Italian ryegrass (first growth) and 556 °Cd for the faba bean-oat intercrop. Italian ryegrass in all sowing dates reached LAI\textsubscript{crit} at different times depending on when it was mown.
Figure 6.4: Leaf area index of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean-oat intercrop (Δ) against accumulated thermal time (Tt) when sown on 16\textsuperscript{th} March (a), 16\textsuperscript{th} April (b) and 15\textsuperscript{th} May (c) 2009 at Lincoln University, Canterbury, New Zealand. Error bar represents standard error of mean (S.E.M) of maximum leaf area index. (↑) indicate time of defoliation Italian ryegrass. Lines are a fitted sigmoid curve. Coefficients are given in Appendix 16.
6.5.3 Total intercepted PAR

6.5.3.1 Experiment 1 (2008)

There was an interaction (P<0.05) between sowing date and species for total intercepted PAR (Figure 6.5). Intercepted radiation declined from 596 MJ m\(^{-2}\) in the 4\(^{th}\) March sowing to 384 MJ m\(^{-2}\) in the 28\(^{th}\) March sowing for faba bean. There was no significant difference in total intercepted PAR among the later sowing dates except on the 12\(^{th}\) May. For oats, total intercepted PAR was greatest in the 4\(^{th}\) March sowing and it declined to 474 MJ m\(^{-2}\) in the 28\(^{th}\) March sowing. There was a consistent pattern of changes in total intercepted PAR for the last three sowing dates. Total intercepted PAR of Italian ryegrass declined after the 4\(^{th}\) March sowing but there were no significant differences thereafter in the last four sowing dates.

![Figure 6.5: Total intercepted photosynthetically active radiation (PAR) of faba bean (●), oats (○) and Italian ryegrass (▼) sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand. Error bar represents least significant differences (LSD) at 5% level.](image)
6.5.3.2 Experiment 2 (2009)

In 2009, Table 6.1 shows the amount of PAR intercepted by the crop canopy was highest (982 MJ m\(^{-2}\)) in the March sowing followed by the April and May sowing dates (P<0.001). For the species, Italian ryegrass intercepted the least PAR at 788 MJ m\(^{-2}\). There was no difference in the amount of intercepted PAR for faba bean and the faba bean-oat intercrop and oats with the faba bean-oat intercrop. Oats intercepted 24% more PAR than the Italian ryegrass. There was no interaction (P<0.09) between sowing date and species for total intercepted PAR (Table 6.1).

Table 6.1: Total intercepted photosynthetically active radiation (PAR) of faba bean, oats, Italian ryegrass and faba bean-oat intercrop sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Total intercepted PAR (MJ m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16(^{th}) March</td>
<td>982(^a)</td>
</tr>
<tr>
<td>16(^{th}) April</td>
<td>896(^b)</td>
</tr>
<tr>
<td>15(^{th}) May</td>
<td>861(^c)</td>
</tr>
<tr>
<td>S.E.M</td>
<td>7.33</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
</tr>
</tbody>
</table>

Species (S)
- Faba bean: 937\(^b\)
- Oats: 977\(^a\)
- Italian ryegrass: 788\(^c\)
- Faba bean-oat intercrop: 952\(^{ab}\)
- S.E.M: 12.6
- Significance: ***

Interaction (SD*S) NS

Sowing dates and species followed by the same letter are not significantly different. ***=P<0.001, NS = Not significant
6.5.4 Radiation use efficiency

6.5.4.1 Experiment 1 (2008)

There was a linear relationship between accumulated DM and accumulated intercepted PAR for all species in all sowing dates (Figure 6.6a, b and c). There was an interaction (P<0.05) between sowing dates and species for RUE (Figure 6.7). The interaction, shown in Figure 6.7, shows that oats had a relatively consistent RUE over the first four sowing dates but declined to 1.9 g DM MJ\(^{-1}\) after the 12\(^{th}\) May sowing. The Italian ryegrass RUE declined markedly after the 28\(^{th}\) March sowing and had a slower decline as sowing was further delayed. Faba bean showed a similar trend to oats for the first three sowing dates and a consistent decline over the last two sowing dates.
Figure 6.6: Accumulated dry matter (DM) against accumulated intercepted photosynthetically active radiation (PAR) of faba bean (a) oats (b) and Italian ryegrass (c) sown on 4th March (●), 28th March (○), 21st April (▼), 12th May (△) and 3rd June (■) 2008 at Lincoln University, Canterbury, New Zealand. The coefficients of linear regressions are presented in Appendix 17.
6.5.4.2 Experiment 2 (2009)

As in 2008, there were linear relationships between accumulated DM and accumulated intercepted PAR for all species and sowing dates (Figure 6.8). The significant interaction (P<0.05) shown in Figure 6.9 shows that oats, Italian ryegrass and the faba bean-oat intercrop all decreased their RUE’s from the 16th March sowing to the 16th April sowing date and the RUE plateaued at the 15th May sowing date. Faba bean, however, showed a large decline in RUE when sown on 15th May.
Figure 6.8: Accumulated dry matter (DM) against accumulated intercepted photosynthetically active radiation (PAR) of faba bean (a) oats (b), Italian ryegrass (c) and faba bean-oat intercrop (d) sown on 16th March (●), 16th April (○) and 15th May (▼) 2009 at Lincoln University, Canterbury, New Zealand. The coefficients of linear regression are presented in Appendix 19.
Figure 6.9: Radiation use efficiency (RUE) of faba bean (●), oats (○), Italian ryegrass (▼) and faba bean-oat intercrop (△) sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand. Error bar represents least significant differences (LSD) at 5% level.
6.6 Discussion

6.6.1 Leaf area index (LAI)

With most sowing dates, the LAI pattern of development followed a sigmoid curve (Figures 6.3 and 6.4). In 2008, the range in the maximum LAI (LAI\text{max}) was from 1.9 to 4.1 for faba bean, 3.4 to 5.1 for oats and 4.3 to 5.5 for Italian ryegrass. However, the LAI of faba bean was low in the 12\textsuperscript{th} May sowing date at 1.0 - 1.9 (Figure 6.3). This was due to severe bird damage at the seedling stage which resulted in poor overall growth and, low and uneven crop establishment.

In addition, faba bean sown on 12\textsuperscript{th} May did not reach LAI_{\text{crit}} (95% PAR intercepted) as well as the faba bean sown on 21\textsuperscript{st} April and 3\textsuperscript{rd} June sowing dates. This failure to reach the LAI_{\text{crit}} would result in a lower total DM yield as reported in section 4.5.1.1 compared with the other forage species. Faba beans sown on 4\textsuperscript{th} March, also reached their LAI_{\text{crit}} very late which was in early September. This was due to plants being attacked by chocolate spot (Botrytis fabae), Ascochyta blight (Ascochytta fabae), rust (Uromyces viciae-fabae), lodging and frost damaged because of a snow fall (Plate 6.1) which occurred during early growth. Most main stems were broken and died, and the crop recovered by producing branches from the base of the main stem. Oats sown on 12\textsuperscript{th} May and 3\textsuperscript{rd} June also failed to attain the LAI_{\text{crit}} however, Italian ryegrass reached the LAI_{\text{crit}} in all sowing dates.

![Plate 6.1: Faba bean on 9\textsuperscript{th} July 2008 after snow falls on 7\textsuperscript{th} June and 5\textsuperscript{th} July 2008. Photo of the 4\textsuperscript{th} March sowing date showing lodged and broken main stems.](image)

Other reasons for low LAI in 2008 was a wilt problem caused by Fusarium oxysporum. This affected faba bean sown on 21\textsuperscript{st} April. While, oats sown on 4\textsuperscript{th} March were affected by barley yellow dwarf virus which also started during early growth. In addition, late sowing (3\textsuperscript{rd} June)
and a shorter duration of growth reduced the time for crop development which resulted in a lower LAI in 2008 (Figure 6.3). However, the Italian ryegrass LAI changed over the season because the plots were cut when the plants lodged. Normally, lodging occurred after canopy closure.

In 2009, leaf area indices were much higher than in 2008 for all crop species with the LAI$_{\text{max}}$ ranging from 5.7 to 7.0 for faba bean, 6.8 to 7.4 for oats, 6.4 to 7.1 for Italian ryegrass and 6.8 to 7.4 for the faba bean-oat intercrop. This was mostly because of more favourable environmental conditions in 2009. There was no snow fall, lodging, uneven plant populations or severe disease in 2009, enabling a higher LAI and more crop growth.

Confalone et al. (2010) found that faba bean sown in autumn-winter had higher LAI$_{\text{max}}$ at physiological maturity (5.1-5.4) than those sown in spring (4.4-4.6). This was due to a shorter growing season for the spring sowings. The LAI$_{\text{max}}$ of faba bean, in the present study, was relatively low (1.9-4.1) in 2008 due to disease infestation, unfavourable growing conditions (snow, lodging, frost damage) and shorter growing durations experienced in that year. The LAI development of the crops, sown in the two growing seasons, depended on the duration of the growth phase, climatic conditions and diseases problem in each season.

6.6.2 Light relations in the canopy

6.6.2.1 Critical leaf area index (LAI$_{\text{crit}}$) and the extinction coefficient ($k$)

Pooling all eight sowing dates for both growing seasons in 2008 and 2009 provided highly significant ($R^2=0.95-0.97$) relationships between fraction of radiation intercepted and the LAI (Figure 6.1). Based on these relationships, the LAI$_{\text{crit}}$ could be represented by only one value for each species for both growing seasons. Critical LAI’s were 3.48 for faba bean, 3.45 for oats, 4.19 for Italian ryegrass and about 3.93 for the faba bean-oat intercrop.

In an experiment on the effects of different irrigation levels and sowing dates on faba bean, Husain (1984), reported that interception of light approached 90% at a LAI of about 5.0 for autumn sown and 6.5 for spring sown faba bean crops in Canterbury, New Zealand. This suggests that time of sowing affects canopy architecture and the LAI$_{\text{crit}}$. Both these values for faba bean were different from the results of the present study. This was probably because of abiotic and biotic factors as discussed previously and also, may have been associated with differences in the cultivars used.

The extinction coefficients varied significantly over both growing seasons, and were: 1.06 for faba bean, 0.96 for oats, 0.98 for Italian ryegrass in 2008 and in 2009 they were: 0.67 for faba bean, 0.77 for oats, 0.72 for Italian ryegrass and 0.72 for the faba bean-oat intercrop (Figure 6.2). This indicated that the canopy architecture was different over the study duration in both years.

Lower $k$ values (0.3-0.5) indicate that photosynthetically active radiation (PAR) could penetrate more deeply into the crop stand and canopy photosynthesis can be spread over a larger area of the canopy (vertical leaf orientation). While higher $k$ values (0.7-1.0) indicate a larger fraction of incoming PAR was intercepted at the top of the canopy and canopy photosynthesis would have been distributed over a smaller leaf area and this has been associated with horizontally aligned leaves (Szeicz, 1974; Yunusa et al., 1993; Hay and Porter, 2006).

The $k$ values reported in the present study for faba bean (1.06 and 0.67) and the faba bean-oat intercrop (0.72) adequately described the canopy for faba bean which had a horizontal broad leaf orientation and the faba bean-oat intercrop had a combination of horizontal and vertical leaf orientation. The $k$ value for oats (0.96 and 0.77) were higher than the expected $k$ values for cereals. Oats had vertically oriented narrow leaves which were expected to give a lower $k$ value. Italian ryegrass, also had a vertical disposition of its youngest leaves and a narrow leaf shape which expected to indicate a lower $k$ value than reported in the present study (0.98 and 0.72). Nevertheless, the effect of $k$ does not influence the amount of intercepted PAR by a crop canopy as much as other aspects such as how rapidly the canopy reaches $\text{LAI}_{\text{crit}}$ or canopy closure.

In the present study, the higher $k$ values in 2008 compared with in 2009 were reported for all species sown. This possibly was associated with the unfavourable environmental factors such as snow fall, lodging and disease infestation which could affect the stability of canopy development. Snow fall, which covers the leaves, would cause the canopy orientation to become flatter and thus high $k$ values would be obtained.
The \( k \) value of faba bean reported in 2009 in the present study (0.67) was in the middle of \( k \) values 0.57-0.83 from previous studies, respectively (Minguez et al., 1993; Madeira et al., 1994; Confalone et al., 2010). However, it was lower than the \( k \) value reported by Thomson and Siddique (1997) of 1.01 in south western Australia. This indicates possible cultivar differences among the studies which could lead to differences in canopy architecture. Fasheun and Dennett (1982) found that \( k \) value decreased as LAI increased in faba beans for all sowing dates studied. The \( k \) value ranged from 0.32 to 0.46 when the LAI exceeded 4. They also reported that the change in \( k \) value over time probably resulted from differences in the arrangement of the leaves. Lower leaves usually have two leaflets and are horizontal, whereas higher leaves have more leaflets and tend to be more vertical in their arrangement. This was not observed in the present study and was probably due to the cultivar used.

In addition, the \( k \) value of 1.06 in 2008 and 0.67 in 2009 in the present study (Figure 6.2) were also higher than the 0.36-0.48 reported for faba bean in Canterbury by Husain (1988). This is probably again associated with cultivar differences which could be associated with differences in leaf orientation.

The higher \( k \) values obtained could also be related to the solar angle. In winter, solar angles are very low and this may give high \( k \) values. Changes of the solar angle also mean there are changes in solar radiation received by the plant canopy (Duncan, 1971). Kirkham (1982), conducted a study to determine any variation in received solar intensity of winter wheat sown in two rows in different directions (north-south (NS) and east-west (EW)) in the Northern Hemisphere (Souther Great Plains of the U.S.A). The results indicated that fraction of radiation transmitted was dependant not only on the leaf angle and the direction of the leaf, but also the sun’s azimuth and altitude angle. The fraction of radiation transmitted was fairly constant for leaves in NS rows, but was greatly variable for leaves in EW rows.

### 6.6.3 Total intercepted PAR

In 2008, there was an interaction between sowing date and species on total intercepted PAR. Sowing date had inconsistent effect on total intercepted PAR (Figure 6.5). From all five sowing dates, the 12\(^{th}\) May sowing intercepted the lowest amount of PAR for faba bean due to bird damage in the seedling stage. Faba bean and oats sown on 4\(^{th}\) March produced the highest intercepted PAR but this was not the case for Italian ryegrass. The first sowing date in 2008 (4\(^{th}\) March) intercepted more PAR because the crops grew for a longer duration resulting in a longer duration of LAI to capture light compared with other sowing dates, despite severe
disease infestation. The total intercepted PAR started to decrease when sowing dates were delayed to 28th March particularly for faba bean. It declined the most and was late to reach canopy closure compared to oats and Italian ryegrass when it was sown at the end of March. Oats and Italian ryegrass were intercepted similar amounts of PAR at all sowing dates for 2008. Thus, the present results were not closely related to variation in total DM in oats and Italian ryegrass in 2008 since the oats had a higher TDM than the Italian ryegrass. While the lowest total DM for faba bean in 2008 was reflected in the lowest intercepted PAR by the crop canopy especially from the 12th May sowing (Figure 6.5).

In 2009, there was no interaction between sowing date and species for total intercepted PAR (Table 6.1). The present study shows that total intercepted PAR decreased as sowing date was delayed. Oats intercepted the highest amount of PAR however there was no difference with faba bean-oat intercrop with a mean of 965 ± 12.6 MJ m⁻². Similarly for faba bean, there was no difference in intercepted PAR with the faba bean-oat intercrop. These results show that the amount of intercepted PAR could not fully explain the variation in the total DM produced in 2009, except for the Italian ryegrass. However, the absolute values show oats intercepted the most PAR (977 MJ²⁻¹) followed by the faba bean-oat intercrop (952 MJ m⁻²) and faba bean (937 MJ m⁻²). This could partly explain the DM yield variation among these species. Italian ryegrass intercepted the least PAR which explains it having the lowest total DM yield (Section 4.5.2.1). Essentially this was because Italian ryegrass was mown four times resulting in a period when the leaf area was well below optimal and it had to re-establish its canopy under cool winter conditions.

Overall, total intercepted radiation was higher in 2009 than in 2008. The range was from 332 to 620 MJ m⁻² in 2008 (Figure 6.5) and 788 to 982 MJ m⁻² in 2009 (Table 6.1). This difference was due to the later harvest dates, of the crops, in 2009. Crops in 2008 had a shorter growing period of 150 to 223 days for the five sowing dates compared with 203 to 263 days for the three sowing dates of 2009. Additionally, the incident solar radiation received from March to October 2009 (except in May) was higher than in 2008 which resulted in greater total intercepted PAR in 2009. The mean of total solar radiation received from March to October in 2009 was 313 MJ m⁻² compared to 288 MJ m⁻² in 2008. As explained, the lower crop performance in 2008 was also due to the occurrence of snow and lodging that affected the amount of intercepted PAR.
The greater PAR intercepted by the oats compared with faba bean in 2008 was in agreement with the results of Giunta et al. (2009). They showed that ‘Claudio’ durum wheat intercepted more PAR (750 MJ m\(^{-2}\)) than ‘Sicilia’ faba bean (639 MJ m\(^{-2}\)). Thus, the cereal crops intercepted a greater amount of PAR than grain legumes during their growing period. This possibly occurred due to their canopy architecture. Cereals usually have vertically oriented leaves. This generally means the canopy can support a greater LAI. This greater LAI in the cereals can result in increased radiation interception while the more erect leaves result in better light penetration and reduced light saturation which may give increased RUE.

The results from this work are less conclusive than from some studies. The lower extinction coefficient in faba bean of 0.69 is difficult to explain (see plates 6.2-6.5) as plate 6.4 shows the faba bean leaves appear to be flatter than the oat leaves. The analysis of variance of single plot measurements did suggest that in 2008 faba bean had slightly flatter leaves than the two grasses, but this was not the case in 2009. However, both species produced similar maximum LAI values of about 5.1 for oats and about 4.1 for faba bean in 2008 and about 7.4 for oats and 7.0 for faba bean in 2009. These values suggest canopy architecture did not vary as much as expected and increased PAR interception was probably due to the slightly higher LAI of oats at most sowing dates.

Plate 6.2: Oats

Plate 6.3: Italian ryegrass
A similar pattern in intercepted PAR in the present study was observed for a wheat-chickpea mixed cropping systems reported by Jahansooz, et al. (2007). They reported that there were no significant differences in the quantity of PAR captured by a sole wheat crop (375 MJ m⁻²) or the mixed crops (331 MJ m⁻²). Chickpea sole crops showed the lowest intercepted PAR at 273 MJ m⁻². They concluded that a mixed crop of wheat and chickpea was unlikely to give any yield advantage in a Mediterranean-type environment in Australia. This was due to the slow growth and short stature of the chickpea which made it incapable of competing against wheat for available resources such as water and light.

### 6.6.4 Radiation use efficiency (RUE)

In 2008, RUE for the first three sowing dates was higher (P<0.05) than at the last two sowing dates for faba bean. While the first two sowing dates were higher (P<0.05) than in the last three sowing dates for Italian ryegrass. However, there were no differences in the first four sowing dates for the oats (Figure 6.7). There was no difference in the RUE of faba bean and Italian ryegrass at all sowing dates except for the 4th March sowing and values ranged from 1.2 to 2.4 g DM MJ⁻¹ (Figure 6.7). Oats had the highest RUE (2.5 – 2.8 g DM MJ⁻¹) in all sowing dates except for the 3rd June sowing (1.9 g DM MJ⁻¹). The early autumn sowing dates in 2008, particularly for faba bean and Italian ryegrass, had higher RUE’s compared with later autumn and winter sowings probably because air temperatures during the early growth stages were warmer than in later autumn and winter sowings. This would allow higher
photosynthesis rates from autumn than from winter sowings. For oats, the changes in air temperature across the first four sowing dates did not affect RUE as much as for the other crops. This suggests that the photosynthesis rates in oats were less sensitive to cool temperature than in the other crops (Brouwer and Flood, 1995). The mean air temperature for the first three sowing dates was 14 °C (March and April) and it was 6 °C for the last two sowing dates (May and June).

In 2009, RUE ranged from 1.8 to 2.5 g DM MJ⁻¹ for all species from the three autumn sowing dates (Figure 6.9). There was no difference in the RUE of oats, Italian ryegrass, the faba bean-oat intercrop and faba bean in all sowing dates except for faba bean sown on 15th May. The differences in RUE for faba bean from the 15th May sowing with the other two sowing dates was possibly because of the changes in the mean air temperature. This possibility was considered as the temperature was 14.8 °C in the March sowing, 12.4 °C for April sowing and 7.1 °C for the May sowing date. The interaction, shown in Figure 6.9, indicated the RUE of oats was not different to the faba bean-oat intercrop in all sowing dates. Again, the absolute RUE values demonstrated that oats had a higher RUE than the faba bean-oat intercrop in all sowing dates. Equation 2.2 (Section 2.3.2.5) explains DM yield as the product of total intercepted PAR and RUE values. For oats and the faba bean-oat intercrop small, but insignificant differences, in both factors combine to explain the 2 t ha⁻¹ DM yield advantage to oats over the intercrop. In contrast, for the Italian ryegrass the yield variation could be explained by its lower intercepted PAR. For the faba bean there was no difference in intercepted PAR with the faba bean-oat intercrop, but the RUE of the faba bean was lower than in the faba bean-oat intercrop specifically on the 16th March and 15th May sowing dates. This was the main reason for the DM yield differences reported in Chapter 4.

The relationship of RUE against mean air temperature, in both years, could explain the effect of temperature on the RUE (Figure 6.10). The relationship between RUE and temperature was calculated only up to the fourth harvest since over the whole growing season the temperature range among the sowing dates was narrow. Figure 6.10 shows a linear increase of RUE for faba bean (Figure 6.10a) and Italian ryegrass (Figure 6.10b) with temperature. Each 1 °C increase in temperature, increased the RUE by 0.08 g DM MJ⁻¹ for faba bean and 0.06 g DM MJ⁻¹ for Italian ryegrass. However, temperature changes did not affect the RUE of oats (Figure 6.10c).
Figure 6.10: Radiation use efficiency (RUE) at fourth harvest against mean air temperature for faba bean (a) Italian ryegrass (b) and oats (c) in 2008 (●) and 2009 (○) at Lincoln University, Canterbury, New Zealand. The equation were; \( y=0.71+0.08x \) \( (R^2=0.48) \) (a) \( y=1.05+0.06x \) \( (R^2=0.21) \) (b) and \( y=1.88+0.01x \) \( (R^2=0.01) \) (c).

In both seasons, there was variation in the RUE with the different sowing dates. The value of RUE, in the present study, was 1.2 - 2.8 g DM MJ\(^{-1}\) in 2008 and 1.8 - 2.5 g DM MJ\(^{-1}\) in 2009 which was higher than the 0.9 - 1.6 g DM MJ\(^{-1}\) reported by Confalone et al. (2010) for autumn sowings in Lugo, Spain.

The reported mean RUE value in the present study for faba bean (1.7 g DM MJ\(^{-1}\)) in 2008 was comparable with the value reported by Ridao et al. (1996) of 1.6 g DM MJ\(^{-1}\) before the grain filling stage and lower than the 2.9 g DM MJ\(^{-1}\) after the grain filling stage under
irrigation at Madrid, Spain. Similar results were reported by Loss et al. (1997), where the estimated RUE of ‘Fiord’ faba bean was higher than the present result of 1.8 g DM MJ\(^{-1}\) for 2008 but was comparable with the RUE value of 2.1 g DM MJ\(^{-1}\) for 2009. They also showed that their value of 1.8 g DM MJ\(^{-1}\) was constant across four sowing dates evaluated from early May to early July in Merredin, South Western Australia. However, a constant RUE across different sowing dates was not supported in this study. Values of RUE can be affected by temperature and other abiotic and biotic stresses and therefore can vary widely between sites and sometimes between seasons (Sinclair and Muchow, 1999).

The lower RUE of faba bean compared with the other crops in this study was due to the biological characteristic of faba bean as a nitrogen-fixing legume. This uses more energy to produce proteins than grasses producing a higher proportion of sugar. As a result, faba bean has a high energy content in its constituents in both vegetative tissues and seeds that are high in protein.

In summary, the higher RUE of oats compared with faba bean in both seasons of the present study was in agreement with the study by Giunta et al. (2009) and with previous reports of other cereals or legumes which generally indicated that C\(_3\) non-legume species had a higher RUE than C\(_3\) legume species (Sinclair and Muchow, 1999; Tesfaye et al., 2006). In addition the results of this study showed that oat was an efficient crop in the use of intercepted radiation for conversion into biomass production when compared with faba bean or Italian ryegrass.

### 6.7 Conclusions

- The critical LAI for faba bean was 3.48, 3.45 for oats, 4.19 for Italian ryegrass and 3.93 for an intercrop of faba bean-oats.
- Accumulated DM produced was strongly correlated with total intercepted PAR.
- Radiation use efficiency differed with species, sowing date and growing season, depending on the temperature, solar radiation received and the leaf characteristic of the crop species.
- Oats was a more light efficient crop than faba bean and Italian ryegrass as indicated by its higher RUE.
Chapter 7
General discussion and conclusions

7.1 Overview

The present study was designed to examine how dry matter (DM) production of three winter forage crops grown under non-limiting soil moisture and nutrient availability responded in Canterbury. The overall objective of the Pastoral 21 feeds programme was to determine if it is possible to produce 45 t DM ha\(^{-1}\) yr\(^{-1}\) with an appropriate rotation of winter, and summer crops. The underlying assumption was that by finding a suitable forage crop species or a combination of crops sown and harvested at the most appropriate time to obtain high DM yield with acceptable nutritive value would ensure a constant supply of feed for ruminant animals throughout the year. The specific objective of this research was to determine the effect of different sowing and harvest dates on DM production of various potential winter forage crops.

To investigate this, five different sowing dates with three different forage species of faba bean, oats and Italian ryegrass were evaluated in the first season in 2008 followed by three different sowing dates of the the same three species plus an intercrop of faba bean and oats in 2009. In 2008, the forage crops were harvested at a relatively early stage of the growing period to give adequate time for land preparation to allow for the sowing of summer forage crops such as maize or kale. In 2009, the crops were allowed to grow for a longer duration to assess maximum DM yield and forage quality over a longer harvest period.

Yield, growth, and nutritive value of the crops, their phenological development and the physiological drivers of crop growth including radiation interception and radiation use efficiency were measured. The intention was to examine the trade-off required to maximize feed supply while maintaining high feed quality.

7.2 Dry matter accumulation and maximizing dry matter yield of winter forage crops

Chapter 4 provides options for manipulating sowing and harvest dates as well as the choice of forage crops to maximize the DM yield of winter forage crops that aim for the industry target
of 45 t DM ha\(^{-1}\) yr\(^{-1}\). In the current study, maximum total dry matter (TDM) of the winter forage species declined with delayed sowing dates in both growing seasons (Table 4.1 and Figure 4.9). These results are similar to those of Annicchiarico and Iannucci (2007) and Loss et al. (1997), who reported that early sowing of pulses resulted in greater DM yields relative to late sowing. The maximum TDM attained was greater in 2009 than in 2008. The maximum TDM yield ranged from 6,360 to 13,490 kg ha\(^{-1}\) in 2008 and from 15,995 to 23,055 kg ha\(^{-1}\) in 2009. The greater DM yield in 2009 compared with 2008 was attributed to the later harvest in a longer growth duration of the crops in 2009. However, if the crops were sown at almost similar dates and were harvested at similar dates the DM yield was actually similar for each, depending on the environmental conditions such as warmer temperatures, high incident solar radiation and adequate rainfall distribution and also pest and disease infestations (Figure 4.1 and Figure 4.10). Nevertheless, the DM yield was higher for later harvested crops particularly in 2009 (Figure 4.10). The present study also demonstrated that oats produced the highest maximum TDM in both growing seasons (Table 4.1 and Figure 4.9).

Among the reasons associated with the variation in DM yield in both seasons, for faba bean were disease infestation with chocolate spot, Ascochyta blight, rust and wilt. In addition there was also bird damage at the seedling emergence stage in the 12\(^{th}\) May sowing date in the first season of study. Higher incident solar radiation in 2009 also influenced the greater DM yield in 2009 than in 2008. These results suggest that the faba beans were agronomically the most difficult of the three crops to grow.

The results of the present study also demonstrated that the DM yield of winter forage crops depended on the growing duration from sowing to harvest, particularly in 2008. Based on functional growth analysis in 2008, crops sown early had a longer growth duration and despite their lower growth rates they still accumulated higher DM yields than later sown crops. In contrast, in 2009, the crops which had a longer growth duration did not produce higher yields. Oats were the highest producing species due to a faster growth rate in 2008 (Appendix 2). In 2009, oat growth rate was no different to that of the intercrop (Table 4.2) and there was also no difference in DUR among, oats, faba bean and the intercrop (Appendix 5).

In summary, the DM yield of winter forage crops could be maximized by sowing oats and Italian ryegrass in early or mid March, and faba bean in the middle of March. A faba bean-oat intercrop should be sown before the middle of March.
7.3 Quality of winter forage crops

Based on the present results, oats attained an herbage metabolisable energy (ME) of 11.5 MJ kg$^{-1}$ DM which is adequate to meet the nutritional requirement for lactation of dairy cows. Oats also provided the highest total ME on a per hectare basis. Italian ryegrass showed a similar trend to oats. It maintained an herbage ME of 11.5 MJ kg$^{-1}$ DM for longer than oats and faba bean due to fresh regrowth after cutting at regular intervals. In addition, if harvesting was delayed, both Italian ryegrass and oats provided an adequate herbage ME of 10 MJ kg$^{-1}$ DM to meet the requirement for liveweight gain of sheep and cattle. In terms of meeting the CP requirement for lactating dairy cows, faba bean produced higher total N values compared with oats and Italian ryegrass and provided sufficient herbage N of 2.4% (15% CP) for lactation of dairy cows. Italian ryegrass also produced an adequate herbage N of 2.4% but gave a slightly lower total N than the faba bean. Overall, herbage ME and herbage N dropped as the crops matured.

7.4 Phenological development of winter forage crops

Chapter 5 described the influence of temperature on the phenological development of faba bean, oats and Italian ryegrass for both of growing seasons in 2008 and 2009. In the present study, the Tt requirement was quantified for various developmental stages of the winter forage crops studied; emergence, leaf appearance, flowering/anthesis and pod filling.

A linear regression model was applied to all species, in both growing seasons, in the present study to determine the base temperature ($T_b$) and the thermal time (Tt) requirements for emergence. It was shown that Tt and $T_b$ for faba bean was 217 °Cd ($T_b$=1.2 °C), 132 °Cd ($T_b$=1.6 °C) for oats and 132 °Cd ($T_b$=1.8 °C) for Italian ryegrass from sowing to 75% emergence (Figure 5.1b). At the leaf appearance stage, a $T_b$ of 2.4 °C was determined for faba bean (Figure 5.4b), 3.0 °C for oats (Figure 5.4d) and 0.7 °C for Italian ryegrass (Figure 5.4f). While at flowering and anthesis, a $T_b$ of 0.8 °C and 0.7 °C was defined for faba bean and oats, respectively (Figure 5.5). There are few published reports on the determination of $T_b$ requirements at particular phenological stages, of these forage crops.

Based on the present study, the phyllochrons of 66 °Cd leaf$^{-1}$ for faba bean, 123 °Cd leaf$^{-1}$ for oats and 120 °Cd leaf$^{-1}$ for Italian ryegrass were calculated from the combination of the eight sowing dates for both experimental seasons. This demonstrated that faba bean had a faster rate
of leaf appearance than oats or Italian ryegrass. These values could be utilized in mechanistic simulation models that quantify growth and development of these crops.

Similarly, for the flowering/anthesis stage, faba bean required less thermal units to initiate flowering than oats. Faba bean had a Tt requirement that ranged from 808 to 946 °Cd from emergence to flowering and the Tt requirements for oats ranged from 1520 to 1584 °Cd for the similar phase. Although faba bean had a faster rate of leaf appearance than oats and Italian ryegrass and flowered earlier than oats, its yield was more variable than the two grasses. It produced lower and higher maximum TDM than Italian ryegrass in 2008 and in 2009, respectively but lower than oats in both seasons. This was because the faba bean intercepted less radiation and had a low radiation use efficiency (RUE) which was a result of it being a legume. Thus it produced a high energy product and supported the N fixation infrastructure that resulted in a low RUE compared with other two species.

The present results also demonstrated that the emergence to flowering stage of faba bean and anthesis for oats was influenced solely by temperature without any photoperiod effect. Prediction of phenological events using Tt would then enable the results of the present study to be extrapolated to other sites and seasons outside the region of study.

The results from the present study also emphasized that using either the soil or air temperature can influence the prediction of crop phenology. However, in a study of wheat phenology, McMaster and Wilhelm et al. (1998) reported that soil and air temperature were equally useful in predicting wheat phenology. In the current study, soil temperature was found to be more suitable to use in T_b and Tt calculations for the emergence stage for all crop species compared with air temperature. This finding was in agreement with Moot et al. (2000) and Forcella et al. (2000). The use of soil temperature in calculating Tt for emergence indicated that the seeds responded to the nearest environment, the soil. Seedling emergence was previously identified as the main phenological event that influenced the successful growing cycle of an annual crop (Forcella et al., 2000).

For faba bean the Tt requirements for leaf appearance were more accurately predicted from air than from soil temperature. For oats using air temperature was more accurate but the soil temperature also provided an acceptable prediction. However, for Italian ryegrass, soil temperature gave the most accurate prediction. In these three species, the location of the growing points played an important role in determining whether air or soil temperature was a more accurate predictor of crop phenology. In the case of faba bean, the rate of leaf
appearance was driven more by the air temperature at the shoot apex which was located above ground, and was always at the top of the plant canopy. In contrast, the vegetative production of Italian ryegrass was most accurately predicted from soil temperature.

7.5 Light interception and radiation use efficiency (RUE)

Chapter 6 showed that the physiological aspects of canopy development in relation to leaf area index (LAI), light interception and RUE of the evaluated species explained the variation in maximum TDM. Leaf area index increased over time and was closely related to thermal time. Leaf area index development in 2008 was lower than in 2009. This was associated with the development of some severe diseases, bird damage, snow fall, lodging, uneven crop establishment but most importantly the shorter growing duration. This resulted in less time for crop development and hence a lower LAI in 2008. The range of maximum LAI of crop species was also higher in 2009 than in 2008. This was associated with greater light interception and crop growth which usually results in higher DM yield (Sinclair and Muchow, 1999).

In 2008, the interaction between sowing dates and species demonstrated the inconsistent effect of sowing dates and species on the total intercepted PAR. Faba bean and oats sown on 4th March 2008 intercepted the greatest PAR, but intercepted the least PAR when sown on 12th May 2008 (Figure 6.5). The earliest sowing date intercepted more PAR due to a longer duration of the LAI compared with the other sowing dates, and produced the greatest DM. The lowest DM yield in 2008 for faba bean could be explained by its lowest amount of intercepted PAR. In addition, faba bean sown on 21st April, 12th May and 3rd June 2008 did not reach canopy closure which meant that yields were less than their potential. However, the variation of DM yield of oats and Italian ryegrass could not be explained by total intercepted PAR since they intercepted similar amounts of PAR in 2008.

In 2009, oats intercepted the most PAR followed by the faba bean-oat intercrop, faba bean and Italian ryegrass which intercepted the least PAR (Table 6.1). The differences in the amounts of intercepted PAR for each species in the present study could explain much of the variation in the maximum TDM yield. This result affirmed previous reports by Monteith (1977) and Gallagher and Biscoe (1978) that crop growth was strongly correlated with the amount of intercepted radiation by the crop canopy. In summary, the amount of PAR intercepted by these crops depended on crop growing duration, the incident solar radiation
received during that particular year and also on unfavourable environmental circumstances such as snow and lodging.

In 2008 oats and Italian ryegrass intercepted similar amounts of PAR and this variation was not related to DM production (Figure 6.5). However, oats had a higher RUE than the Italian ryegrass (Figure 6.7) and this does explain the higher maximum TDM yield of the oats, compared with Italian ryegrass, in the first season.

In 2009, oats had a higher RUE’s than the faba bean-oat intercrop, Italian ryegrass and faba bean at all sowing dates (Figure 6.9) (Appendix 20). This explains the higher DM yield of the oats over the intercrop and the other species. However, the significant interaction, shown in Figure 6.9, suggests that while oats, intercrop and Italian ryegrass showed a reduced RUE as the sowing date was delayed. Faba bean had a maximum RUE at the 16th April sowing. This may have been due to a lower optimum temperature for photosynthesis in faba bean. It may also be a statistical aberration because the P value is only just significant at 0.043. This interaction is unlikely to be biologically important. Faba bean had the lowest RUE in both seasons which was attributed to the energy cost of fixing atmospheric nitrogen. This process requires more energy than non-legumes (oats and Italian ryegrass) and is often a reason for lower DM production from legumes (Sinclair and Muchow, 1999).

The high RUE of oats is also likely to be associated with its canopy architecture. Oats have long, narrow, erect leaves which are likely to result in less light saturation of the photosynthetic pathway and allow light deeper into the canopy. This greater light penetration would allow for increased canopy photosynthesis when compared with the more horizontal leaves of the faba bean. However, there was no evidence of large differences in canopy architecture in this project with only a small difference in $k$ in 2008 and no significant differences in 2009. This suggests that the higher RUE of oats compared with faba bean was probably a result of greater net photosynthesis due to the reasons given above.

7.6 Potential of achieving 45 t DM ha$^{-1}$ yr$^{-1}$

The New Zealand Dairy industry has set a target annual DM of 45 t DM ha$^{-1}$ yr$^{-1}$ and has provided funding through the Pastoral 21 programme to achieve this target. The production of 45 t DM ha$^{-1}$ yr$^{-1}$ in New Zealand will require maximizing yields in an annual rotation using appropriate winter and summer species (de Ruiter et al., 2009).
In the present study, oats sown on 4th March 2008 produced a maximum TDM of 15 t ha\(^{-1}\) by late September. If this 15 t of DM was combined with summer crops of maize sown in October (Table 7.1) approximate yields of 43 t DM ha\(^{-1}\) yr\(^{-1}\) or 38.2 t DM ha\(^{-1}\) yr\(^{-1}\) would have been obtained. While 36.3 t DM ha\(^{-1}\) yr\(^{-1}\) would be obtained if 15 t DM of oats was combined with kale (21.3 t ha\(^{-1}\)) as the following summer crop (de Ruiter et al., 2009). However, oats need to be harvested in end of August if farmers require higher herbage ME and total ME for lactation of their dairy cows. Nevertheless, oat harvesting could be delayed until late September, but the crops will have a lower value of herbage ME and would only be adequate for increased liveweight gain of sheep and cattle. However, in 2009, if the oats were allowed to grow for longer the maximum TDM obtained was 26.3 t ha\(^{-1}\) when harvested in early November. This would have given an approximate DM yield of 37.7 t DM ha\(^{-1}\) yr\(^{-1}\) if combined with the yield of kale of 11.4 t ha\(^{-1}\) sown in middle of December as a subsequent summer crop by Chakwizira (2010). Obviously, a number of these potential rotations come very close to meeting the industry target of 45 t DM ha\(^{-1}\) yr\(^{-1}\).

For Italian ryegrass, the maximum TDM was 12.7 t ha\(^{-1}\) (sown on 4th March) in 2008 and 17.9 t ha\(^{-1}\) (sown on 16th March) in 2009 harvested in the middle of October and early December, respectively. An approximate DM yield of 34.2 t DM ha\(^{-1}\) yr\(^{-1}\) would have been obtained in combination with maize sown in November with a DM yield of 21.5 t ha\(^{-1}\) reported by Kosgey, (2011) in the second season of his experiment. If Italian ryegrass was harvested in early December an approximate yield of 29.3 t DM ha\(^{-1}\) yr\(^{-1}\) could have been produced if it was combined with kale DM of 11.4 t ha\(^{-1}\) from a mid December sowing (Chakwizira et al., 2010).

For faba bean sown on 4th March in 2008 the maximum TDM obtained was 11.4 t ha\(^{-1}\) when harvested in the middle of October. A potential yield of 32.9 t DM ha\(^{-1}\) yr\(^{-1}\) could be achieved with a combination of 21.5 t ha\(^{-1}\) of maize, sown in November (Kosgey, 2011). In 2009, a maximum TDM of 19.7 t ha\(^{-1}\) of the crop sown on 16th March was attained when it was harvested in early November. A DM yield of 31.1 t DM ha\(^{-1}\) yr\(^{-1}\) could be produced with a combination of 11.4 t ha\(^{-1}\) of kale which was sown in December (Chakwizira et al., 2010). A summary of the total maximum DM yield in the present study with the combination of other summer crops in previous studies is presented below (Table 7.1):
Table 7.1: Calculated annual dry matter (DM) yields for a range of crop rotations.

<table>
<thead>
<tr>
<th>Crop/Sow date</th>
<th>Yield (t ha⁻¹)</th>
<th>Crop/Sow date/Author</th>
<th>Yield (t ha⁻¹)</th>
<th>Total yield (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oats / 4ᵗʰ March 08</td>
<td>15.0</td>
<td>Maize / October / Kosgey (2011)</td>
<td>28.0</td>
<td>43.0</td>
</tr>
<tr>
<td>Oats / 4ᵗʰ March 08</td>
<td>15.0</td>
<td>Maize / October / de Ruiter (2009)</td>
<td>23.2</td>
<td>38.2</td>
</tr>
<tr>
<td>Oats / 4ᵗʰ March 08</td>
<td>15.0</td>
<td>Kale / October / de Ruiter (2009)</td>
<td>21.3</td>
<td>36.3</td>
</tr>
<tr>
<td>Oats / 16ᵗʰ March 09</td>
<td>26.3</td>
<td>Kale / December / Chakwizira (2010)</td>
<td>11.4</td>
<td>37.7</td>
</tr>
<tr>
<td>Italian ryegrass / 4ᵗʰ March 08</td>
<td>12.7</td>
<td>Maize / November / Kosgey (2011)</td>
<td>21.5</td>
<td>34.2</td>
</tr>
<tr>
<td>Italian ryegrass / 16ᵗʰ March 09</td>
<td>17.9</td>
<td>Kale / December / Chakwizira (2010)</td>
<td>11.4</td>
<td>29.3</td>
</tr>
<tr>
<td>Faba bean / 4ᵗʰ March 08</td>
<td>11.4</td>
<td>Maize / November / Kosgey (2011)</td>
<td>21.5</td>
<td>32.9</td>
</tr>
<tr>
<td>Faba bean / 16ᵗʰ March 09</td>
<td>19.7</td>
<td>Kale / December / Chakwizira (2010)</td>
<td>11.4</td>
<td>31.1</td>
</tr>
</tbody>
</table>

In summary the approximate potential annual DM yields ranged from 29.3 to 43 t DM ha⁻¹ yr⁻¹ depending on the subsequent summer crops used in the rotation. This means that the industry target of 45 t DM ha⁻¹ yr⁻¹ is within reach in Canterbury. Overall, the combination of oats and maize DM yield produced the highest potential yield. Maize is the most productive summer crop to grow since it gave a higher DM yield compared with kale or rape (Pritchard, 1987; de Ruiter et al., 2009; Chakwizira et al., 2010; Kosgey, 2011) and are the highest yielding summer crops in major cropping regions of the North Island (Douglas, 1980). The estimated annual DM yield, in the present study was comparable with the 30 t DM ha⁻¹ reported by Densley et al. (2006) using maize-based cropping systems combined with winter forage crops (triticale, Italian ryegrass and oats) in the Waikato. Garcia et al. (2006) attained similar yields in New South Wales, Australia. They reported a potential forage yield of 41.2 t DM ha⁻¹ yr⁻¹ in their complementary forage rotation system of maize, forage rape (Brassica napus) and Persian clover (Trifolium resupinatum) from the period of autumn-winter to spring-summer.

Fletcher et al. (2011) demonstrated that based on their simulation study, an optimum total annual DM yield of 33.5 t ha⁻¹ was obtained from a long season maize hybrid combined with the yield from a following winter cereal (oats, barley, wheat, triticale or ryecorn) in Canterbury. This total yield was lower than obtained in Waikato of 41.6 t DM ha⁻¹ with a similar maize hybrid and a winter cereal. They also emphasized it was necessary to balance
the yield increases with the potential decreases for both forage species which require further work in their simulation model.

In summary, the findings from the current study showed that winter forage crop production could be maximized by sowing and harvesting at appropriate dates and combining oats and maize in the rotation. This can produce a potential annual DM yield approaching 43 t DM ha\(^{-1}\) in Canterbury.

### 7.7 Recommendations for farmers

Based on the current research findings, some recommendations can be proposed to Canterbury farmers for maximizing their winter forage production:

1. **To maximize DM yield, have different sowing dates for each forage crop.** Sow oats and Italian ryegrass in early or mid March. Sow faba bean in the middle of March.
2. **To maximize DM yield of high herbage ME and total ME, oats is the crop to sow. The alternative is Italian ryegrass.** Oats need to be sown in early March and harvested at the end of August or delayed until late September. Italian ryegrass should be sown from early March to mid April and harvested anytime before the end of November for lactation of dairy cows or could be delayed until the end of November. A delay to the end of November gives a higher yield and maintains a high herbage ME particularly for liveweight gain of sheep and cattle. The flexibility of the suggested harvest dates for both the oats and Italian ryegrass would ensure sufficient time for land preparation to sow summer crops such as maize or kale from October to December.
3. **For a high N yield (high CP), faba bean is the most appropriate crop to sow.** To achieve a high N yield, faba bean should be sown in early March until about mid April and harvested at the end of November. This limited time will still give about two weeks for land preparation to sow kale or rape in the middle of December. A second option would be to sow Italian ryegrass in early to mid March and harvest it in mid October to get a high herbage and N yield. Farmers can choose to sow faba bean mixed with oats for sufficient herbage N of 1.6% (10% CP) for growth of sheep and cattle. This needs to be sown in mid March and harvested in the second week of November.
7.8 General conclusions

- Suitable sowing and harvest dates are important to determine quantity and quality of winter forage crops and they tended to differ in relation to each other depending on the year.

- The duration of the growing period of the crops sown was identified as an important determinant of crop DM yield.

- Forage yield and quality changed with harvest date. Delaying harvest resulted in increased DM yield and decreased forage quality.

- Information on the phenological development of winter forage crops based on their $T_h$ and $T_t$ requirements would be useful in further simulation studies.

- Temperature was identified as a major factor influencing crop development events, particularly for the winter forage crops considered in this study.

- The environment influenced the DM yield of the species sown primarily via the interception of PAR and secondly the RUE.

- Annual DM yields of between 29 t DM ha$^{-1}$ and 43 t DM ha$^{-1}$ are achievable using rotations of various combinations of winter crops of oats, faba bean and Italian ryegrass and summer crops of maize and kale.

7.9 Recommendations for future research

- The use of superior cultivars of faba bean and oats which are resistant to disease and lodging is recommended to improve radiation capture and RUE.

- Further crop simulation studies based on the present results could be useful for integrating information about the many processes underlying the formation and realization of yield in annual whole farm rotations.

- A study to quantify the potential annual DM yields by sowing successive summer crops of maize or kale after terminating the winter forage crops would be useful and could help verify the simulation modelling studies mentioned above.
Appendices

Appendix 1: The coefficients and coefficient of determination ($R^2$) for generalized logistic curves fitted to total dry matter yield for faba bean, oats and Italian ryegrass in 2008 sown on five sowing dates at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Species</th>
<th>B</th>
<th>M</th>
<th>T</th>
<th>C</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th March</td>
<td>Faba bean</td>
<td>0.02</td>
<td>85.5</td>
<td>0.01</td>
<td>11793</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.01</td>
<td>130.9</td>
<td>0.01</td>
<td>22656</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.01</td>
<td>263.3</td>
<td>0.01</td>
<td>42268</td>
<td>0.97</td>
</tr>
<tr>
<td>28th March</td>
<td>Faba bean</td>
<td>0.18</td>
<td>166</td>
<td>10.9</td>
<td>7507</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.16</td>
<td>169</td>
<td>9.59</td>
<td>12870</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.25</td>
<td>187</td>
<td>17.1</td>
<td>10063</td>
<td>0.98</td>
</tr>
<tr>
<td>21st April</td>
<td>Faba bean</td>
<td>0.62</td>
<td>176</td>
<td>19</td>
<td>7992</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.47</td>
<td>174</td>
<td>19</td>
<td>12937</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.39</td>
<td>174</td>
<td>19</td>
<td>8675</td>
<td>0.99</td>
</tr>
<tr>
<td>12th May</td>
<td>Faba bean</td>
<td>0.47</td>
<td>159</td>
<td>8.53</td>
<td>4470</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.18</td>
<td>147</td>
<td>4.26</td>
<td>10079</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.13</td>
<td>141</td>
<td>2.94</td>
<td>6493</td>
<td>0.99</td>
</tr>
<tr>
<td>3rd June</td>
<td>Faba bean</td>
<td>0.78</td>
<td>139</td>
<td>19</td>
<td>5735</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.91</td>
<td>133</td>
<td>19</td>
<td>5735</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.89</td>
<td>144</td>
<td>19</td>
<td>9584</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Appendix 2: The effect of sowing date and species on the weighted mean absolute growth rate (WMAGR), duration of the exponential growth phase (DUR) and maximum crop growth rate ($C_{max}$) of three different species sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>WMAGR</th>
<th>DUR</th>
<th>$C_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg DM ha⁻¹ d⁻¹)</td>
<td>(days)</td>
<td>(kg DM ha⁻¹ d⁻¹)</td>
</tr>
<tr>
<td>4th March</td>
<td>67 b</td>
<td>172 a</td>
<td>71 c</td>
</tr>
<tr>
<td>28th March</td>
<td>73 b</td>
<td>145 b</td>
<td>127 b</td>
</tr>
<tr>
<td>21st April</td>
<td>118 a</td>
<td>90 f</td>
<td>213 a</td>
</tr>
<tr>
<td>12th May</td>
<td>139 a</td>
<td>54 d</td>
<td>235 a</td>
</tr>
<tr>
<td>3rd June</td>
<td>133 a</td>
<td>50 d</td>
<td>232 a</td>
</tr>
<tr>
<td>S.E.M</td>
<td>6.86</td>
<td>2.12</td>
<td>13.52</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

Species (S)

<table>
<thead>
<tr>
<th>Species</th>
<th>WMAGR</th>
<th>DUR</th>
<th>$C_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oat</td>
<td>134 a</td>
<td>101 b</td>
<td>226 a</td>
</tr>
<tr>
<td>Faba bean</td>
<td>98 b</td>
<td>92 c</td>
<td>161 b</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>85 b</td>
<td>114 a</td>
<td>139 b</td>
</tr>
<tr>
<td>S.E.M</td>
<td>6.13</td>
<td>2.82</td>
<td>11.28</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

Interaction (SD*S)

| Sowing date and species followed by the same letter are not significantly different, *=P<0.05, **=P<0.01, ***=P<0.001 |
Appendix 3: Maximum total dry matter (TDM) during the growing season of three different species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Maximum TDM (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16(^{th}) March</td>
<td>22,917(^a)</td>
</tr>
<tr>
<td>16(^{th}) April</td>
<td>19,744(^b)</td>
</tr>
<tr>
<td>15(^{th}) May</td>
<td>17,227(^c)</td>
</tr>
<tr>
<td>S.E.M</td>
<td>460.7</td>
</tr>
</tbody>
</table>

Species (S)
- Oats: 23,055\(^a\)
- Faba bean: 19,645\(^c\)
- Italian ryegrass: 15,995\(^d\)
- Faba bean-oat intercrop: 21,155\(^b\)

Significance
- ***

Interaction (SD* S)
- **

Sowing date and species followed by the same letter are not significantly different. **=P<0.01, ***=P<0.001

Appendix 4: The coefficients and coefficient of determination (R\(^2\)) for generalized logistic curves fitted to total dry matter yield for faba bean, oats, Italian ryegrass and faba bean-oat intercrop in 2009 sown at three sowing dates at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Species</th>
<th>B</th>
<th>M</th>
<th>T</th>
<th>C</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16(^{th}) March</td>
<td>Faba bean</td>
<td>0.27</td>
<td>217.9</td>
<td>19</td>
<td>19814</td>
<td>99.2</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.24</td>
<td>223.2</td>
<td>15.2</td>
<td>26431</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.02</td>
<td>183.9</td>
<td>1.17</td>
<td>19738</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>Faba bean-oat intercrop</td>
<td>0.28</td>
<td>223.6</td>
<td>19</td>
<td>24928</td>
<td>99.8</td>
</tr>
<tr>
<td>16(^{th}) April</td>
<td>Faba bean</td>
<td>0.13</td>
<td>193.5</td>
<td>5.43</td>
<td>21612</td>
<td>99.5</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.08</td>
<td>187.4</td>
<td>2.82</td>
<td>22997</td>
<td>99.8</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.015</td>
<td>179.6</td>
<td>0.01</td>
<td>24487</td>
<td>99.4</td>
</tr>
<tr>
<td></td>
<td>Faba bean-oat intercrop</td>
<td>0.08</td>
<td>177.7</td>
<td>2.75</td>
<td>19287</td>
<td>99.9</td>
</tr>
<tr>
<td>15(^{th}) May</td>
<td>Faba bean</td>
<td>0.09</td>
<td>165.7</td>
<td>2.85</td>
<td>15649</td>
<td>99.7</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>0.07</td>
<td>162.9</td>
<td>1.65</td>
<td>20714</td>
<td>99.7</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>0.04</td>
<td>153</td>
<td>0.61</td>
<td>15353</td>
<td>99.7</td>
</tr>
<tr>
<td></td>
<td>Faba bean-oat intercrop</td>
<td>0.13</td>
<td>167.7</td>
<td>4.11</td>
<td>18935</td>
<td>99.6</td>
</tr>
</tbody>
</table>
Appendix 5: Effects of sowing dates and species on duration of the exponential phase of growth (DUR) of three different species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>DUR (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16th March</td>
<td>173\textsuperscript{a}</td>
</tr>
<tr>
<td>16th April</td>
<td>137\textsuperscript{b}</td>
</tr>
<tr>
<td>15th May</td>
<td>109\textsuperscript{c}</td>
</tr>
<tr>
<td>S.E.M</td>
<td>5.61</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
</tr>
</tbody>
</table>

Species (S)

- Oats: 119\textsuperscript{b}
- Faba bean: 118\textsuperscript{b}
- Italian regrass: 199\textsuperscript{a}
- Faba bean-oat intercrop: 122\textsuperscript{b}
- S.E.M: 5.29
- Significance: ***

Interaction (SD x S): ***

Sowing date and species followed by the same letter are not significantly different, ***=P<0.001

Appendix 6: The coefficients for the linear relationship between the rate of 75% emergence against mean soil temperature for faba bean, oats and Italian ryegrass sown on five sowing dates in 2008 and three dates in 2009 at Lincoln University, New Zealand.

<table>
<thead>
<tr>
<th>Species</th>
<th>a</th>
<th>s.e.</th>
<th>b</th>
<th>s.e.</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean</td>
<td>-0.00573</td>
<td>0.003</td>
<td>0.00460</td>
<td>0.0003</td>
<td>0.97</td>
</tr>
<tr>
<td>Oats</td>
<td>-0.01177</td>
<td>0.006</td>
<td>0.00755</td>
<td>0.0005</td>
<td>0.96</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>-0.01353</td>
<td>0.009</td>
<td>0.00756</td>
<td>0.0007</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Appendix 7: The coefficients and standard error (s.e) for the linear relationship between the rate of leaf appearance from days after emergence of faba bean (0-13 leaves) and oats (0-6 leaves) against mean air temperature and against mean soil temperature for Italian ryegrass (0-5 leaves) sown on five sowing dates in 2008 and three dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Species</th>
<th>a</th>
<th>s.e.</th>
<th>b</th>
<th>s.e.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean</td>
<td>-0.00356</td>
<td>0.002</td>
<td>0.00147</td>
<td>0.0002</td>
<td>0.85</td>
</tr>
<tr>
<td>Oat</td>
<td>-0.00494</td>
<td>0.001</td>
<td>0.00167</td>
<td>0.0001</td>
<td>0.97</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>-0.00116</td>
<td>0.001</td>
<td>0.00169</td>
<td>0.0001</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Appendix 8: The coefficients for the linear relationship between the duration and rate of flowering/anthesis from days after emergence of faba bean for five sowing dates in 2008 and three sowing dates in 2009 and oats against mean air temperature for two sowing dates in 2008 and three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Species</th>
<th>a</th>
<th>s.e.</th>
<th>b</th>
<th>s.e.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean</td>
<td>-0.00109</td>
<td>0.001</td>
<td>0.00130</td>
<td>0.0002</td>
<td>0.87</td>
</tr>
<tr>
<td>Oats</td>
<td>-0.00045</td>
<td>0.001</td>
<td>0.00068</td>
<td>0.0001</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Appendix 9: Thermal time (Tt) at temperature base (Tb) 0 °C from emergence to flowering of faba bean sole crop (●) and faba bean in the intercrop (○) (a) and oats sole crop (●) and oats in the intercrop (○) (b) against photoperiod (P) at emergence for five sowing dates in 2008 for faba bean and three sowing dates for faba bean in the intercrop in 2009 and two sowing dates in 2008 and three sowing dates in 2009 for oats and oats in the intercrop at Lincoln University, Canterbury, New Zealand.
Appendix 10: Thermal time (Tt) at temperature base (Tb) 0 °C from emergence to flowering of faba bean sole crop (●) and faba bean in the intercrop (○) (a) and oats sole crop (●) and oats in the intercrop (○) (b) against photoperiod (P) from emergence to flowering for five sowing dates in 2008 for faba bean and three sowing dates in 2009 for faba bean and faba in the intercrop and two sowing dates in 2008 and three sowing dates in 2009 for oats and oats in the intercrop at Lincoln University, Canterbury, New Zealand.
Appendix 11: Thermal time (Tt) at temperature base (T\(_b\)) 0.8 °C from emergence to flowering of faba bean sole crop (●) and faba bean in the intercrop (○) (a) and at T\(_b\) 0.7 °C for oats sole crop (●) and oats in the intercrop (○) (b) against photoperiod (P) at emergence for five sowing dates in 2008 for faba bean and three sowing dates for faba bean and faba bean in the intercrop in 2009 and two sowing dates in 2008 and three sowing dates for oats and oats in the intercrop in 2009 at Lincoln University, Canterbury, New Zealand.
Appendix 12: Thermal time (Tt) at temperature base ($T_b$) 0.8 °C from emergence to flowering of faba bean sole crop (●) (a) and faba bean in the intercrop (○) and $T_b$ 0.7 °C for oats sole crop (●) and oats in the intercrop (○) (b) against photoperiod (P) from emergence to flowering for five sowing dates in 2008 for faba bean and three sowing dates for faba bean in the intercrop in 2009 and two sowing dates in 2008 and three sowing dates for oats and oats in the intercrop in 2009 at Lincoln University, Canterbury, New Zealand.
Appendix 13: Extinction coefficient ($k$) of three species sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Extinction coefficient ($k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th March</td>
<td>1.01</td>
</tr>
<tr>
<td>28th March</td>
<td>1.02</td>
</tr>
<tr>
<td>21st April</td>
<td>0.95</td>
</tr>
<tr>
<td>12th May</td>
<td>0.93</td>
</tr>
<tr>
<td>3rd June</td>
<td>0.99</td>
</tr>
<tr>
<td>S.E.M</td>
<td>0.04</td>
</tr>
<tr>
<td>Significance</td>
<td>NS</td>
</tr>
</tbody>
</table>

Species (S)
- Faba bean: $1.05^a$
- Oats: $0.96^b$
- Italian ryegrass: $0.93^b$
- S.E.M: $0.02$
- Significance: $**$

Interaction (SD x S): NS

Sowing date and species followed by the same letter are not significantly different, $**=P<0.01$, NS = Not significant.

Appendix 14: Extinction coefficient ($k$) of three species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Extinction coefficient ($k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16th March</td>
<td>$0.77^a$</td>
</tr>
<tr>
<td>16th April</td>
<td>$0.73^{ab}$</td>
</tr>
<tr>
<td>15th May</td>
<td>$0.68^b$</td>
</tr>
<tr>
<td>S.E.M</td>
<td>0.02</td>
</tr>
<tr>
<td>Significance</td>
<td>*</td>
</tr>
</tbody>
</table>

Species (S)
- Faba bean: 0.71
- Oats: 0.75
- Italian ryegrass: 0.72
- Faba bean-oat intercrop: 0.71
- S.E.M: 0.02
- Significance: NS

Interaction (SD x S): *

Sowing date and species followed by the same letter are not significantly different, *=P<0.05, NS = Not significant.
Appendix 15: The coefficients for sigmoid curve of leaf area index against accumulated thermal time (Tt) for three different species sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Species</th>
<th>a</th>
<th>b</th>
<th>x₀</th>
<th>s.e.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th March</td>
<td>Faba bean</td>
<td>3.58</td>
<td>214.53</td>
<td>531.71</td>
<td>0.1800</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>4.59</td>
<td>244.91</td>
<td>734.80</td>
<td>0.1439</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass 1st growth</td>
<td>8.52</td>
<td>304.00</td>
<td>1025.34</td>
<td>0.2508</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass 2nd growth</td>
<td>5.14</td>
<td>93.77</td>
<td>1389.73</td>
<td>0.7474</td>
<td>0.90</td>
</tr>
<tr>
<td>28th March</td>
<td>Faba bean</td>
<td>4.13</td>
<td>104.42</td>
<td>691.26</td>
<td>0.0670</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>5.11</td>
<td>144.07</td>
<td>599.95</td>
<td>0.2030</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass 1st growth</td>
<td>7.89</td>
<td>151.82</td>
<td>952.05</td>
<td>0.2928</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass 2nd growth</td>
<td>5.25</td>
<td>62.11</td>
<td>1233.48</td>
<td>0.9921</td>
<td>0.85</td>
</tr>
<tr>
<td>21st April</td>
<td>Faba bean</td>
<td>3.19</td>
<td>182.37</td>
<td>704.17</td>
<td>0.3001</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>4.68</td>
<td>126.12</td>
<td>580.88</td>
<td>0.1207</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass 1st growth</td>
<td>4.41</td>
<td>55.74</td>
<td>663.56</td>
<td>0.3090</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass 2nd growth</td>
<td>4.10</td>
<td>48.33</td>
<td>1141.95</td>
<td>0.8939</td>
<td>0.82</td>
</tr>
<tr>
<td>12th May</td>
<td>Faba bean</td>
<td>1.94</td>
<td>29.53</td>
<td>769.42</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>3.48</td>
<td>101.31</td>
<td>701.74</td>
<td>0.1165</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>15.22</td>
<td>116.51</td>
<td>865.42</td>
<td>0.1648</td>
<td>0.99</td>
</tr>
<tr>
<td>3rd June</td>
<td>Faba bean</td>
<td>2.57</td>
<td>113.24</td>
<td>505.46</td>
<td>0.6782</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>3.00</td>
<td>91.25</td>
<td>454.28</td>
<td>0.6985</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td>5.13</td>
<td>113.83</td>
<td>541.93</td>
<td>0.4496</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Note: Equation , \( y = \frac{d}{1+e^{-\left(\frac{x-x_0}{b}\right)}} \)
Appendix 16: The coefficients for sigmoid curve of leaf area index against accumulated thermal time (Tt) for three different species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Species</th>
<th>a</th>
<th>b</th>
<th>xo</th>
<th>s.e.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>16&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>Faba bean</td>
<td>5.43</td>
<td>125.55</td>
<td>488.91</td>
<td>0.8039</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>7.34</td>
<td>139.53</td>
<td>618.09</td>
<td>1.7633</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; growth</td>
<td>5.02</td>
<td>93.87</td>
<td>549.40</td>
<td>0.3950</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; growth</td>
<td>6.11</td>
<td>63.91</td>
<td>1047.19</td>
<td>0.5294</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; growth</td>
<td>6.51</td>
<td>34.56</td>
<td>1308.05</td>
<td>0.4927</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>4&lt;sup&gt;th&lt;/sup&gt; growth</td>
<td>5.00</td>
<td>85.03</td>
<td>1816.75</td>
<td>0.1286</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Faba bean-oat</td>
<td>6.65</td>
<td>132.95</td>
<td>489.17</td>
<td>0.5171</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Intercrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16&lt;sup&gt;th&lt;/sup&gt; April</td>
<td>Faba bean</td>
<td>6.69</td>
<td>134.17</td>
<td>641.24</td>
<td>0.3223</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>8.58</td>
<td>147.97</td>
<td>745.72</td>
<td>0.2571</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; growth</td>
<td>8.57</td>
<td>97.97</td>
<td>734.10</td>
<td>0.1491</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; growth</td>
<td>4.92</td>
<td>47.63</td>
<td>1076.59</td>
<td>0.6322</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; growth</td>
<td>4.88</td>
<td>56.42</td>
<td>1591.09</td>
<td>0.2726</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Faba bean-oat</td>
<td>8.28</td>
<td>134.63</td>
<td>616.62</td>
<td>0.1712</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Intercrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>Faba bean</td>
<td>10.89</td>
<td>163.80</td>
<td>693.64</td>
<td>0.4758</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>11.72</td>
<td>159.54</td>
<td>774.36</td>
<td>0.6296</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Italian ryegrass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; growth</td>
<td>7.11</td>
<td>67.57</td>
<td>587.56</td>
<td>0.0320</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; growth</td>
<td>5.17</td>
<td>41.62</td>
<td>895.49</td>
<td>0.8443</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; growth</td>
<td>3.38</td>
<td>54.01</td>
<td>1300.04</td>
<td>0.5546</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Faba bean-oat</td>
<td>13.19</td>
<td>158.22</td>
<td>691.37</td>
<td>0.6163</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Intercrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Equation, \( y = \frac{a}{1+e^{-\left(\frac{x-x_0}{b}\right)}} \)
## Appendix 17: The coefficients for linear relationship between accumulated DM and accumulated intercepted of photosynthetically active radiation (PAR) for three species sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sowing date</th>
<th>a</th>
<th>s.e.</th>
<th>b</th>
<th>s.e.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>47.41</td>
<td>58.07</td>
<td>1.92</td>
<td>0.17</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>28&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>0.26</td>
<td>9.15</td>
<td>2.09</td>
<td>0.05</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>21&lt;sup&gt;st&lt;/sup&gt; April</td>
<td>-9.32</td>
<td>22.85</td>
<td>1.87</td>
<td>0.12</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>12&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-22.19</td>
<td>40.97</td>
<td>1.29</td>
<td>0.18</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; June</td>
<td>-37.67</td>
<td>31.13</td>
<td>1.27</td>
<td>0.12</td>
<td>0.96</td>
</tr>
<tr>
<td>Faba bean</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-79.77</td>
<td>20.43</td>
<td>2.75</td>
<td>0.06</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>28&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-26.77</td>
<td>11.94</td>
<td>2.89</td>
<td>0.05</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>21&lt;sup&gt;st&lt;/sup&gt; April</td>
<td>-15.11</td>
<td>23.09</td>
<td>2.57</td>
<td>0.09</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>12&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-29.75</td>
<td>23.80</td>
<td>2.71</td>
<td>0.11</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; June</td>
<td>-87.07</td>
<td>54.97</td>
<td>1.96</td>
<td>0.20</td>
<td>0.95</td>
</tr>
<tr>
<td>Oats</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-56.02</td>
<td>19.67</td>
<td>2.45</td>
<td>0.07</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>28&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-1.44</td>
<td>15.83</td>
<td>2.41</td>
<td>0.08</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>21&lt;sup&gt;st&lt;/sup&gt; April</td>
<td>28.16</td>
<td>1.80</td>
<td>1.80</td>
<td>0.07</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>12&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-20.47</td>
<td>23.77</td>
<td>1.51</td>
<td>0.09</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; June</td>
<td>-24.15</td>
<td>22.66</td>
<td>1.23</td>
<td>0.08</td>
<td>0.98</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-56.02</td>
<td>19.67</td>
<td>2.45</td>
<td>0.07</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>28&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-1.44</td>
<td>15.83</td>
<td>2.41</td>
<td>0.08</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>21&lt;sup&gt;st&lt;/sup&gt; April</td>
<td>28.16</td>
<td>1.80</td>
<td>1.80</td>
<td>0.07</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>12&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-20.47</td>
<td>23.77</td>
<td>1.51</td>
<td>0.09</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; June</td>
<td>-24.15</td>
<td>22.66</td>
<td>1.23</td>
<td>0.08</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Note: Equation of the form $y = a + bx$

## Appendix 18: Total intercepted photosynthetically active radiation (PAR) and radiation use efficiency (RUE) of faba bean, oats and Italian ryegrass sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Total intercepted PAR (MJ m&lt;sup&gt;-2&lt;/sup&gt;)</th>
<th>RUE (g DM MJ&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>589&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>28&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>432&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.4&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>21&lt;sup&gt;st&lt;/sup&gt; April</td>
<td>465&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>12&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>398&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1.8&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; June</td>
<td>452&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>1.4&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>S.E.M</td>
<td>18.27</td>
<td>0.09</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

Species (S)
- Faba bean: 422<sup>b</sup> 1.7<sup>c</sup>
- Oats: 490<sup>a</sup> 2.5<sup>a</sup>
- Italian ryegrass: 490<sup>a</sup> 1.8<sup>b</sup>
- S.E.M: 10.79 0.06

Significance
- ***

Interaction (SD x S)
- **

Sowing date and species followed by the same letter are not significantly different, **=P<0.01, ***=P<0.001.
Appendix 19: The coefficients for linear relationship between accumulated DM and accumulated intercepted photosynthetically active radiation (PAR) for three species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand

<table>
<thead>
<tr>
<th>Species</th>
<th>Sowing date</th>
<th>a</th>
<th>s.e.</th>
<th>b</th>
<th>s.e.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean</td>
<td>16&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-39.80</td>
<td>28.90</td>
<td>2.05</td>
<td>0.06</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>16&lt;sup&gt;th&lt;/sup&gt; April</td>
<td>-75.39</td>
<td>38.37</td>
<td>2.3</td>
<td>0.08</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>15&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-75.98</td>
<td>26.63</td>
<td>1.77</td>
<td>0.05</td>
<td>0.99</td>
</tr>
<tr>
<td>Oats</td>
<td>16&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-135.47</td>
<td>38.83</td>
<td>2.59</td>
<td>0.08</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>16&lt;sup&gt;th&lt;/sup&gt; April</td>
<td>-100.32</td>
<td>27.99</td>
<td>2.48</td>
<td>0.06</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-116.15</td>
<td>33.61</td>
<td>2.35</td>
<td>0.07</td>
<td>0.99</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>16&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-7.19</td>
<td>34.24</td>
<td>2.20</td>
<td>0.08</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>16&lt;sup&gt;th&lt;/sup&gt; April</td>
<td>-46.22</td>
<td>19.74</td>
<td>2.11</td>
<td>0.05</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-53.50</td>
<td>18.26</td>
<td>2.06</td>
<td>0.05</td>
<td>0.99</td>
</tr>
<tr>
<td>Faba bean-oat intercrop</td>
<td>16&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>-123.71</td>
<td>29.43</td>
<td>2.45</td>
<td>0.06</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>16&lt;sup&gt;th&lt;/sup&gt; April</td>
<td>-47.19</td>
<td>30.07</td>
<td>2.20</td>
<td>0.07</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>-90.28</td>
<td>38.59</td>
<td>2.24</td>
<td>0.08</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Note: Equations of the form \( y = a + bx \)

Appendix 20: Total intercepted photosynthetically active radiation (PAR) and radiation use efficiency (RUE) of faba bean, oats, Italian ryegrass and faba bean-oat intercrop sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Total intercepted PAR (MJ m&lt;sup&gt;-2&lt;/sup&gt;)</th>
<th>RUE (g MJ&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16&lt;sup&gt;th&lt;/sup&gt; March</td>
<td>982&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>16&lt;sup&gt;th&lt;/sup&gt; April</td>
<td>896&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.2&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>15&lt;sup&gt;th&lt;/sup&gt; May</td>
<td>861&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>S.E.M</td>
<td>7.33</td>
<td>0.04</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>**</td>
</tr>
</tbody>
</table>

Species (S)

<table>
<thead>
<tr>
<th>Species</th>
<th>Total intercepted PAR (MJ m&lt;sup&gt;-2&lt;/sup&gt;)</th>
<th>RUE (g MJ&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean</td>
<td>937&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.1&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Oats</td>
<td>977&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.4&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>788&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.1&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Faba bean-oat intercrop</td>
<td>952&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.3&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>S.E.M</td>
<td>12.6</td>
<td>0.05</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

Interaction (SD*S)

| Sowing date and species followed by the same letter are not significantly different, *=P<0.05, **=P<0.01, ***=P<0.001. |
Appendix 21: Plant population (per m$^2$) at emergence of three species sown on five sowing dates in 2008 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Species</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Faba bean</td>
<td></td>
</tr>
<tr>
<td>4$^{th}$ March</td>
<td>64</td>
<td>315$^{b}$</td>
</tr>
<tr>
<td>28$^{th}$ March</td>
<td>67</td>
<td>325$^{b}$</td>
</tr>
<tr>
<td>21$^{st}$ April</td>
<td>54</td>
<td>383$^{a}$</td>
</tr>
<tr>
<td>12$^{th}$ May</td>
<td>41</td>
<td>350$^{ab}$</td>
</tr>
<tr>
<td>3$^{rd}$ June</td>
<td>54</td>
<td>337$^{ab}$</td>
</tr>
<tr>
<td>Mean</td>
<td>56$^{c}$</td>
<td>742$^{a}$</td>
</tr>
<tr>
<td>S.E.M</td>
<td>13.4</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Sowing dates and species followed by the same letter are not significantly different.

Appendix 22: Plant population (per m$^2$) at emergence of three species sown on three sowing dates in 2009 at Lincoln University, Canterbury, New Zealand.

<table>
<thead>
<tr>
<th>Sowing date (SD)</th>
<th>Plant population</th>
</tr>
</thead>
<tbody>
<tr>
<td>16$^{th}$ March</td>
<td>245</td>
</tr>
<tr>
<td>16$^{th}$ April</td>
<td>248</td>
</tr>
<tr>
<td>15$^{th}$ May</td>
<td>244</td>
</tr>
<tr>
<td>S.E.M</td>
<td>11.9</td>
</tr>
<tr>
<td>Significance</td>
<td>NS</td>
</tr>
</tbody>
</table>

Species (S)
Faba bean         | 69$^{d}$         |
Faba bean (intercrop) | 30$^{d}$       |
Oats              | 256$^{b}$        |
Oats (intercrop)  | 154$^{c}$        |
Italian ryegrass  | 720$^{a}$        |
S.E.M             | 15.6             |
Significance      | ***              |
Interaction (SD x S)| NS             |

Sowing date and species followed by the same letter are not significantly different. ***=P<0.001, NS = Not significant.
Appendix 23: The extinction coefficient ($k$) of faba bean (a), oats (b) and Italian ryegrass (c) against days after sowing (DAS) sown on 4th March (●), 28th March (○), 21st April (▼), 12th May (△) and 3rd June (■) 2008 at Lincoln University, Canterbury, New Zealand.
Appendix 24: The extinction coefficient ($k$) of faba bean (a), oats (b), Italian ryegrass (c) and faba bean-oat intercrop (d) against days after sowing (DAS) sown on 16th March (●), 16th April (○), and 15th May (▼) 2009 at Lincoln University, Canterbury, New Zealand.
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Caradus, J. R. 2006. 75 years of scientific and technological advances in pastoral agriculture - what will it take to continue to deliver? *Proceedings of the New Zealand Grassland Association, 68*, 33-68.


