Development of a novel crop-pasture system for mixed farms in the higher rainfall zone of southern Australia

A thesis submitted for the degree of Doctor of Philosophy

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Table of Contents

List of Figures

List of Tables

Abstract of Thesis

The use of annual-based pasture and/or annual crops is now common practice in the higher rainfall regions of southern Australia where livestock grazing is the traditional practice. The lower water use of these annual-based systems, compared with systems based on perennial pastures, exacerbates issues of waterlogging, rising watertables and salinity in these regions. For environmental reasons farming systems used in the higher rainfall regions should target the use of more perennials in the landscape, but this should not be done at the expense of farm productivity or profitability. Intercropping, where the pasture component of the system is a perennial species, may provide the opportunity to maintain or improve farm productivity whilst delivering favourable environmental outcomes. A study of crop/perennial pasture intercrops is the core investigation undertaken in this thesis. Perennial pasture species lucerne (*Medicago sativa*) and chicory (*Cichorium intybus*) were established and maintained for three seasons with annually sown (2006-08 seasons) crop species (wheat (*Triticum aestivum)*, lupin (*Lupinus angustifolius)* and canola (*Brassica napus))*, in a double skip row arrangement. These intercrops were compared for production, resource use and farm productivity with the individual crops and pastures grown as monocultures.

Yields of grain crops were reduced when grown in intercrop with lucerne and chicory. Grain yield reductions ranged from 0-46% for wheat, 45-74% for lupins and 8-83% for canola. Pasture dry matter was also reduced when intercropped, ranging from 0-78% for lucerne and 19-78% for chicory. Despite the reduction in crop and pasture production, the Land Equivalent Ratio (LER) (used as a measure of the productivity of the intercropping system) ranged from 0.71-1.66, with all intercrop combinations over-yielding (LER 1.01 - 1.66) in favourable growing seasons.

With soil moisture becoming limited during September/October (measured using Time Domain Reflectometry), the grain yield components of wheat heads/m^2, number of lupin branches/plant, pod number/plant and pasture dry matter were reduced by competition. Lucerne intercrops gave higher yield penalties to the companion species, attributed to greater competition for soil moisture between the component species. Higher soil moisture (9-25mm) for monoculture chicory, compared to monoculture lucerne, indicates chicory growing in intercrop was not likely to compete as strongly for water as lucerne. Plant height and Leaf Area Index (LAI) measurements were taken to assess light capture and showed minimal incidence of light competition in the intercrops. As a result, it was concluded that competition for water was the main resource competition responsible for yield reductions in intercrops.

The Agricultural Production System Simulator (APSIM) model was used to try to assess longer-term intercrop productivity. The model was satisfactory in simulating monoculture crop production; however there was poor agreement for monoculture lucerne production and this subsequently affected the modelled agreement with intercrop production. Notwithstanding these discrepancies, some of the modelled data and extrapolated data were used to produce a medium-term productivity dataset for economic analysis. Economically, the intercrops were found to have higher gross margin returns than monoculture pastures, and lower gross margins of $39-55/ha when compared to monoculture crops. Despite yield reductions in the intercrop components, intercropping increased productivity compared to growing the components as monoculture stands. It also provided an environmental benefit of retaining perennial pastures in the system, and produced comparable economic returns to the growing of monocultures stands/swards.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Penny Roberts Craig and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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The use of sheep in a grazing experiment as reported in Chapter 7 was approved by the University of Adelaide Animal Ethics Committee, project number S-038-2008.

Roberts Craig, P, Coventry, D & Hocking Edwards, J 2010, 'A comparison of land equivalent ratios and water use in lucerne and chicory based intercrops ', paper presented to 15th Australian Agronomy Conference, Christchurch, New Zealand.

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Chapter 1. <u>General Introduction</u>

The higher rainfall zones of southern Australia are characterised by an annual average rainfall of 450-900mm. This extensive zone has been, and still is, dominated by pasture reliant livestock production supporting over 40% of Australian primary producers (Zhang *et al.* 2006). However, lower returns from livestock and improvements in cropping technologies have seen an increase in the areas sown annually to grain crops in this region (Poole *et al.* 2002; Zhang *et al.* 2006). The changes in these landscapes from the native vegetation cleared for livestock production, to annual-based pastures and crops, has contributed to a changed hydrology for these regions (White *et al.* 2003). The lower water use of these annual-based systems has led to increased water movement past the root zone (Crawford & Macfarlane 1995). For example, the average drainage, at a site with 600mm annual average rainfall, under an annual crop was 49mm/year, and 35mm/year under an annual pasture, compared with no drainage measured under lucerne (Ridley *et al.* 2001). This increased recharge can contribute to environmental problems such as increased incidence of rising watertables, waterlogging and salinity (Williams & Gascoigne 2003).

The prediction of extensive problems associated with dryland salinity in south-east Australia (Ridley *et al.* 2001) and Western Australia (Latta *et al.* 2002) within the next 20 years, highlights the importance of the issue of recharge in the higher rainfall zones of southern Australia. To reduce the impact of the low water use of annual systems, the introduction of higher water-use systems is promoted (Latta *et al.* 2001). Perennial pastures utilise more water than annual systems and reduce water recharge (Crawford & Macfarlane 1995; Hirth *et al.* 2001; Zhang *et al.* 2005). Using a deep-rooted perennial species, such as lucerne, has been the focus of much of the work on incorporating perennials back into the landscape (Dolling *et al.* 2005a; Hayes *et al.* 2010a; Latta *et al.* 2002). When grown in short rotations, lucerne is able to create a drainage buffer at depth (Dolling *et al.* 2005a; Lolicato 2000). In a still predominately grazing-dominant region, the inclusion of productive perennial species provides forage for stock consumption, in addition to environmental benefits (Hayes *et al.* 2010a).

The need for new farming systems that integrate annual and perennial plants is recognised as important in reducing the amount of water contributing to recharge. There are examples of systems that have been developed to achieve this, such as the introduction of a lucerne phase into the cropping rotation (Ridley *et al.* 2001). The introduction of a 2-3 year lucerne phase into an annual cropping rotation improves the hydrology in comparison to an annual-based cropping system (Hirth *et al.* 2001). A problem with this system is the adequate removal of lucerne at the end of the pasture phase (Davies & Peoples 2003) and potential yield reductions in crops following the pasture phase (Hirth *et al.* 2001; McCallum *et al.* 2001a).

To overcome the problem of lucerne removal its over-cropping cereals has been the subject of research in Australia. This over-cropping system generally results in a yield reduction in each of the component species. However, the overall productivity of the system can be greater than growing the monoculture components as separate stands/swards (Harris *et al.* 2007; Humphries *et al.* 2004). In addition to production benefits, the intercropping system is able to use more of the water resource than an annual system by exploiting the deep-rooted perennial pasture species (Harris *et al.* 2008a).

The cereal/lucerne intercrop system has limitations within the higher rainfall zones. Lucerne is not suited to low pH soils or waterlogging conditions found within these regions (Humphries & Auricht 2001), and continuous cereal rotations could lead to the build-up of pests and disease (Kirkegaard *et al.* 1994). It is therefore important to explore a broader range of grain crop/perennial pasture intercrop combinations, in order to develop options that can be used in rotation and that increase the adaption of intercropping to the higher rainfall zones of southern Australia. Improvements in precision agriculture provide the opportunity to develop intercropping systems based on row arrangements which separate the component elements (Humphries *et al.* 2004). This has the potential to reduce competition between components and allow a more equal capture of resources by the intercrop species (Chen *et al.* 2004).

The aim of the study encompassed in this thesis is to determine the suitability of intercropping systems in the higher rainfall zones of southern Australia, using a range of crop/perennial pasture intercrop combinations. This study will explore the source and timing of intercrop competition and its impact on the intercrop species, and increase understanding of how an intercropping system can improve the economic productivity of farming in the study region.

The following flow chart provides an overview of the structure of this thesis, how the chapters relate, and the research questions addressed in each chapter.

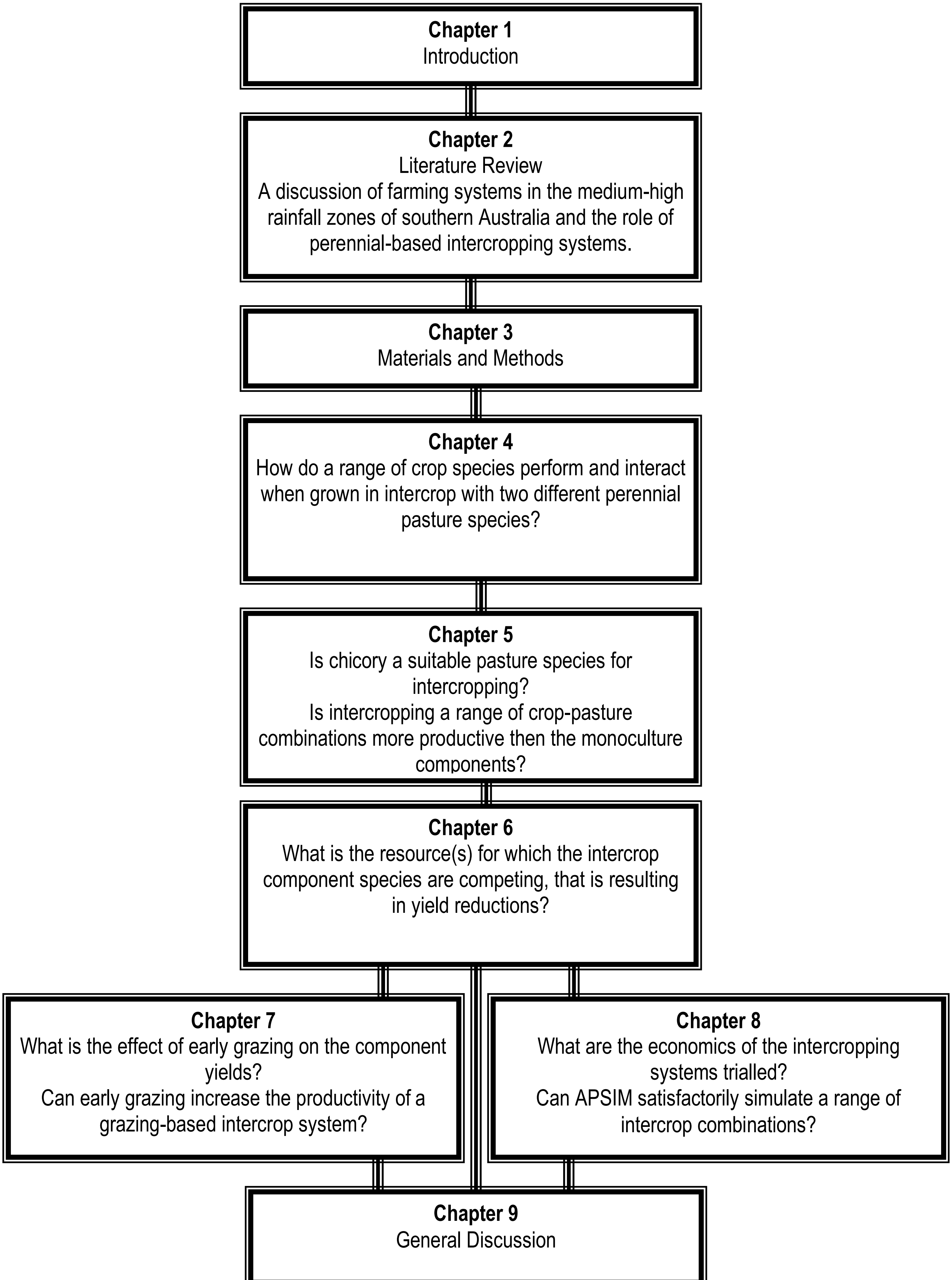

Figure 1-1 Structure of thesis

Chapter 2. Literature Review

2.1 Introduction

The purpose of this literature review is to: 1) provide background information relevant to subsequent chapters, 2) discuss the need for perennial plants to be included in a systems approach suited to the higher rainfall zones of southern Australia, 3) examine the potential development of a novel crop/forage system for mixed farms in the focus region, 4) clarify the understanding of intercropping systems, and 5) identify areas where information is limited and research is required. Following this discussion the aims of the project will be presented.

2.2 Higher rainfall farming systems of southern Australia

The study has its content in the higher rainfall zones (450-900mm) in a Mediterranean climate region of Australia (Figure 2-1). This area is characterised by cool, wet winters and long, hot, dry summers, and are mostly situated near the coast. The soil types in these areas can be extremely variable. The agricultural activities within these areas are traditionally grazing-dominant, however in recent years there has been an increasing trend towards the inclusion of more cropping in the system (Zhang *et al.* 2006). This change is a result of the relatively higher returns from cropping compared with the traditional grazing enterprises (Ewing & Flugge 2004; Poole *et al.* 2002). With a winter-dominant rainfall, the crop growing season generally extends from May through to October (Richards 1991). There is variation in rainfall distribution within the region from more winter-dominant in south-west Western Australia, to uniform in the slopes of New South Wales (Zhang *et al.* 2006). Notwithstanding these regions being defined as winter-dominant rainfall, there are significant amounts of rain falling outside of the crop growing season.

The higher rainfall areas have some environmental issues in common, including the risk of waterlogging in the winter months, salinity and high watertables (Dear *et al.* 2003; Dolling *et al.* 2005a). These issues have negative impacts on pasture and crop growth, typically reducing biomass and yields (Angus *et al.* 2001; McCallum *et al.* 2001a). The study region, along with other areas in southern Australia, regularly experience the impact of low water use by plants as a result of the change to, and reliance on, annual-based plant systems (White *et al.* 2003). Compared to the original predominately native perennial system, the annual system results in a higher amount of water recharge, leading to problems associated with higher watertables (Lolicato 2000; White *et al.* 2003). In situations where waterlogging, salinity and high watertables are not evident, there is still the need to increase productivity of agricultural systems through higher water use of both pasture and crop based systems (Singh *et al.* 2003).

Another issue facing all Australian agricultural areas is the declining terms of trade, and as cost of production increases, it is necessary to increase income in order to remain economically viable (Robertson 2010). Income increases are tied to increases in the productivity of the system and utilise all available resources, not just during the growing season, but throughout the year. Such increases in productivity will come through the development of new technologies, new production systems and production efficiencies (Robertson 2010).

NOTE:
This figure is included on page 5 of the print copy of the thesis held in the University of Adelaide Library.

Figure 2-1 Rainfall zones of Australia (Australian Government: Bureau of Meteorology 2011)

2.3 Limitations to production and opportunities in the focus region

Land use change in the higher rainfall zones of southern Australia initially involved clearing the native annual/perennial system for agricultural production, and establishing a predominately pasture-based grazing system (Whitfield *et al.* 1992). Recently, this has changed again to include more annual-based cropping (Poole *et al.* 2002; Zhang *et al.* 2006). These annual-based systems have been recognised as "leaky" systems, resulting in increased water flow past the plant root zone (Poole *et al.* 2002). In addition, there is a large gap between potential yields and actual yields of grain crops, with waterlogging recognised as a widespread limiting factor to grain production in the higher rainfall zones (McCallum *et al.* 2001b; Zhang *et al.* 2006). It has been calculated that actual grain yields are about 50% of potential (Zhang *et al.* 2006). Many of the soil types in the higher rainfall zones of southern Australia are classified as duplex thus are susceptible to waterlogging due to low permeability of the subsoil (Zhang *et al.* 2006). In addition to managing the waterlogging problems within these regions, it is important to reduce the amount of water moving beyond the root zone.

In order to utilise more of the available water, the adoption of lucerne has been encouraged in these regions (Robertson 2006) because of its greater rooting depth. As an example, to achieve a reduction in water table movement, 30% of a high rainfall zone Western Australian farm would need to be sown to a perennial pasture (Poole *et al.* 2002). The adoption of more perennials in the landscape would have a secondary benefit of increasing root growth into the subsoils (McCallum *et al.* 2004). This is also an important consideration in duplex soils, as it can increase plant access to water and nutrients (Zhang *et al.* 2006).

Clearly, an opportunity exists for increased adoption of summer-active perennial pasture species, such as lucerne, in the higher rainfall zones of southern Australia. This is due to the pattern of summer rainfall and soil water carry-over. Based on suitability criteria for lucerne growth, large portions of the higher rainfall zones in South Australia, Western Australia, Victoria and New South Wales have been identified as suitable for lucerne production (Figure 2-2) (Robertson 2006).

Out-of-growing season rainfall (November-March) can make up a high proportion of annual total rainfall, and can range from 18% to 37% of the long-term annual average as shown in Table 2-1. This rainfall is also reasonably reliable, as seen in Table 2-2, with the median out-of-growing season rainfall ranging from 11% to 29% of the long term median annual total. This out-of-season rainfall is at present an under utilised resource that, in an annual-based system, will be contributing to groundwater recharge. It is this reliable out-of-growing season rainfall that provides an opportunity within these higher rainfall zones to grow summer active perennial pasture species.

NOTE:
This figure is included on page 7 of the print copy of the thesis held in the University of Adelaide Library.

Figure 2-2 Potential areas for dryland lucerne in Western Australia, South Australia, Victoria and New South Wales. Source: (Robertson 2006)

Table 2-1 Mean average in and out of growing season rainfall (mm) for locations in the higher rainfall zones of southern Australia

	Mean Average Rainfall			
Location	In-Growing Season (April-October)	Out-Growing Season (November-March)	Out-Growing season as percent total	Annual Total
Katanning, WA	389	88	18%	480
Naracoorte, SA	435	137	26%	537
Wagga Wagga, NSW	350	202	37%	551
Hamilton, VIC	486	203	29%	689

Source: Rainman StreamFlow v4

Table 2-2 Median average rainfall (mm) for locations in the higher rainfall zones of southern Australia

	Median Average Rainfall			
Location	In-Growing Season (April-October)	Out-Growing Season (November-March)	Out-Growing season as percent total	Annual Total
Katanning, WA	354	50	11%	473
Naracoorte, SA	412	109	19%	574
Wagga Wagga, NSW	317	154	29%	537
Hamilton, VIC	464	176	26%	674

Source: Rainman StreamFlow v4

2.4 Water balance in soils

Water balance of land under agricultural production has changed in many areas, particularly where native annual/perennial vegetation has been cleared and replaced with annual plants (Singh *et al.* 2003). Changes in vegetation type, resulting in a change in hydrological balance, can lead to increases in recharge of groundwater (Gregory *et al.* 1992). This can lead to problems of waterlogging, high watertables and salinity, each of which affects or influences the growth of plants (Angus *et al.* 2001; McCallum *et al.* 2001a). The effect these changes have on soil water dynamics was examined in Western Australia where forest clearing for pasture production took place. Within two years of changing from a perennial eucalyptus forest to an annual pasture, there was a significant increase in soil water storage, occurring predominately at depths 2m and greater (Sharma *et al.* 1987). In this situation, increased recharge to the underlying aquifer occurred as a result of increased drainage under the annual pasture, and the relatively low water holding capacity of the soil.

Water balance can be analysed through the mass balance equation for water in the root zone where:

$$P + U = I + R + E + T + D + L + \triangle S$$

P – precipitation; U – upward capillary flow into the root zone; I – interception by the plant canopy; R – surface runoff; E – evaporation from the soil surface; T – transpiration; D – vertical drainage out of the root zone; L – lateral movement (subsurface runoff or through flow) from the root zone; $\triangle S$ – is the change (increase) in soil water storage (Gregory *et al.* 1992).

Changes in plant rooting depth and water use patterns, as the landscape has changed from perennial native forest to annual pasture, has resulted in a reduction in evapotranspiration ($E + T$). This has led to greater amounts of drainage below the root zone, resulting in groundwater recharge (Williamson 1987). Such hydrological studies have led to an increasing awareness of the issue of water use and recharge under annual systems (Sharma *et al.* 1987; White *et al.* 2003). As a consequence, there is increased research into the potential replacement annual systems with perennial plants that may more closely simulate the native perennial landscape.

2.5 Water use of annual systems in higher rainfall zones

With the higher rainfall zone now mostly reliant on annual pasture species, or incorporating annual-based crop rotations into the system, the amount of soil water used in these systems, compared to a perennial system, is raised (White *et al.* 2003). A comparison of water use by wheat, *Hordeum vulgare* (barley), canola and lucerne in the higher rainfall zones shows that during the winter months, the water use of annual crops was less than rainfall received (Zhang *et al.* 2005). Data from the study of Zhang *et al.* (2005) is shown in Table 2-3. The deep-rooted perennial pasture species lucerne had a water use similar to that of the annual crop species during winter and spring. However, in summer and autumn lucerne used 80-100mm more water. Lucerne also uses water at greater depths compared to annual cropping systems.

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Table 2-3 Depletion of soil water (mm) for spring wheat, canola and lucerne in selected soil layers in the post-anthesis period from 2001-2003. Average of measurements from 2001-2003.

NOTE:
This table is included on page 9 of the print copy of the thesis held in the University of Adelaide Library.

Modified from (Zhang *et al.* 2005)

Similarly, there was greater water use by lucerne compared to wheat and *Pisum sativum* (field pea) crops (McCallum *et al.* 2001a). Plant available soil water was found to be, on average, 48mm less for lucerne-based pastures after 3-4 years, compared to these annual crops. Where lucerne was the preceding crop/pasture treatment, the plant available water was lower for the continuous annual crop/pasture treatments (McCallum *et al.* 2001a). A summary of data from the study of McCallum *et al.* (2001a) is shown in Table 2-4. In a high rainfall region of Victoria, a larger soil water deficit was present with a lucerne-based system compared with an annual pasture system (Crawford & Macfarlane 1995).

These studies are consistent in showing that with an annual-based system, whether pasture or cropping, there is more water passing through the root zone. This leads to increasing recharge that exacerbates the problems of waterlogging, rising watertables and in some instances, salinity. In addition, it is shown that where deep-rooted perennial pastures are used, there is greater water use and this can provide an opportunity to reduce recharge.

Table 2-4 The amount of plant-available water (mm) remaining in the profile after various crop and pasture treatments

NOTE:
This table is included on page 10 of the print copy of the thesis held in the University of Adelaide Library.

Modified from (McCallum *et al.* 2001a)

2.6 Importance of new agriculture systems in the higher rainfall zone

There will always be factors such as compaction, water use, timeliness of operations, soil structure decline and nutrient loss that limit the opportunity to increase productivity in Australian agriculture. In some cases, to overcome these limiting factors there is a need to develop new or modified systems.

Some recent examples of development of new or modified systems that address these factors include zero-till cropping (McGarry *et al.* 2000), surface and subsurface drainage (MacEwan *et al.* 1992), grain and graze

(Price & Hacker 2009) and controlled traffic (Taylor 1983). However, this review will mostly concentrate on one constraint to production, namely management of waterlogging.

Waterlogging started being more recognised as a limiting factor to production in higher rainfall areas when producers began incorporating cropping into traditional grazing enterprises. Waterlogging was quickly identified as having a major impact on crop yields, with, for example, up to 100% yield losses reported in both Western Australia and Victoria (Riffkin & Evans 2003). As a result, average crop yields in high rainfall regions were well below expectations based on water available from rainfall, and trials were initiated to determine the effectiveness of raised beds in reducing waterlogging. The aim of such trials was to increase grain yields by improving soil properties in the root zone, and to try to minimise the effects of waterlogging (Riffkin & Evans 2003). The logic of raised bed farming is that it improves lateral water movement away from the root zone into the drains/furrows between each bed. This is achieved by making the drainage pathway short and thus maximising the hydraulic gradient (Figure 2-3) (Bakker *et al.* 2001).

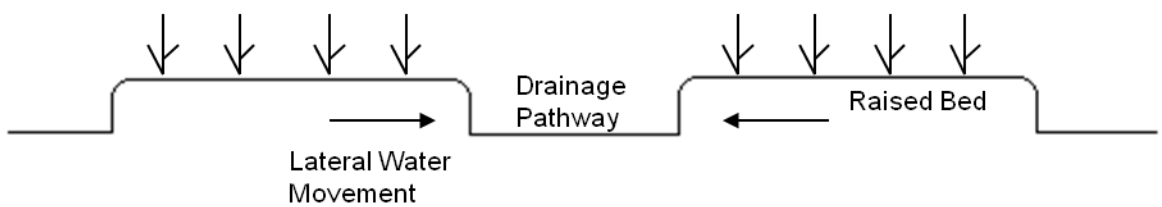


Figure 2-3 Movement of water away from the root zone in Raised Bed Cropping

Crops grown on raised beds had higher yields than wheat grown conventionally in both Western Australia and Victoria (Armstrong *et al.* 2001; Bakker *et al.* 2001; Riffkin & Evans 2003). Raised beds improved soil structure and prevented waterlogging and, as a result, dry matter production and grain yields were increased (Bakker *et al.* 2001). For example, in the Western Australian situation, the average yield increase achieved was 26% (Bakker *et al.* 2001). However as a downside, it was also found that once the unproductive area of the drainage pathways was taken into account, conventional sowing could produce a greater tonnage per hectare than the raised beds (Riffkin & Evans 2003). The study concluded that raised beds were likely to be favourable under conditions where yield losses of conventionally sown crops were greater than 25-30% (Riffkin & Evans 2003).

Raised bed cropping, when developed in western Victoria (as a system called 'Controlled Traffic Raised Bed Cropping'), used a farmer group approach through Southern Farming Systems (SFS) for its validation and adoption. This system had broad acre adoption, starting initially with eight SFS members developing 40ha each of raised beds, and by 1999 SFS estimated that 30,000ha of raised beds had been sown in the high rainfall regions of south eastern Australia (Bluett & Wightman 1999). Adoption of raised beds in Western Australia was also high, with over 6000ha sown after 2 years of research results and associated promotion (Bakker *et al.* 2001). While raised beds have consistently been able to deplete soil water in the upper parts of the soil profile, their impact on soil water deeper in the profile has not been as evident as with perennial pastures (Armstrong *et al.* 2001). Raised bed cropping has overcome yield penalties caused by waterlogging but has not necessarily improved environmental outcomes.

2.7 Integrating livestock and cropping to improve productivity

The previous section has given examples of a new cropping system in the higher rainfall zones that overcomes productivity, and possibly environmental, constraints. Notwithstanding the opportunities for increasing the cropping component of farming enterprises in these zones, livestock production is likely to remain the dominant farm enterprise (Zhang *et al.* 2006). Further integration of livestock and cropping systems is a way of increasing livestock production in all agricultural regions. For example, in the regular cropping zones it is common practice to graze crop stubbles with sheep and cattle to increase productivity of the livestock enterprise. Whilst the nutritional value of crop residue is low, the stock preference is to graze the green matter (weed or volunteer crop species) in the stubbles, leaving much of the crop residue (Mulholland *et al.* 1976a; Mulholland *et al.* 1976b). There is further potential to improve livestock production by grazing crops during the winter period (dual-purpose crops) (Harrison *et al.* 2010; Kelman & Dove 2009).

Grazing of crops during winter has a variable effect on grain yields, as shown in Table 2-5, and is dependent on crop type, growth stage and length of grazing period. Early grazing for a short period (15 days) was found to have no effect on grain yields, however longer grazing treatments (51 days) reduced grain yields (Virgona *et al.* 2006). There was also a slowing of crop development due to grazing, with a one day development delay for every 4-5 days of grazing (Virgona *et al.* 2006). Similarly, early grazing of winter canola crops varieties did not affect yield or oil when grazed in winter before bud elongation, and when seasonal conditions (late winter and spring rainfall) allowed for compensatory growth (Kirkegaard *et al.* 2008).

However, even in situations of grain yield reduction, the grazing benefit can make this system more profitable than un-grazed crops, as shown in Table 2-6 (Kelman & Dove 2007; Kirkegaard *et al.* 2008;

McMullen & Virgona 2009; Virgona *et al.* 2006). The economic grazing benefit of canola was more profitable than a grain-only system, even when there were grain yield penalties (Kirkegaard *et al.* 2008). In addition, returns were significantly higher in three of the four grazed dual-purpose wheat and *Avena sativa* (oat) crops. This was despite a reduction in grain yield in the grazed treatments compared to un-grazed treatments (Kelman & Dove 2007).

Dual purpose cropping studies have shown the economic benefits of integrating grazing with cropping systems in higher rainfall areas. These systems, whilst potentially improving farm economics, do not address the important issue of improved water use in order to reduce water recharge.

Table 2-5 Summary of grain yields (kg/ha) from grazed and un-grazed grain crops

Crop Variety	Un-grazed	Grazed	Comments
Wheat var. MacKellar (after fallow)	5062	2909	Grazing had a negative significant
Oats var. Blackbutt (after fallow)	3283	2312	effect on yield
2004 sowing, (Kelman & Dove 2007)			
Canola var. Hyola 60	4800	4600	Grazing had no significant
Canola var. Maxol	4100	4300	effect on yield
Canola var. Capitol	4100	4000	
2004 sowing, (Kirkegaard *et al.* 2008)			
Wheat var. Wedgetail	2300	2880	Grazing had a positive significant
2003 sowing, (Virgona *et al.* 2006)			effect on yield

Table 2-6 Economic comparison of grazed and un-grazed grain crops

Crop Variety	Un-grazed	Grazed
Wheat var. MacKellar (after fallow)	$534	$461
Oats var. Blackbutt (after fallow	$171	$301
Wheat var. MacKellar (after Spring brassica)	$1021	$1117
Oats var. Blackbutt (after Spring brassica)	$831	$1081
2004 sowing, (Kelman & Dove 2007)		
Canola var. Maxol	$982	$1,247
2004 sowing, (Kirkegaard *et al.* 2008)		

2.8 Integrating perennial pastures into cropping systems

Given the awareness in the agricultural community that annual based systems may not be sustainable in the longer term, methods for introducing deep-rooted perennial pastures have become the focus of studies in higher rainfall zones of southern Australia (Lolicato 2000; Zhang *et al.* 2005). In many studies, the inclusion of perennial pastures within a cropping system has predominately focused on the use of lucerne as the perennial component (Hirth *et al.* 2001; Latta *et al.* 2001; McCallum *et al.* 2001a). The integration of crops and perennial pastures has generally been achieved through the introduction of a perennial pasture phase in a cropping rotation. The aim is for lucerne to deplete soil water during the pasture phase, allowing the growing of annual crops with a reduced impact on the soil water balance (Ridley *et al.* 2001). This pasture phase of the rotation can be for one or multiple years. For example, lucerne-crop rotations with two years of lucerne, followed by several years of crop, resulted in a greater overall use of soil water due to soil water depletion during the lucerne phase (Latta & Blacklow 2001). This outcome is supported in another study where soil water content decreased under lucerne (with a sampling depth of 2m) for the first 18 months after establishment, and in subsequent years remained relatively similar (Angus *et al.* 2001). A simulation comparison of water use following either a lucerne phase or continuous cropping showed that the soil profile would become recharged to a level similar to that of continuous cropping between 1.5 and 5 years, depending on environmental conditions and management practices (McCallum *et al.* 2001a). Recharge following the removal of a lucerne phase in a cropping system appears to be affected by the duration of the lucerne phase. Drainage is likely to occur in the second crop after a two year lucerne phase, compared to drainage occurring in the third to fourth crop after a 3-4 year lucerne phase (Ridley *et al.* 2001).

These studies, carried out in the regular cropping zone of southern Australia, show lucerne can be effectively used as a pasture phase in a cropping rotation to improve soil water use and dry the profile. However, a problem with this system, as shown by Davies and Peoples (2003), and well-known to producers, is the difficulty experienced in lucerne removal prior to returning to the cropping phase of the rotation. Control of lucerne is generally done with chemicals which, as reported in a producer survey, achieved a lucerne kill of only 80%, a level of control regarded as unsatisfactory by producers (Davies & Peoples 2003). There is also a risk of yield penalties in crops following lucerne pasture, with simulations predicting an average yield decrease of 0.4t/ha, and ranging from 0-0.8t/ha depending on seasonal conditions (McCallum *et al.* 2001a). This is due to drying of the soil profile in the subsequent crop's root zone. As such, the yield of crops would depend on the reliance on conserved summer moisture for growth. This is consistent with field trials that showed crop yields following a lucerne phase were largely dependent on seasonal rainfall of the first crop year (Hirth *et al.* 2001). In wet years, crop grain yields were equal to or greater than the control, and in a drier season yields were reduced. These studies show that incorporating lucerne as a perennial pasture phase into a cropping rotation is an effective means of reducing soil water recharge in an annual-based cropping system. However, a weakness of this system can be the removal of lucerne at the end of the pasture phase.

2.9 Intercropping perennial pastures and annual grain crops

As the crop-lucerne rotation system relies on successful removal of the lucerne at the end of the pasture phase, a possible alternative is to permanently integrate the lucerne with the crop (Davies & Peoples 2003). Over-cropping or intercropping is a system where two species are grown together in the same paddock, with the aim of increasing per hectare productivity. This system relies on minimising potential competition between the species and maximising their complementary traits (Midmore 1993). Intercropping is done with or without distinct row arrangement (Figure 2-4). This study will refer to the practice of sowing into existing pasture stands as over-cropping, whilst systems sown on distinct row arrangements will be referred to as intercropping (Figure 2-4). The intercropping system overcomes the need for lucerne removal in the rotation system and has the benefit of summer grazing post crop harvest (Davies & Peoples 2003). Over-cropping a cereal directly into an established pasture stand, generally lucerne, each year, has been the focus of pasture cropping in Australia. Lucerne over-cropping generally results in grain yield reductions; for example 13-63% in wheat (Humphries *et al.* 2004), 6-62% for barley (Egan & Ransom 1996) and 17% for cereals, wheat and barley (Harris *et al.* 2007).

Whilst there are generally yield reductions with these published examples, there is the additional benefit of grazing the lucerne after the crop has been harvested. When this is accounted for, intercropping systems can, in some cases, be more productive than growing the components as monoculture swards/crops (Harris *et al.* 2007; Humphries *et al.* 2004). These studies show that incorporation of perennial pasture into cropping systems has the potential to improve productivity and water use of pasture and crop-based systems in the higher rainfall zones of southern Australia. However, more work needs to be undertaken to improve understanding of crop yield reductions in these systems, and to look beyond the dependency on lucerne as the companion pasture species.

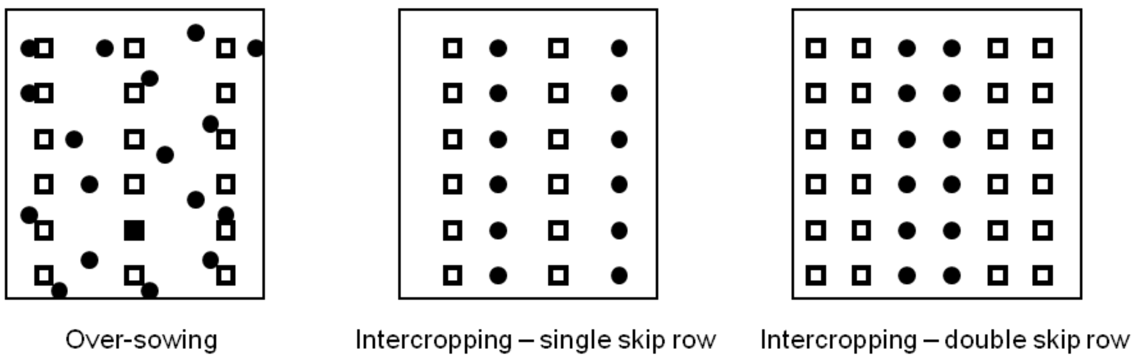


Figure 2-4 Different intercrop sowing arrangements □- species 1, pasture ● – species 2, crop

2.10 Intercropping benefits

Internationally, there are many reasons given why intercropping is used; namely, to reduce the risk of food failure, to broaden the nutritional base in local food production, and reduce the risk of pest and disease attack and spread to susceptible species (Jolliffe & Wanjau 1999). Intercrop systems are also used to increase efficiency of resource use, such as where legumes are used as a system component to reduce Nitrogen (N) fertiliser requirements (Chen *et al.* 2004; Thorsted *et al.* 2006) and to achieve higher land use efficiency (Willey 1979).

In Australia, intercropping is undertaken mostly to reduce input requirements where legumes and grasses are grown together, and for the environmental benefits of reducing water seepage into groundwater (Humphries *et al.* 2004). In addition to productivity increases, benefits of this system include summer weed control and soil structural benefits (Humphries *et al.* 2004).

Intercropping has often been found to increase resource use efficiency and be more productive than growing the components as monocultures (Carruthers *et al.* 2000). It is reported that intercrops take up an additional 43% Phosphorus (P) and 35% Potassium (K) compared to the monoculture components (Morris & Garrity 1993a). Similarly, an increase in water use efficiency of between 18 and 99% has been reported in intercropping (Morris & Garrity 1993b). Australian over-cropping studies have shown that in the higher rainfall zones of southern Australia higher levels of production can be achieved in intercropping systems compared to growing the two species as separate monoculture swards/crops (Harris *et al.* 2007; Humphries *et al.* 2004).

Intercropping cereal crops and perennial pastures has the benefit of extracting soil moisture to depth and utilising more soil moisture than an annual system. In a comparative study, it has been shown that over-cropping lucerne with cereals maintained a drier subsoil than the monoculture cereal, although the driest soil was with monoculture lucerne (Harris *et al.* 2008a). As mentioned above, there are other benefits to the inclusion of perennial species, including nitrogen fixation where legumes are utilised (Humphries *et al.* 2004) and soil improvement, through the creation of biopores, due to increased rooting depth of the perennial species (McCallum *et al.* 2004). Intercroppping can also provide greater flexibility for producers to change between enterprises, should either prices or cost of production make livestock or grain production uneconomical. The production and environmental benefit of intercropping appear to make this system well suited to the higher rainfall zones of southern Australia.

2.11 Intercrop species competition

Intercropping can cause competition for resources including water, light, and nutrients, between the two component species (Fukai 1993; Keating & Carberry 1993). The degree of competition is determined by the effect of each component's growth on the other and the growing environment (Fukai & Trenbath 1993). To reduce competition, careful selection of component species, agronomic inputs, planting times, spatial design, planting density, soil moisture and agronomic manipulation is required.

In a South Australian crop-crop intercrop study, there was no yield advantage found from intercropping wheat and *Cicer arietinum* (chickpea), and this was attributed to poor canopy development of the chickpea component early in the season, resulting in low crop yield (Jahansooz *et al.* 2007). The slow development and low growth habit of the chickpea, compared to that of wheat, reduced its ability to compete for resources, particularly water. This study suggests different seeding times may alter peak demand times for water and result in reduced competition.

Similarly, when cassava was intercropped with *Cajanus cajan* (pigeonpea), it was found that *Manihot esculenta* (cassava) emerged more slowly and was shorter in height than pigeonpea (Cendekdee & Fukai 1992). This system was generally less productive than the monoculture components, due to prolonged competition between component species, with plant height reported as the most likely source of competition. A second experiment by these authors found intercropping cassava with *Glycine max* (soyabean), which is shorter and early-maturing, resulted in a lesser yield reduction of the cassava (Cendekdee & Fukai 1992).

In wheat-lucerne over-cropping studies it was found that competition for light and N early in the crop growing season was the likely cause of grain yield reductions (Harris *et al.* 2008a; Humphries *et al.* 2004). Here, it was suggested that limiting lucerne growth early in the season, and using N fertiliser and higher cereal seeding rates, may reduce over-cropping competition and/or increase grain yields (Harris *et al.* 2008a). Similarly, strategic placement and timing of N fertiliser applications; herbicide suppression of lucerne and changing spatial arrangements were suggested as possible opportunities to reduce competition for resources in cereal-lucerne over-cropping (Humphries *et al.* 2004).

When there is competition for more than one resource, competition is intensified (Donald 1997). An example of this is when one intercrop component dominated competition for light due to plant height, the uptake of nutrients, N and P, were reduced in the suppressed species (Morris & Garrity 1993a). However, it was found that using late and early-maturing species enabled recovery of the late-maturing species once the early-maturing species had been harvested. Similarly, it was found that competition for one resource can also cause competition for a previously non-limiting resource (Donald 1997). An example of this is where one plant is able to capture more soil available moisture, leading to an increase in stem and leaf growth, which leads to a greater water requirement and may also lead to shading of the other plant.

These studies show that selection of the component intercrop species and agronomic management of the intercropping system are important considerations in reducing competition for resources.

2.12 Row intercropping

Recent advances in sowing technology that allow precision row alignment of the introduced seed, provides the opportunity to utilise concurrent row intercropping of perennial and annual species (Humphries *et al.* 2004). There are many possible row configurations. Two commonly used in intercrop crop/crop studies are single alternate row and double alternate row (Figure 2-4).

Mixed plant arrangements, where component species are sown mixed in the same row, have been found in one study to be the most productive and produce the greatest biomass compared to single and double alternate rows (Chen *et al.* 2004). However, double alternate row arrangements were shown to improve the outcome where there is a suppressed component of the intercrop (Chen *et al.* 2004; Morris & Garrity 1993a). With a crop-crop intercrop (barley and peas), grown in mixed arrangements, the cereal was the dominant contributor to the total biomass (Chen *et al.* 2004). The use of row configurations however, allowed greater contribution of the pea component to overall production. While production was lower than the mixed arrangement, productivity was higher than that of the monoculture components. Similarly, intercropped wheat and chickpea had the highest yield when grown in mixed arrangements, compared to single and double alternate row arrangements (Jahansooz 1999). However, the growth of chickpea, the suppressed species, was improved when grown in a double alternate row arrangement with wheat. These studies indicate inter-species competition can be reduced with the use of double alternate row arrangements. This is supported by a study that reported growing wheat on double alternate row arrangements, while resulting in lower yields compared to the single alternate row arrangement, allowed greater water conservation in the inter-row of the double alternate row arrangement for use by the subsequent summer active forage (Giles *et al.* 2006).

Double row spacing decreases rectangularity, the distance between the rows divided by the in-row plant distance (i.e. the arrangement becomes more square), and this has been found to increase wheat yields under lower plant densities (40 to 77 plants/m^2) (Kemp *et al.* 1983). This is likely due to the ability of the plants in a square arrangement to grow for a longer period before encountering space occupied by neighbouring plants. Compared to that of the rectangular design where available space would have been occupied early (Kemp *et al.* 1983). The square arrangement enables higher early growth rates. This early growth rate in the low density square arrangements resulted in production of more tillers per plant and was a major reason for the grain yield advantage of the square arrangements (Kemp *et al.* 1983). Similarly, increased rectangularity of intercropping, as with alternate row plantings, is reported to delay the start of competition and capitalises on the border effect (Midmore 1993).

Double row spacing appears to provide a productivity advantage over mixed and single row spacing through delaying of the onset of competition. Creating a greater physical gap between rows allows the exploitation of resources for a longer period during early crop growth, and greater access to the light resource by the suppressed species (Jahansooz 1999). As such, double row spacing will be used in the experiments reported in this thesis, to allow greater resource use and delay the onset of intercrop competition.

2.13 Selection of crop and pasture intercrop species

In order to reduce the antagonistic effect of intercropping, species need to be selected carefully. Ideally, selected species would have different growth durations, resource requirements and area of resource capture, in order to avoid both species having their greatest requirement for resources at the same time (Fukai & Trenbath 1993).

Crop/pasture intercropping in Australia has focused on lucerne (legume) with cereal crops as the companion species. This system aims to reduce competition between companion species and increase productivity. This is achieved by selecting species with different peak resource requirements and differing rooting depths, and therefore areas of resource capture, such as, shallow-rooted spring annual grain crop and deep-rooted summer active perennial pasture.

There are limitations to this lucerne/cereal system. Within the higher rainfall zones of southern Australia, there are regions not suited to growing lucerne, particularly where soil pH is lower. Lucerne is also not well-suited to waterlogged conditions (Humphries & Auricht 2001). It is therefore important to consider alternative perennial pasture species that could be used in a crop/pasture intercrop.

Production and species persistence trials conducted to identify perennial legumes and herbs suited to mixed farming in southern Australia identified chicory as a non-lucerne species that had immediate potential in these regions (Li *et al.* 2008). Chicory is a deep-rooted, summer active perennial herb, adapted to the higher rainfall zones of southern Australia. Chicory produces high quality feed suitable for stock finishing (Kemp *et al.* 2002) and, as with many lucerne biotypes, chicory is winter dormant and produces most of its annual biomass in late spring, summer and into autumn (Li *et al.* 2010). Chicory is able to grow in areas characterised by acidic and waterlogging-prone soils that lucerne is not well-suited to (Li *et al.* 2010). Thus, chicory is a commercially-available perennial pasture species that is suited to some areas of the higher rainfall zones of southern Australia that lucerne is not suited to. These growth characteristics could mean that chicory, similarly to lucerne, would be a suitable crop/pasture intercropping species.

The crop-pasture intercropping system is designed to allow long sequence cropping, but this may lead to problems of disease and pest build-up. To avoid the build-up of disease and pests in all systems in the traditional cropping areas, a break crop is included in the rotation (Gregory 1998; Kirkegaard *et al.* 1994). Break crops in southern Australia are generally canola or a legume species such as lupin, *Phaseolus vulgaris* (bean), pea, chickpea or *Lens culinaris* (lentil). There is no data to date on the results of intercropping with break crop species, particularly in the higher rainfall regions. Thus, a focus in this thesis is investigation of the use of chicory as a perennial intercrop species along with lucerne, and also the inclusion of some non-cereal crops in the crop/pasture intercrop.

2.14 Assessing the productivity and economics of intercropping systems

Comparing the productivity of monoculture and intercrop treatments is not as straightforward as comparing yields of the intercrop components with that of the monoculture stands. Yields of the intercrop component species are generally lower than that of the monoculture components grown separately (Mead & Willey 1980). To overcome this problem, an index that expresses yield advantage of intercropping based on the relative land required by the monoculture stands to produce the same yields as the intercrop, is used (Mead & Willey 1980). This index is known as the Land Equivalent Ratio (LER) and is an expression of the proportion of the yields from each species when grown together, compared to the monoculture components grown separately. LER can be used as a measure of yield advantage/disadvantage. If a LER is greater than 1, it would mean the monoculture crops alone would require more land than that of the intercrop to produce the same yield, and vice versa with a value of less than 1 (Mead & Willey 1980). A LER value greater than 1 also indicates relatively higher efficiency of the intercrop compared to the monoculture (Willey 1985).

Land Equivalent Ratio is expressed as:

$$LER = L_A + L_B = \frac{Y_A}{S_A} + \frac{Y_B}{S_B}$$

L_A and L_B – are the LER for the individual crops

Y_A and Y_B – are the individual crop yields in intercropping

S_A and S_B – are the yields as sole crops of the intercrop

(Mead & Willey 1980)

LER values have been used in intercropping studies to assess the advantage of mixed species systems, where the production of both species is equally desired (Dhima *et al.* 2007). LER can be based on a range of factors including grain yield, dry matter production, nutrients, nutrition and economics (Willey 1985).
Dry matter-based LER of intercropped common vetch (*Vicia sativa L.*) and a range of cereal species produced LER values of greater and less than 1, depending on the species combination and ratio of the two species in the mixture (Dhima *et al.* 2007). This led to the recommendation that the most suitable and profitable intercrop combinations and species ratios for intercropping were common vetch-oats and vetch-wheat. Intercrop grain yield LER of wheat and chickpea resulted in values of 1.01-1.02, whilst dry matter LER values were 0.97-1.00 (Jahansooz *et al.* 2007). Based on these results, it was concluded this intercrop combination was not likely to provide an advantage to production in the study region.

LER have also been used to compare different intercropping row arrangements. Biomass yield results of intercropped barley and peas show higher dry matter LER values in the mixed arrangement compared to the single and double skip row (Chen *et al.* 2004). This study also used LER to assess protein production of the different intercropping arrangements. With dry matter LER values ranging from 1.05-1.24 and protein from 1.05-1.26, it was concluded that there was a production advantage with intercropping compared to growing the components as monocultures. A cereal-lucerne over-cropping study also used LER to assess the productivity of the system (Humphries *et al.* 2004). This was achieved using over-cropped lucerne grain yield and out-of-growing season biomass production (that available for grazing), compared to that of total monoculture lucerne production and monoculture grain yield. Depending on the winter activity of the lucerne variety used, it was found that lucerne-wheat over-cropping could be more productive (LER>1) than growing the components as monocultures.

LER provides an insight into the comparative productivity of intercropping compared to the monoculture components. LER can also be used to evaluate the maximum economic outcome of intercropping.

However, it should only be used in cases where both components of the intercrop are marketable cash crops (Willey 1985). Egan and Ransom (1996) provided a simple economic analysis of a cereal-lucerne over-cropping system showing an increase in the gross margin return from lucerne pastures of $80/ha compared to annual pastures, and a reduction in grain income from the intercrop of $71/ha. This is based on data from one year and one over-crop combination, using regionally averaged production and costs. Economics is an important consideration in the adoption of new technologies and systems, but to date there is little understanding of the on-farm economic implications of intercropping systems studied in southern Australia.

2.15 Longer-term assessment of intercropping systems

In order to gain a better understanding of the longer-term performance of agricultural systems, modelling programs such as the Agricultural Production System Simulator (APSIM) can be utilised (Keating *et al.* 2003; Teixeira *et al.* 2010). APSIM has been tested against field data for its ability to simulate cereal-lucerne against over-cropping in Australia (Harris *et al.* 2008b, 2010; Robertson *et al.* 2004).
APSIM was found to satisfactorily simulate field production data in a wheat-lucerne over-crop, (Harris *et al.* 2008b), provided soil mineral N was reset in the over-cropping simulation in autumn. This avoided over-simulation of lucerne production and under-simulation of wheat production. This study concluded APSIM could be utilised to simulate longer-term over-crop performance in a range of seasons and under differing management (Harris *et al.* 2008b). Similarly, APSIM was satisfactory for simulating field observations of over-cropping systems involving wheat, canola and lucerne (Robertson *et al.* 2004). This study also concluded APSIM could be suitable for simulating over-cropping outcomes for a range of areas and circumstances.

These studies show the APSIM model's ability to successfully simulate pasture-crop over-cropping in Australia and indicate it would be suitable in simulating a longer-term production output for other cereal-lucerne systems such as those being proposed in this study.

2.16 Summary

Information presented in this literature review has covered the integration of perennial pasture and cropping in a livestock dominant farming zone. The need to improve water use of annual-based systems to reduce the potential for environmental problems of rising watertables, waterlogging and salinity, and to improve productivity, has been discussed in the context of farming in the higher rainfall zones of southern Australia. In addition, the importance of developing new or modified systems in agriculture, to overcome constraints to productivity, has been highlighted. The potential for crop-pasture intercropping to overcome the constraint of lower water use of annual systems, and to improve productivity within these regions, has been shown. The review also presents information on techniques for assessing productivity as they relate to the experimental work undertaken in this thesis.

A number of areas where there are gaps in the knowledge of crop-pasture intercropping systems have been highlighted in this review of literature. These include an understanding of the outcome of using a double alternate row arrangement in intercropping to reduce the onset of early competition, and how this affects the cause, timing and duration of intercrop competition. In addition, it is not known if this arrangement will improve productivity of the intercropping system compared to the monoculture components.

There is a limitation of the current pasture-crop over-cropping system's adaption to some regions in the higher rainfall zones of southern Australia, due to dependency on the use of lucerne as the perennial pasture component. Likewise, there is a need to reduce reliance on a continuous cereal rotation in these intercropping systems. There may be potential to increase productivity of the system through the livestock enterprise by grazing of intercrops prior to stem elongation.

It is also not known if APSIM can satisfactorily be used to simulate the field data of a range of cereal-lucerne intercrop combinations to enable longer-term assessment of the productivity of these systems. In addition, there is limited understanding of the whole farm economic outcome of intercropping in the study region.

The purpose of this thesis is therefore to address the question:

Can a range of crop and perennial pasture intercrop combinations improve the productivity and adaptability of intercropping in the grazing-dominated higher rainfall zones of southern Australia?

The hypothesis is that:

Intercropping with a range of crop/perennial pasture intercrops will be more productive than monoculture production in the higher rainfall zones of southern Australia.

The following chapters will address the specific questions of:

What is the effect on yield of the timing and duration of competition between the annual crop and perennial pasture components of the intercrop? (Chapter 4 & 5)

What is the suitability of cereal and break-crop species grown in intercrop with perennial pasture species lucerne and chicory? (Chapter 4)

Is chicory a suitable intercrop species? (Chapter 5)

Will a range of crop-pasture intercrop combinations be more productive in the focus region than the monoculture components? (Chapter 5)

What is the source and timing of intercrop competition? (Chapter 6)

What is the impact of early grazing on the component yields and the productivity of wheat-pasture intercrops? (Chapter 7)

Can APSIM satisfactorily simulate field data for a range of crop-lucerne intercrops? (Chapter 8)

What is the economic cost/benefit of a crop-pasture intercrop system in the higher rainfall zones of southern Australia? (Chapter 8)

The final chapter (Chapter 9) will discuss the implications of the study findings.

Chapter 3. Material and Methods

3.1 Experimental site

The experimental site was located in the higher rainfall zone of western Victoria, at Benayeo, approximately 12km east of the South Australia/Victoria border. The site was located on the property Nalda Park (latitude 36˚50' longitude 141˚30') (Figure 3-1).

The soil type at the site is a duplex soil consisting of a sandy loam A horizon and a bleached A2 horizon over a clay B horizon (Figure 3-2). The A horizon has a pHw of 5.5 – 5.9 and the B horizon of pHw 7.0 – 9.5, with pH increasing with depth. Some physical and chemical properties of the soil, measured at the end of 2008, are presented in Table 3-1 and Table 3-2. Note there was contamination of the 60-90cm depth sample at site 1, which was therefore excluded from averaging in the development of the soil profile for APSIM.

The climate of the site is similar to that of a Mediterranean type, with cold, wet winters and hot, dry summers. The long term average annual rainfall at this site is 500mm, with the majority falling between April and October, which will be defined as 'in-growing season' in this study. While the majority of the rainfall occurs during the growing season, there are significant rainfall events that occur out of the growing season. Rainfall records for the duration of the trial can be seen in Table 3-3. The 2006 season was a severe drought, with growing season rainfall of 155.5mm and a yearly total of 252.5mm, which is less than half the average. In 2007, 503.5mm fell for the year, although a large amount of this fell outside of the growing season and a dry finish to the grain crop growing season was experienced (Table 3-3). In 2008, the total average rainfall was below average (433.5mm), however the in-growing season rainfall was higher than both 2006 and 2007. Late spring (October) was dry in this year (Table 3-3).

NOTE:
This figure is included on page 27 of the print copy of the thesis held in the University of Adelaide Library.

Figure 3-1 Location of experimental site at Benayeo, Victoria Source: (The South Australian Tourism Commission 2011)

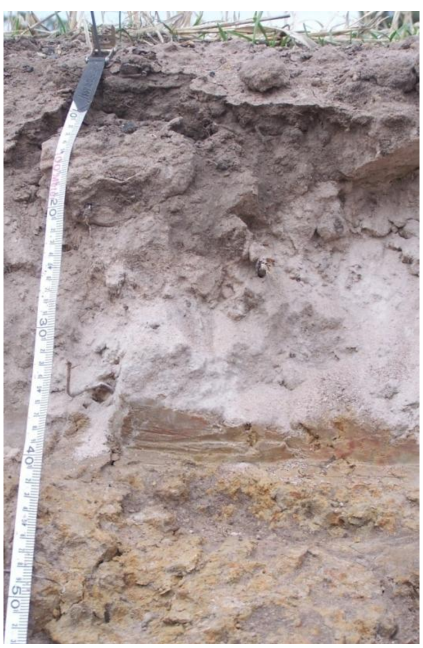


Figure 3-2 Site soil profile, the pit is located 200m from trial site

Table 3-1 Physical and chemical properties of the soil from 0-90cm, taken December 2008, Site 1

Depth (cm)	Nitrate (mg/kg)	Ammonium (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Sulphur (mg/kg)	Organic Carbon (%)	Conductivity (dS/m)
0 10	18	2	44	224	4.9	1.58	0.096
10 30	4	2	8	192	5.4	0.5	0.077
30 60	3	1	3	137	6.2	0.31	0.175
60 90	10	3	26	198	19.2	1.22	0.323

pH_$CaCl_2$ (pH)	pH_H_2O (pH)	Exc_Ca (meq/100g)	Exc_Mg (meq/100g)	Exc_Na (meq/100g)	Exc_K (meq/100g)	Exc_Al (meq/100g)	PBI (Index)
4.6	5.5	3.09	0.93	0.13	0.63	0.16	34.2
6	7	8.28	7.18	1.31	0.54	0	127.9
7.6	8.6	7.35	5.84	1.8	0.37	0	73.9
7.2	8	12.04	3.36	0.98	0.44	0	110.4

Note: Exc = Exchangeable cations PBI = Phosphate Buffering Index

Table 3-2 Physical and chemical properties of the soil from 0-90cm, taken December 2008, Site 2

Depth (cm)	Nitrate (mg/kg)	Ammonium (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Sulphur (mg/kg)	Organic Carbon (%)	Conductivity (dS/m)
0 10	13	3	26	171	6.6	1.65	0.078
10 30	3	1	6	204	4.1	0.49	0.095
30 60	2	1	5	196	5.1	0.35	0.134
60 90	3	1	5	214	14.6	0.29	0.274

pH_$CaCl_2$ (pH)	pH_H_2O (pH)	Exc_Ca (meq/100g)	Exc_Mg (meq/100g)	Exc_Na (meq/100g)	Exc_K (meq/100g)	Exc_AL (meq/100g)	PBI (Index)
5.2	5.9	4.73	1.51	0.27	0.4	0.01	34.1
6.5	7.3	7.32	7.57	1.6	0.64	0	122
8	9	8.59	7.96	2.28	0.55	0	85.1
8.5	9.5	9.36	11.15	4.39	0.66	0	81.4

Table 3-3 Monthly rainfall and rainfall days summary for 2006-2008

	Monthly Rainfall (mm)			Rainfall Days		
Month	2006	2007	2008	2006	2007	2008
January	28.5	94.5	0	3	5	0
February	22.5	8.5	0	2	1	0
March	36	10.5	4	2	2	1
April	42.5	31	32.5	10	1	6
May	23.5	93.5	78	5	13	6
June	5	8.5	38.5	2	4	4
July	35	76	50.5	14	12	8
August	11.5	36	73	4	6	12
September	34	40.5	50.5	7	7	9
October	4	21.5	8	2	7	2
November	4	49	18.5	2	5	7
December	6	34	80	2	1	5
Total	252.5	503.5	433.5	55	64	60
Growing Season	155.5	307	331	44	50	47

3.2 Soil type

To determine crop lower limits (CLL) rainout shelters were installed at the start of December 2008. Soil samples were taken on 22/12/2008, with additional samples taken for nutrient analysis and to determine soil characteristics. Further soil samples were taken on the lucerne and chicory on 23/02/2009 to confirm the CLL measurements taken in December.

Two sites were installed, one in each of site 1 and 2, to determine drained upper limit (DUL) and these soil samples were taken on 23/01/2009. The sample sites were wet-up using a ponded water procedure. An area 4m X 4m was selected. An earth bund was created up to prevent water exiting the area and then the area was regularly filled with water. The bund was then knocked down and the site covered with heavy gauge plastic to minimize evaporation. The site was allowed to drain for 2 day prior to sampling.

Soil measurement consisted of three cores per plot or sampling area to a depth of 90cm. Cores were cut to the lengths shown in Figure 3-3 and the three samples bulked. Due to restricted access to equipment the core diameters were 30mm for samples taken from 0-60cm and 26mm for samples taken from 60-90cm. There were only 3 sample depths for the CLL, due to difficulties in keeping cored samples together and to avoid the risk of sample contamination.

The samples were weighed, then dried at 105 degrees for 48hrs and weighed again. Soil characteristics were then calculated using the methods described by Dalgliesh and Foale (1998). Soil samples were sent to a laboratory for nutrient analysis.

Figure 3-3 1. Sample depths for drained upper limit 2. Sample depths for crop lower limit 3. Sample depths for nutrients and soil characteristics

3.3 Experimental design

There were two sites established as part of this study. Site 1 was established in 2006 and site 2 was established in 2007. Both sites were then maintained until the autumn of 2009.

The treatments and the years in which they were included in the trial at site 1 are detailed in Table 3-4. The treatments used in site 2 were:

Monoculture: Wheat, lucerne and chicory

Intercrops: Wheat-lucerne and wheat-chicory

Treatments were replicated four times in a randomised block design. Yearly treatment rotations for each plot at site 1 and 2 are shown in Figure 3-5 and Figure 3-6. The crops in site 1 were rotated on an annual basis with the aim of preventing pest and disease affecting the performance of the crop. Where possible the rotation was lupin, wheat, canola. Each plot was 2.8m x 10m, with 16 rows per plot. Prior to harvest, the two ends of each plot were mown back 1m to create 8m long plots for harvest.

The treatments were sown with a combine fitted with knife points and press wheels. The small seed (lucerne and chicory) was sown out of a small seed box, dropped onto the surface and then pressed in with the press wheels. In the establishment year, 2006 in site 1 and 2007 in site 2, the crop and pasture components of the intercrops were sown at the same time. In subsequent years the tines that represented the pasture rows were lifted out of the way so as not to disturb the established pasture, and only the grain crop component of the intercrop was sown. To assist with this, the holes corresponding with the pasture rows were blocked to prevent seed entering the tubes in the pasture rows.

The intercrop plots were sown on double alternate rows, with seeding rates maintained per row. The half monoculture plots were sown in the same double alternate row arrangement as the intercrop (Figure 3-4). In 2006, monoculture wheat and wheat-lucerne intercrop treatments were also sown at a higher seeding rate.

The half monoculture treatments were included in the study to allow the assessment of competition. As the half monoculture and intercrop treatments were sown at the same seeding rates and row design it is expected if there is no competition occurring in the intercrop treatments then the results should not differ between the half monoculture and intercrop treatments.

Table 3-4 Treatments and years of inclusion from 2006-08 in site 1

Treatment	2006	2007	2008
Monoculture wheat	X	X	X
Monoculture lupin	X	X	X
Monoculture canola		X	X
Half monoculture wheat	X	X	X
Half monoculture lupin	X	X	X
Monoculture lucerne	X	X	X
Monoculture chicory	X		
Intercrop wheat-lucerne	X	X	X
Intercrop wheat-chicory	X	X	X
Intercrop lupin-lucerne	X	X	X
Intercrop lupin-chicory	X	X	X
Intercrop canola-lucerne		X	X
Intercrop canola-chicory		X	X
High sowing rate monoculture wheat	X		
High sowing rate intercrop wheat-lucerne	X		

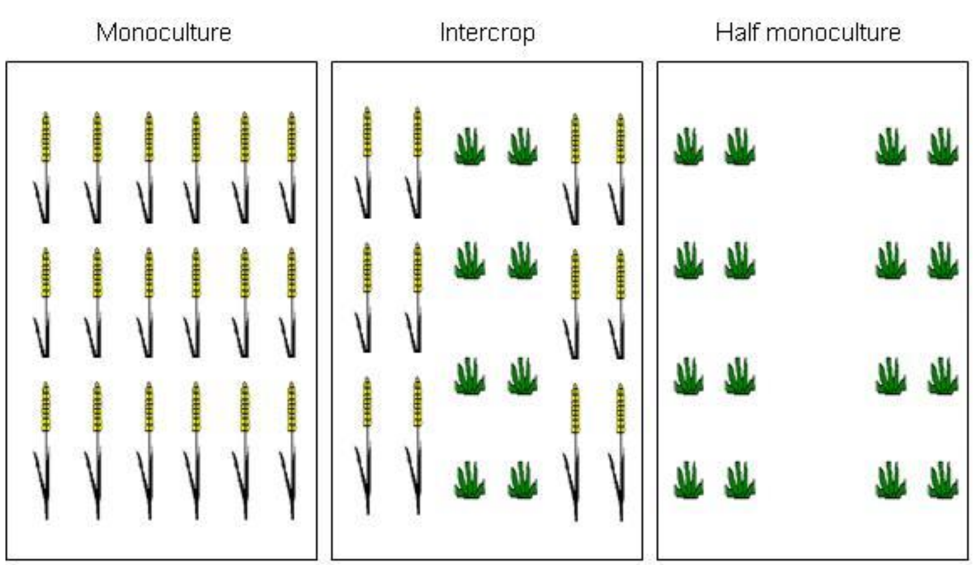


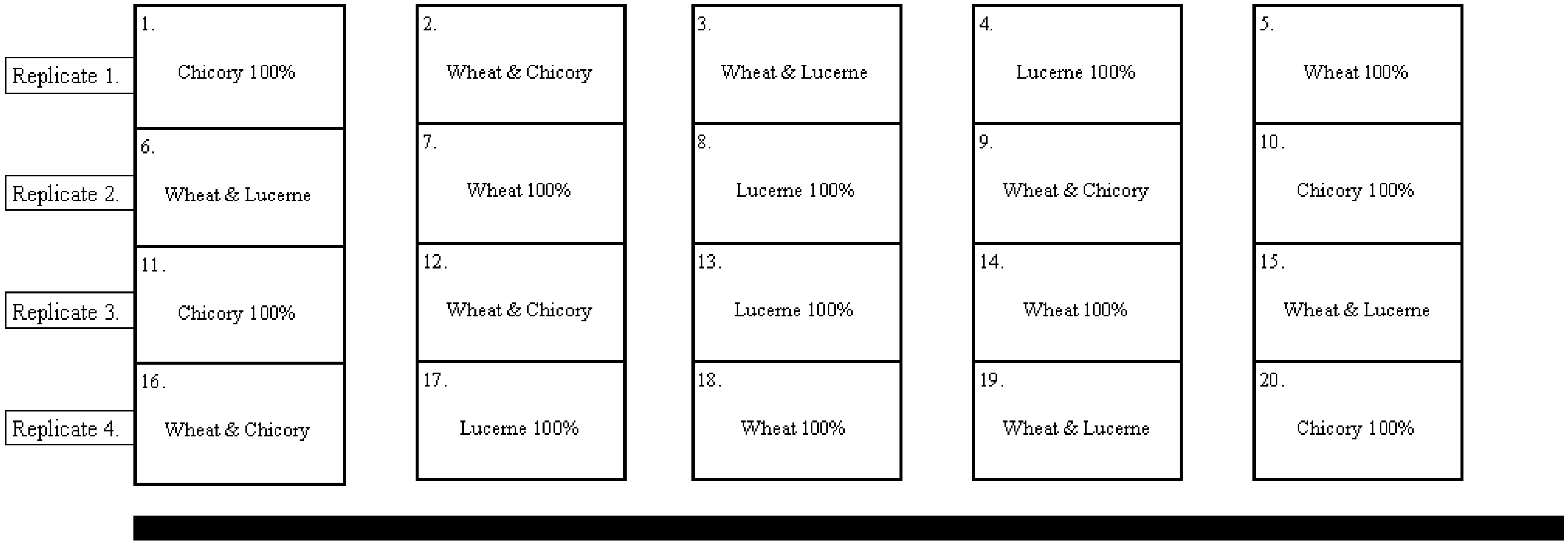
Figure 3-4 Row arrangements of monoculture, intercrop and half monoculture treatments

Replicate 1.	1. 06: Lupins 100% 07: Wheat 100% 08: Canola 100%	2. 06: ↑ Wheat 100% 07: Lupins 100% 08: Wheat 100%	3. 06: ↑ Wheat & Lucerne 07: Lupins & Lucerne 08: Wheat & Lucerne	4. 06: Wheat & Lucerne 07: Canola & Lucerne 08: Lupins & Lucerne	5. 06: Wheat & Chicory 07: Canola & Chicory 08: Lupins & Chicory	6. 06: Chicory 50% 07: Lupins & Chicory 08: Wheat & Chicory	7. 06: Lupins 50% 07: Wheat 50% 08: Lupins 50%
	8. 06:Lupins & Lucerne 07: Wheat & Lucerne 08: Canola & Lucerne	9. 06: Chicory 100% 07: Chicory 100% 08: Chicory 100%	10. 06: Lucerne 100% 07: Lucerne 100% 08: Lucerne 100%	11. 06: Lupins & Chicory 07: Wheat & Chicory 08: Canola & Chicory	12. 06: Lucerne 50% 07: Lucerne 50% 08: Lucerne 50%	13. 06: Wheat 50% 07: Lupins 50% 08: Wheat 50%	14. 06: Wheat 100% 07: Canola 100% 08: Lupins 100%
Replicate 2.	15. 06:↑ Wheat & Lucerne 07: Lupins & Lucerne 08: Wheat & Lucerne	16. 06: Chicory 50% 07: Lupins & Chicory 08: Wheat & Chicory	17. 06: Lupins 100% 07: Wheat 100% 08: Canola 100%	18. 06: Chicory 100% 07: Chicory 100% 08: Chicory 100%	19. 06:Lupins & Lucerne 07: Wheat & Lucerne 08: Canola & Lucerne	20. 06: Lupins 50% 07: Wheat 50% 08: Lupins 50%	21. 06: Wheat & Chicory 07: Canola & Chicory 08: Lupins & Chicory
	22. 06: Lucerne 100% 07: Lucerne 100% 08: Lucerne 100%	23. 06: Wheat 100% 07: Canola 100% 08: Lupins 100%	24. 06: Lupins & Chicory 07: Wheat & Chicory 08: Canola & Chicory	25. 06: Lucerne 50% 07: Lucerne 50% 08: Lucerne 50%	26. 06: Wheat 50% 07: Lupins 50% 08: Wheat 50%	27. 06: ↑ Wheat 100% 07: Lupins 100% 08: Wheat 100%	28. 06: Wheat & Lucerne 07: Canola & Lucerne 08: Lupins & Lucerne
Replicate 3.	29. 06: Wheat & Chicory 07: Canola & Chicory 08: Lupins & Chicory	30. 06: Wheat 50% 07: Lupins 50% 08: Wheat 50%	31. 06: ↑ Wheat 100% 07: Lupins 100% 08: Wheat 100%	32. 06: Lucerne 50% 07: Lucerne 50% 08: Lucerne 50%	33. 06: Wheat & Lucerne 07: Canola & Lucerne 08: Lupins & Lucerne	34. 06: Wheat 100% 07: Canola 100% 08: Lupins 100%	35. 06: Lupins & Chicory 07: Wheat & Chicory 08: Canola & Chicory
	36. 06: Lucerne 50% 07: Lupins & Lucerne 08: Wheat & Lucerne	37. 06: Lucerne 100% 07: Lucerne 100% 08: Lucerne 100%	38. 06: Lupins 50% 07: Wheat 50% 08: Lupins 50%	39. 06: Chicory 100% 07: Chicory 100% 08: Chicory 100%	40. 06: Lupins 100% 07: Wheat 100% 08: Canola 100%	41. 06: Chicory 50% 07: Lupins & Chicory 08: Wheat & Chicory	42. 06: Lupins & Lucerne 07: Wheat & Lucerne 08: Canola & Lucerne
Replicate 4.	43. 06: Lucerne 50% 07: Lupins & Lucerne 08: Wheat & Lucerne	44. 06: Lupins 100% 07: Wheat 100% 08: Canola 100%	45. 06: Wheat 50% 07: Lupins 50% 08: Wheat 50%	46. 06: Wheat & Chicory 07: Canola & Chicory 08: Lupins & Chicory	47. 06: ↑ Wheat 100% 07: Lupins 100% 08: Wheat 100%	48. 06: Lupins 50% 07: Wheat 50% 08: Lupins 50%	49. 06: Wheat 100% 07: Canola 100% 08: Lupins 100%
	50. 06: Lucerne 100% 07: Lucerne 100% 08: Lucerne 100%	51. 06: Chicory 100% 07: Chicory 100% 08: Chicory 100%	52. 06: Wheat & Lucerne 07: Canola & Lucerne 08:Lupins & Lucerne	53. 06: ↑Wheat & Lucerne 07: Lucerne 50% 08: Lucerne 50%	54. 06: Lupins & Chicory 07: Wheat & Chicory 08: Canola & Chicory	55. 06: Lupins & Lucerne 07: Wheat & Lucerne 08: Canola & Lucerne	56. 06: Chicory 50% 07: Lupins & Chicory 08: Wheat & Chicory

Road

Figure 3-5 Treatment rotations per plot from 2006-08 in site 1

Note: 100% = monoculture, 50% = half monoculture, ↑ = high sowing rate



Intercropping Trial sown 2006

Figure 3-6 Treatment rotations per plot from 2007-2008 in site 2

3.4 Agronomy

Prior to the study commencing in 2006 the experimental site paddock had been sown to *Brassica napus* (forage rape) in 2005. The forage rape was grazed over the spring and summer with the remaining plants removed by spraying prior to sowing of site 1 in 2006. The site was sown late in 2006 (9/7/2006) once the site had received adequate rainfall to ensure germination of the species sown. Site 2 was sown to wheat in 2006, prior to the establishment of this site in 2007. Prior to 2005 the paddock was a permanent pasture with a strong *Trifolium subterraneum* (sub-clover) base.

All treatments were sown with 90kg/ha of DAP fertiliser. The fertilizer was sown with the seed of both the crop and pasture in 2006. In 2007 and 2008 the fertilizer was sown with the crop seed and spread on the surface of the pastures. The sowing rates for each monoculture species were, wheat (variety Whistler) 85kg/ha; lupin (variety Wonga) 100kg/ha; lucerne (variety Aurora) 6kg/ha; chicory (variety Puna) 4kg/ha. The sowing dates were: 09/07/2006; 18/05/2007; 25/05/2008.
Weeds and insects were controlled using the appropriate herbicides and pesticides, along with hand-weeding.

Herbicides and pesticides used in this study along with rates are listed in Appendix 1.

3.5 Measurements taken

3.5.1 Plant numbers

Crop establishment was measured on 8/11/2006, 19/07/2007 and 22/07/2008 for wheat, lupin and canola. Crop establishment and plant density counts were taken late in the growing season in 2006 due to the late sowing of the trail in this year. Additionally the late season counts accounted for the higher mortality rate of the plants due to drought conditions.

Pasture density counts for lucerne and chicory were taken during the crop growing season and in the autumn prior to seeding. For both crop establishment and pasture density measurements, plant numbers were recorded in three randomly selected locations per plot. Numbers were recorded along a 0.5m row, then averaged and converted to calculate plants/m^2.

3.5.2 Crop and pasture production

Above ground crop dry matter production was measured in all seasons, 2006-08, for each crop when the wheat crop reached cereal growth stages, first node (GS31), anthesis (GS65) and maturity (GS95). In addition pasture dry matter was measured when the cereal crop reached cereal growth stages GS31, GS65 and GS95 during the crop growing season. Pasture dry matter was also measured out of the crop growing season, when there were sufficient amounts of biomass to require harvesting. Crop and pasture measurements (three per plot at each sampling) were taken per plot using a randomly placed quadrat. Plant material within each quadrat was cut to a 2cm height. These samples were then dried at 80 degrees Celsius until the samples were fully dry, than weighed.

Pasture monoculture plots were mown, following each dry matter harvest, to a height of 2cm to simulate grazing. The intercrop plots were mown to a height of 2cm following each harvest of dry matter, post grain harvest.

3.5.3 Crop grain yield measurements

Tiller counts were measured early in the growing season of 2008, at wheat growth stage GS31: first node on the main stem. Tillers were counted on a 0.5m row in three randomly selected locations per plot, then converted to tillers/m^2.

Wheat grain heads per m^2 were counted, along with the number of unviable heads (taken in 2008), grains per head, spikelets per head and grains per spikelet when the wheat crop reached maturity. Lupin pods per m^2, in addition to number of branches, pods per branch and seeds per pod, were also counted at crop maturity.

These yield component measurements were done using a randomly placed quadrat, within each plot 3 measurements were taken.

The grain crops were machine-harvested in December each year. A strip was harvested from the middle of each plots to eliminate the edge effect, of the 16 rows, rows 5 through to 12 were harvested. The grain was weighed for each plot to give t/ha of grain. Grain samples were taken from each plot at the time of harvest. Wheat subsamples were used to measure screenings and 1000 grain weights. Wheat, lupins and canola subsamples from 3 of the 4 replicates were sent for protein (wheat and lupins) and oil (canola) analysis. Lupins were not harvested in 2006 due to the seed count being low to nil for all treatments and replicates.

3.5.4 Soil water measurement

Volumetric soil waters content (θ, cm^3 cm^{-3}) were measured in both site 1 and 2 using a TRASE time domain reflectometer (TDR). Marine grade stainless steel TDR probes of 0-15cm and 0-35cm were permanently installed at the start of the 2007 and 2008 monitoring seasons in three replicates of each of the monoculture and intercrop treatments. The TDR probes were removed each year prior to harvest. Within the intercrop plots, 5 measurements were taken in-row and inter-row for both the grain crop and pasture components, in addition to a between crop and pasture row measurement. Within the monoculture plots, two measurements were taken, in-row and inter-row (Figure 3-7). Data was analysised to determine differences due to positioning of the probes and on a whole plot basis using the average of the readings for each plot (details of statistics presented in section 3.5.7). Volumetric soil water content was converted to mm using the following equation:

Volume moisture (m3/m3) x depth of soil (mm)

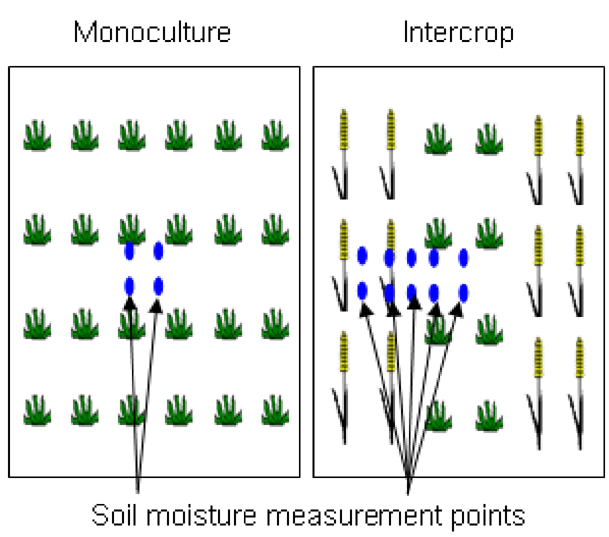


Figure 3-7 TDR probe locations for monoculture and intercrop treatments

3.5.5 Leaf Area Index (LAI) and plant height measurement

Leaf Area Index (LAI) was measured in 2006 and 2007 using a LICOR-2000. Measurements were taken within the crop growing season at site 1 and 2 for each monoculture and intercrop treatment.

Plant height was measured during the crop growing season in 2006 and 2008 due to unavailability of the LICOR. The height of individual plants was measured along a 0.5m row in three randomly selected locations per plot for each species.

3.5.6 Land Equivalent Ratio (LER)

Land equivalent ratio values (LER) were calculated to give an indication of the productivity of the intercropping system. LER values are presented and were calculated in three ways using the formula described by Mead and Willey (1980).

$$LER = L_A + L_B = \frac{Y_A}{S_A} + \frac{Y_B}{S_B}$$

L_A and L_B – are the LER for the individual crops

Y_A and Y_B – are the individual crop yields in intercropping

S_A and S_B – are the yields as sole crops of the intercrop

The first calculation was based on the economically important traits of grain yield and pasture available for livestock grazing (based on out-of-growing season dry matter and pasture dry matter available at harvest). The second and third calculations are based on crop and pasture dry matter production, indicating resource use. The second calculation, growing season dry matter production, is based on dry matter production taken for both the crop and pasture at the point in time when the crop had produced the maximum of the dry matter. In this case, wheat anthesis was used for all species. The third calculation was the annual total dry matter produced. For all crop species, this measurement was taken when the wheat crop reached anthesis. For the monoculture pastures, the figure used was the cumulative total of dry matter produced. For the intercrops, the out-of-growing season dry matter was used, in addition to the dry matter cut taken when the wheat crop reached maturity. This assumes that peak production in all years and for all species was at wheat anthesis. There was variation between years and treatments, and this variation would cause the pasture dry matter production to be slightly underestimated, therefore the final LER would be slightly lower.

LER for the grazing study conducted at site 2 in 2008 were calculated using the method described above. Cumulative crop dry matter production (which included crop dry matter removed by grazing) was used in dry matter based LER calculations. Crop dry matter removed by grazing was included in the economic LER calculation.

3.5.7 Statistical analysis

Analysis of variance (ANOVA) was used to determine treatment differences for data presented, except for soil water. The analysis was done using GenStat 11 (Release 11.1, VSN International Ltd, Hertfordshire, UK). Levels of probability of greater than 0.05 (P>0.05) were considered non-significant, and least significant differences (l.s.d) were calculated to compare treatment means when ANOVA P-values were less than 0.05.

The statistical method of restricted maximum likelihood (REML) was used to model soil water over time, using a selected variance – covariance structure. The selection was via a sequence of likelihood ratio tests on several nested models. For site 1 2007 data (15 & 35 cm depths) and site 2 2007 15 cm depth data a power model was selected as the most appropriate, in which the correlation between observations from the same plot decays as the delay between the observations increases. For all other data a heterogeneous power model in which the correlations follow the power model and the variances can be different at each time were considered the most appropriate. Data were log-transformed (natural log) where necessary. After the variance–covariance model had been selected, the appropriate main effects or interactions were investigated via Wald tests and specific pairs of means were compared using the SEDLSI procedure in GENSTAT. Given a variate or table of parameter estimates (typically treatment means) and a corresponding standard error of the difference (s.e.d.), the procedure SEDLSI computes δ such that $[\delta_i + \delta_j] \cong$ s.e.d. and constructs least significant intervals (LSIs) for graphical presentation of the means. LSIs are intervals (or error bars) that are designed to overlap where there is no significant difference between estimates, and to be disjoint where there are significant differences. Data were back-transformed, where appropriate, after analysis and presented on the original scale.

Raw data is presented in Appendix 3 and 4.

Chapter 4. Intercropping and Grain Crops

4.1 Introduction

Integrating grain crops and pasture species in an intercropping system generally results in a reduction in grain yield compared to the yield of the crop monoculture (Egan & Ransom 1996; Harris *et al.* 2007; Humphries *et al.* 2004). This reduction in grain yield is attributed to competition for resources between component species of the intercrop. Previous crop/perennial pasture over-cropping studies have given indications that the timing of competition is from early to late in the growing season (Egan & Ransom 1996; Harris *et al.* 2007). Early intercrop competition reduces biomass at cereal first node and lowers the number of wheat tillers produced, leading to the suggestion that competition affecting grain yield occurs prior to cereal stem elongation (Harris *et al.* 2008a; Harris *et al.* 2007). In contrast, late season competition in cereal-lucerne over-cropping produced similar cereal dry matter between the intercrop and monoculture cereal at anthesis, leading to the conclusion that strong competition occurred post anthesis (Egan & Ransom 1996).

The current study aims to gain a better understanding of the timing and duration of competition between the component intercrop species. By examining components of yield, in addition to dry matter production and quality attributes of the grain, this study aims to gain a better understanding of competition and its effect on the crop component of the intercrop. Previous work on crop-pasture over-cropping has predominately involved sowing directly into existing pasture stands. Here, the plants have been sown in a double row arrangement, allowing assessment of the effect of changing the spatial arrangement and seeding rate from a monoculture to double row intercrop. This is an important consideration of an intercropping design, as previous studies on wider row cropping have shown both positive and negative effects of this practice on a range of grain crops (Amjad & Anderson 2006; Chen *et al.* 2004).

Intercropping in Australia to date has focused on the use of cereal crops and lucerne as the component species. In the medium to high rainfall zones of southern Australia, cereals are not used in a continuous rotation due to problems associated with weed and disease control. To overcome these problems, break-crops of legumes and brassicas are used in rotation with cereals. Accordingly, canola and lupin, in addition to wheat, were included in this study with the aim of determining the suitability of each of these crops in an intercropping system with perennial pasture species lucerne and chicory.

4.2 Materials and Methods

A description of the trial site, and the materials and methods, are presented in Chapter 3.

4.3 Results

4.3.1 Crop grain yields

Wheat yields were less than 200kg/ha due to drought in 2006 and there were no significant differences between treatments in this year (Table 4-1). Most lupin plants failed to survive to maturity and, as a result, the plots were not harvested due to very low numbers of grains in 2006.

With the majority of treatments, years and sites, the crop monocultures produced significantly higher grain yields ($P<0.05$) than the intercrop treatments and the half monoculture treatments (Table 4-1). Chicory intercrops in 2007 and 2008 were not significantly different from the wheat and lupin half monoculture treatments (Table 4-1). There were differences between the lucerne-lupin intercrop and half monoculture lupin treatments in 2007 and 2008, and the wheat-lucerne intercrop and half monoculture wheat in 2008 (Table 4-1).

Grain yield as a percentage of the monoculture treatments ranged from 103% at site 1 in 2008 for the wheat-chicory intercrop, to 54% for the wheat-lucerne intercrop at site 2 in 2008. Lupin varied from 26% for lupin-lucerne intercrop to 55% for lupin-chicory intercrop. Canola had high relative grain yield percentages in 2007, 81% and 92%, for lucerne and chicory intercrops respectively, and in 2008, 28% and 17% respectively.

Wheat and lupin monocultures produced significantly more grain than the other treatments, with the exception of wheat at site 1 in 2008 (Table 4-1). The wheat-lucerne intercrop at site 1 in 2008 produced less grain ($P<0.05$) than the other treatments (Table 4-1).

In 2007, monoculture canola had a higher grain yield ($P<0.05$) than the canola-lucerne intercrop (Table 4-1). In 2008, the canola yield was less than in 2007 due to insect damage, which reduced plant establishment. In this season, the monoculture canola produced more grain ($P<0.05$) than both intercrop combinations (Table 4-1). The canola intercrop yields did not differ significantly from each other in either 2007 or 2008 (Table 4-1).

There was no significant difference in grain yields between standard and high seeding rates (Table 4-2).

Table 4-1 Mean wheat, lupin and canola grain yields (t/ha) from site 1 and 2 in years 2006-08

	Site 1			Site 2	
Treatment	2006	2007	2008	2007	2008
Monoculture wheat	0.18	3.33 *a*	4.28 *a*	3.58 *a*	4.59 *a*
Wheat-lucerne	0.09	1.87 *b*	2.93 *b*	2.87 *b*	2.48 *b*
Wheat-chicory	0.13	1.95 *b*	4.39 *a*	2.91 *b*	2.65 *b*
Half monoculture wheat	0.10	2.19 *b*	4.31 *a*		
l.s.d (P<0.05)	n.s.	0.705	0.944	0.238	1.143
Monoculture lupin	0.00	1.97 *a*	2.05 *a*		
Lupin-lucerne	0.00	0.52 c	0.57 *c*		
Lupin-chicory	0.00	1.02 *b*	1.12 *b*		
Half monoculture lupin	0.00	1.75 *b*	1.42 *b*		
l.s.d (P<0.05)	n.s.	0.321	0.534		
Monoculture canola		1.76 *a*	1.43 *a*		
Canola-lucerne		1.43 *b*	0.40 *b*		
Canola-chicory		1.62 *ab*	0.25 *b*		
l.s.d (P<0.05)		0.263	0.749		

Table 4-2 Mean wheat yield (kg/ha) of standard and high seeding rates, site 1 2006

Treatment	Standard seeding rate	High seeding rate
Monoculture wheat	181	319
Wheat-lucerne	93	173
l.s.d (P<0.05)	n.s.	n.s.

Note: Means within each treatment column followed by a different letter are significantly different (P<0.05) Not significant = n.s.

4.3.2 Crop dry matter production

The monoculture treatments for wheat, lupin and canola generally produced greater amounts of dry matter (P<0.05) throughout the season compared to the other treatments (Table 4-3, Table 4-4 and Table 4-5). The monoculture wheat produced more dry matter (P<0.05) than all other treatments at all measured growth stages in 2006 and 2007. The exceptions to this were half monoculture wheat in 2006 and wheat-chicory in 2007 when measured at anthesis (Table 4-3). The monoculture wheat also produced more dry matter (P<0.05) than the wheat-lucerne intercrop at both site 1 and 2, for the majority of measurements in the 2008 season. In this same season, monoculture wheat at site 2 also produced more dry matter (P<0.05) than the wheat-chicory intercrop (Table 4-3). Growth measured at maturity (GS95) was generally lower (P<0.05) than that measured at anthesis.

At the first node measurement, monoculture wheat produced significantly more dry matter (P<0.05) than the other treatments in 2007 and 2008 at site 1 and in 2007 at site 2 (Table 4-3). At site 2 in 2008, half monoculture wheat and the wheat-chicory intercrop produced more dry matter (P<0.05) than both the monoculture wheat and the wheat-lucerne intercrop (Table 4-3). Dry matter production was low at site 2 in 2008 due to a heavy ryegrass infestation.

Dry matter production at wheat anthesis, expressed as a percentage of the monoculture wheat, was greater than 50% for the intercrop and half monoculture treatments in all years at site 1, and in 2007 at site 2 (Table 4-3). Monoculture wheat produced significantly more dry matter (P<0.05) than the intercrops in both years at site 2 and in 2006 at site 1 (Table 4-3). At site 1 in 2007, the monoculture wheat produced significantly more dry matter (P<0.05) than the wheat-lucerne intercrop and the half monoculture treatment (Table 4-3).

Wheat dry matter at maturity was greater (P<0.05) for monoculture wheat, than for the all other treatments in 2006 at site 1, and in 2008 at site 2 (Table 4-3). In 2008 at site 1, the wheat-lucerne intercrop produced less dry matter (P<0.05) than the other treatments, which were not significantly different from each other (Table 4-3). Dry matter production measured at maturity for intercrop and half monoculture treatments was greater than 50% for the majority of treatments (Table 4-3).

Monoculture lupin generally produced a greater amount of dry matter (P<0.05) compared to the other treatments at all sampled growth stages (Table 4-4). Dry matter production measured at the first node wheat growth stage was higher (P<0.05) for the monoculture lupin than the other three treatments in 2007, with no significant differences between treatments in 2008 (Table 4-4). The percentages of monoculture dry matter, at wheat first node, were below 50% for all treatments in 2007 and above 50% in 2008 (Table 4-4).

The monoculture lupin produced more dry matter ($P<0.05$), measured at wheat anthesis, than the other treatments in both 2006 and 2007 (Table 4-4). The lupin-lucerne intercrop produced less dry matter ($P<0.05$) than all other treatments measured at wheat anthesis in 2007. The lupin-lucerne intercrop also produced less dry matter ($P<0.05$) at maturity in 2008 than the monoculture and half monoculture lupin (Table 4-4). Monoculture and half monoculture lupin produced more dry matter ($P<0.05$) measured at wheat anthesis than the lupin-lucerne intercrop in 2007 (Table 4-4).
The lupin-chicory intercrop and half monoculture lupin, produced dry matter percentages of greater than 50% of the monoculture, in all years measured at wheat anthesis. In all years, the lupin-lucerne intercrop produced less than 50% of the dry matter of the monoculture at both wheat anthesis and maturity (Table 4-4).

In 2006 and 2008, the monoculture lupin treatment produced more dry matter ($P<0.05$) than all other treatments at maturity (Table 4-4). There was also significantly more dry matter produced in the half lupin monoculture than the lupin-lucerne intercrops in 2008 (Table 4-4).

Canola intercrop dry matter yields varied between the two years. Dry matter production of all treatments was not significantly different measured at wheat anthesis in 2007, but when measured at wheat first node, the monoculture canola produced more dry matter ($P<0.05$) than the two intercrops (Table 4-5).
Monoculture canola produced more dry matter ($P<0.05$) at all growth points, compared to the two intercrops, in 2008. The canola-chicory intercrop also produced significantly more dry matter at all growing points than the canola-lucerne intercrop in the 2008 season (Table 4-5).

Table 4-3 Dry matter (kg/ha) of wheat treatments in site 1 and 2 in years 2006-08

Wheat growth stage Date sampled		Monoculture wheat	Wheat-lucerne	Percent of monoculture	Wheat-chicory	Percent of monoculture	Half monoculture wheat	Percent of monoculture	l.s.d (P<0.05)
First Node (GS31)									
2/09/2007	Site 1. 2007	3980 *a*	1730 *b*	43%	1870 *b*	47%	1900 *b*	48%	516.9
10/09/2008	Site 1. 2008	5680 *bc*	4444 *c*	78%	6446 *ab*	113%	7063 *a*	124%	1338.3
2/09/2007	Site 2. 2007	4206 *a*	2536 *b*	60%	1971 *b*	47%			1151.0
18/08/2008	Site 2. 2008	1618 *a*	971 *b*	60%	777 *b*	48%			519.7
Anthesis (GS65)									
10/10/2006	Site 1. 2006	3459 *a*	2082 *b*	60%	2032 *b*	59%	2704 *ab*	78%	1271.7
25/10/2007	Site 1. 2007	12509 *a*	9944 *b*	79%	10635 *ab*	85%	10322 *b*	83%	2055.2
6/11/2008	Site 1. 2008	13769 a	7771 *b*	56%	12626 *a*	92%	11574 *a*	84%	3367.0
25/10/2007	Site 2. 2007	15667 *a*	11207 *b*	72%	8350 *c*	53%			1380.2
12/11/2008	Site 2. 2008	12848 *a*	7623 *b*	59%	5299 *b*	41%			2845.8
Maturity (GS95)									
7/12/2006	Site 1. 2006	2582 *a*	1907 *b*	74%	1621 *b*	63%	1755 *b*	68%	431.5
16/12/2008	Site 1. 2008	14278 *a*	6032 *b*	42%	12735 *a*	89%	14142 *a*	99%	6181.0
16/12/2008	Site 2. 2008	12501 *a*	8545 *b*	68%	7827 *b*	63%			2745.5

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Table 4-4 Dry matter (kg/ha) of lupin treatments in site 1 in years 2006-08

Wheat growth stage Date sampled		Monoculture lupin	Lupin-lucerne	Percent of monoculture	Lupin-chicory	Percent of monoculture	Half monoculture lupin	Percent of monoculture	l.s.d (P<0.05)
First Node (GS31)									
2/09/2007	2007	933 *a*	245 *b*	26%	369 *b*	40%	414 *b*	44%	367.9
10/09/2008	2008	1155	955	83%	824	71%	998	86%	n.s.
Anthesis (GS65)									
10/10/2006	2006	968 *a*	450 *b*	46%	504 *b*	52%	565 *b*	58%	267.6
25/10/2007	2007	8165 *a*	1887 *c*	23%	4306 *b*	53%	4462 *b*	55%	2383.6
6/11/2008	2008	8330 *a*	3934 *b*	47%	6416 *ab*	77%	8548 *a*	103%	4204.9
Maturity (GS95)	Site 1.								
7/12/2006	2006	817 *a*	370 *c*	45%	436 *c*	53%	523 *b*	64%	81.9
16/12/2008	2008	11986 *a*	4159 *c*	35%	6215 *bc*	52%	8748 *b*	73%	3131.2

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Table 4-5 Dry matter (kg/ha) of canola treatments in site 1 in years 2006-08

Wheat Growth Stage Date sampled		Monoculture canola	Canola-lucerne	Percent of monoculture	Canola-chicory	Percent of monoculture	l.s.d (P<0.05)
First Node (GS31)							
2/09/2007	2007	5327 *a*	3201 *b*	60%	2543 *b*	48%	1689.3
10/09/2008	2008	2007 *a*	944 *c*	47%	1479 *b*	74%	516
Anthesis (GS65)							
25/10/2007	2007	10894	8384	77%	9387	86%	n.s.
6/11/2008	2008	12721 *a*	1951 *c*	15%	5790 *b*	46%	3749
Maturity (GS95)							
16/12/2008	2008	6193 *a*	1174 *c*	19%	3602 *b*	58%	1731.8

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

4.3.3 Grain quality

Screenings

Wheat screenings were below the commercially desired 5% level for all treatments, in all years and at all sites (Table 4-6). Screening levels were only different between treatments in 2008 at site 1, when the intercrop treatments were both lower (P<0.05) than the monoculture and half monoculture treatments (Table 4-6). The monoculture and half monoculture wheat were also significantly different from each other (Table 4-6).

These results are unusual as it would be expected that, especially in the drought year of 2006, the screening levels should be much higher. The wheat variety used, Whistler, does not necessarily have lower screenings than other varieties, and has moderate to high screenings levels (personal communication with Dr Peter Martin, breeder of the Whistler variety). This unusual finding of low levels of screenings was not isolated to this trial site. The property on which the experiment was conducted has never had a load of Whistler wheat go over 5% screenings in all the years it has been grown, including in 2006 (personal communication, Nalda Park manager Nathan Craig).

Table 4-6 Wheat screenings (%) for treatments at site 1 and 2 in years 2006-08

	Site 1			Site 2	
Treatment	2006	2007	2008	2007	2008
Monoculture wheat	3.1	2.6	4.2 *a*	2.9	2.3
Wheat-lucerne	2.9	3.4	2.0 *c*	2.9	2.2
Wheat-chicory	3.6	3.2	2.2 *c*	2.9	1.1
Half monoculture wheat	4.1	3.2	3.2 b		
l.s.d (P<0.05)	n.s.	n.s.	0.67	n.s	n.s

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Protein and oil

There was variation in both wheat and lupin protein percentages, across sites and seasons (Table 4-7). Wheat protein was not significantly different between any of the treatments in 2007 and 2008 at site 2 (Table 4-7). There were significant differences between wheat grain protein levels at site 1, in 2006 and 2008. In the drought year (2006) protein levels were very high for all treatments (Table 4-7). The wheat-chicory intercrop however, had lower protein ($P<0.05$) than the monoculture and half monoculture treatments (Table 4-7). Monoculture and half monoculture wheat had higher protein ($P<0.05$) than the two intercrop treatments at site 1 in 2008 (Table 4-7). In this year, the wheat-lucerne intercrop had lower protein ($P<0.05$) than the wheat-chicory intercrop (Table 4-7).

Lupin protein percentage was not significantly different between treatments in 2007 (Table 4-7). Monoculture lupin had lower protein ($P<0.05$) than lupin-lucerne intercrop and half monoculture lupin in 2008 (Table 4-7).

Canola oil percentages were not significantly different between any of the treatments in 2007 or 2008 (Table 4-7).

Table 4-7 Wheat and lupin grain protein (%) and canola oil (%) at site 1 and 2 in 2006-08

	Site 1			Site 2	
Treatment	2006	2007	2008	2007	2008
Monoculture wheat	20.30 *a*	14.38	14.88 *a*	14.33	12.69
Wheat-lucerne	20.08 *ab*	17.41	10.27 *c*	14.12	11.66
Wheat-chicory	19.19 *b*	13.80	12.97 *b*	13.58	10.45
Half monoculture wheat	20.28 *a*	14.74	15.38 *a*		
l.s.d (P<0.05)	1.065	n.s.	0.974	n.s.	n.s.
Monoculture lupin		28.78	25.96 *b*		
Lupin-lucerne		26.97	28.69 *a*		
Lupin-chicory		27.17	27.47 *ab*		
Half monoculture lupin		28.92	28.28 *a*		
l.s.d (P<0.05)		n.s.	2.218		
Monoculture canola		43.1	42.3		
Canola-lucerne		43.6	42.6		
Canola-chicory		43.1	44.3		
l.s.d (P<0.05)		n.s.	n.s		

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

4.3.4 Grain yield components

Plant number

Plant numbers per m^2 of the half monoculture and intercrop treatments were generally between 40% and 60% of that of the monoculture (Figure 4-1). However, the wheat intercrop and half monoculture treatments at site 1 in 2007 had low plant numbers compared to the control (Figure 4-1). It was observed there had been plant removal post-emergence, likely due to birds, which would account for this discrepancy. The canola intercrops at site 1 in 2008 also had low plant numbers compared to the control, likely due a lower rate of survival of seedlings due to insect damage. (Figure 4-1). Canola plant numbers were lower ($P<0.05$) in 2008 than in 2007 (Figure 4-1), due to insect damage at crop emergence.

There was a positive relationship between plant number and yield in wheat at site 2 in 2007 ($R^2= 0.89$; $P<0.05$) and canola at site 1 in 2008 ($R^2= 0.84$; $P<0.05$) (Figure 4-2).

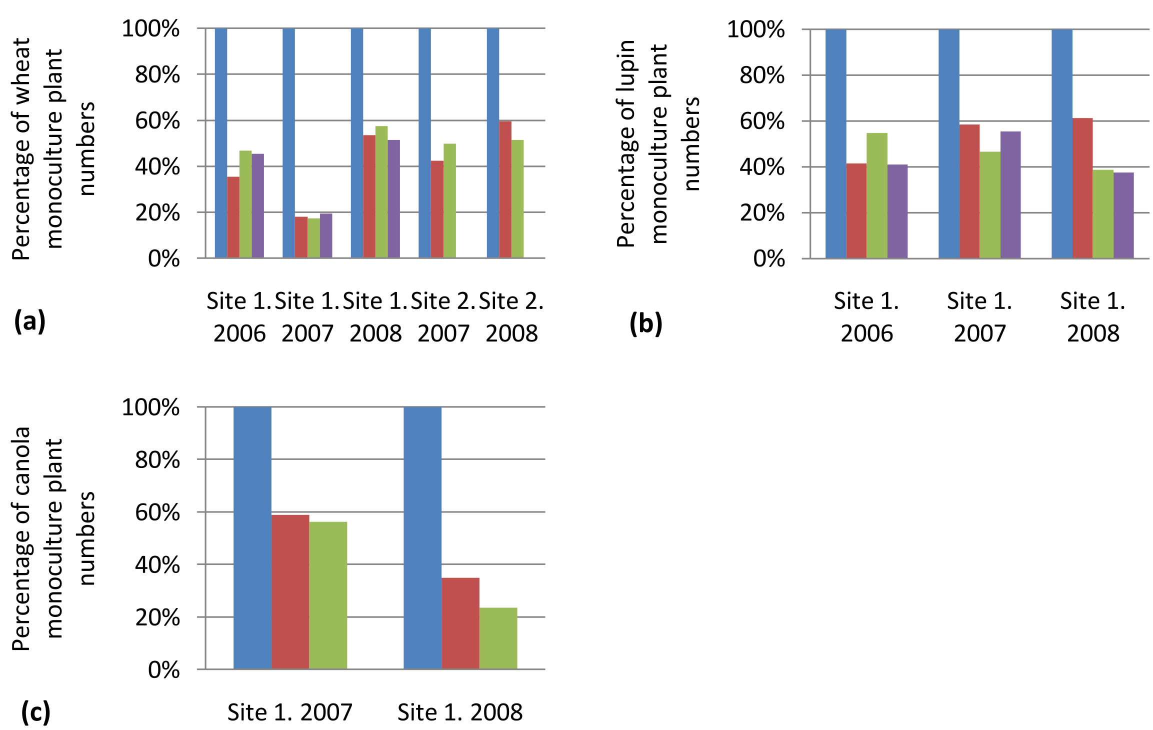


Figure 4-1 (a) Wheat, (b) lupin, (c) canola plants as a percentage of monoculture at site 1 and 2 from 2006-08

Legend: ■ monoculture, ■ chicory intercrop, ■ lucerne intercrop, ■ half monoculture

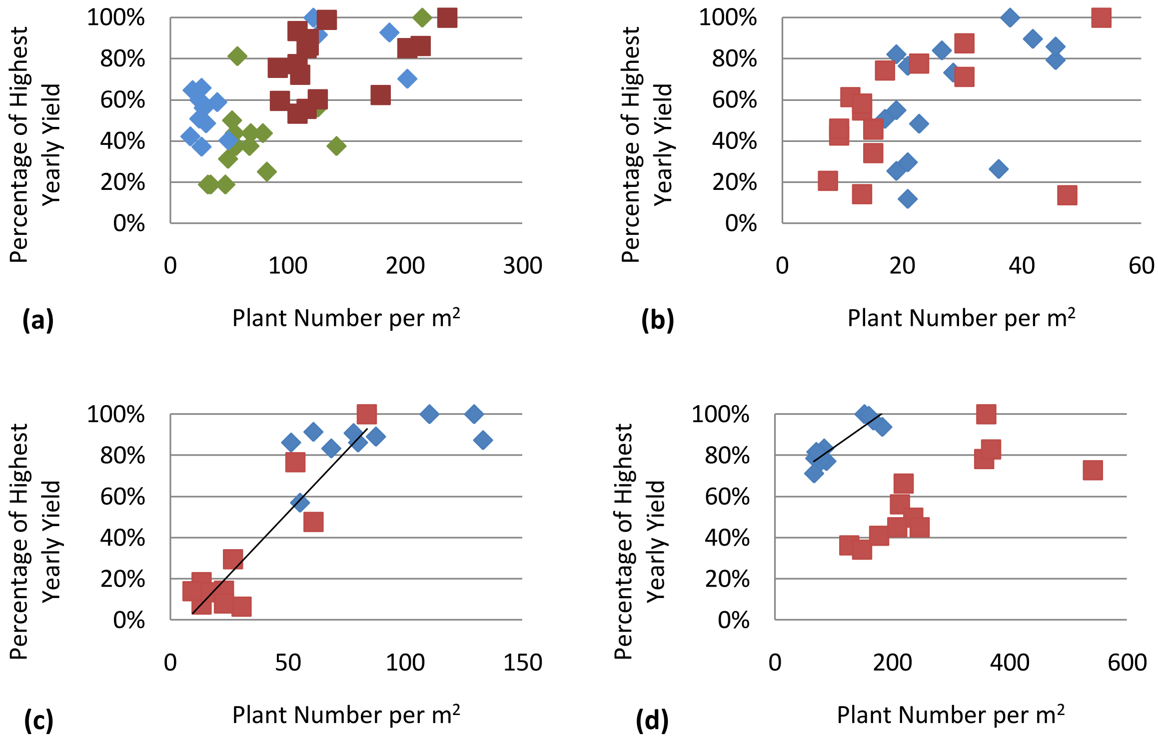


Figure 4-2 Grain yield and plant numbers/m² in years ◆ 2006, ◆ 2007 and ■ 2008 at site 1 of (a) wheat, (b) lupin, (c) canola and site 2 (d) wheat

Tillers

There was no significant difference in the number of tillers per wheat plant, early in the season, between any of the four treatments at either site 1 or 2 (Table 4-8).

Monoculture wheat had significantly higher numbers of unviable heads at maturity at site 1, but not at site 2 (Table 4-9).

Table 4-8 Tiller numbers (including main) for wheat treatments at site 1 and 2 in 2008

Treatment	Site 1	Site 2
Monoculture wheat	4.9	4.0
Wheat-lucerne	4.5	3.7
Wheat-chicory	3.7	3.5
Half monoculture wheat	3.8	
l.s.d ($P<0.05$)	n.s.	n.s.

Table 4-9 Unviable wheat head numbers per m^2 measured at maturity at site 1 and 2 in 2008

Treatment	Site 1	Site 2
Monoculture wheat	16 *a*	0.0
Wheat-lucerne	1 *b*	1.5
Wheat-chicory	2 *b*	0.5
Half monoculture wheat	4 *ab*	
l.s.d ($P<0.05$)	13.7	n.s.

Note: Means within each treatment row followed by a different letter are significantly different ($P<0.05$) Not significant = n.s.

Heads and pods

There were more wheat heads ($P<0.05$) produced in the half monoculture in 2008 at site 1, than in the intercrops and monoculture wheat. The wheat-chicory intercrop produced more heads ($P<0.05$) than the wheat-lucerne intercrop (Table 4-10). The monoculture wheat produced significantly more heads than the intercrops at site 2 (Table 4-10).

The half monoculture lupin had a greater number of pods per m^2 ($P<0.05$) than the lupin-lucerne intercrop, but were not significantly different from the other two treatments (Table 4-11). In the drought year of 2006, pod counts were very low and there was no significant difference between treatments (Table 4-11).

Table 4-10 Wheat heads per m^2 for treatments at site 1 and 2 in 2008

Treatment	Site 1	Site 2
Monoculture wheat	354 *b*	407 *a*
Wheat-lucerne	200 *c*	177 *b*
Wheat-chicory	297 *b*	217 *b*
Half monoculture wheat	557 *a*	
l.s.d (P<0.05)	90.4	103.0

Table 4-11 Lupin pods per m^2 for treatments at site 1 in 2006 and 2008

Treatment	2006	2008
Monoculture lupin	12	383 *a*
Lupin-lucerne	3	174 *b*
Lupin-chicory	3	307 *ab*
Half monoculture lupin	11	429 *a*
l.s.d (P<0.05)	n.s.	201.0

Note: Means within each treatment row followed by a different letter are significantly different ($P<0.05$) Not significant = n.s.

Grain weight

Wheat intercrops produced higher grain weights ($P<0.05$) than the monoculture and half monoculture in two of three years (Table 4-12). The wheat, when grown as an intercrop generally had higher grain weight ($P<0.05$) than the monoculture wheat (Table 4-12). At site 1 in 2007 and 2008, both of the intercrops had higher grain weight ($P<0.05$) than the monoculture wheat (Table 4-12). In 2008, the intercrops had significantly higher grain weight than the half monoculture wheat (Table 4-12). The only significant difference at site 2 was in 2007, when the wheat-lucerne intercrop had a higher 1000 grain weight ($P<0.05$) than the monoculture wheat (Table 4-12).

The half monoculture lupin had a significantly higher 1000 grain weight than all other treatments in 2008, and was higher than the lupin-chicory intercrop in 2007 (Table 4-12). The monoculture lupin had a higher grain weight ($P<0.05$) than the lupin-chicory intercrop in 2007 (Table 4-12).

There were no significant differences in grain weight between treatments for canola in either 2007 or 2008 (Table 4-12).

Table 4-12 Wheat, lupin and canola 1000 grain weight (gm) for treatments at sites 1 and 2 in 2006-08

	Site 1			Site 2	
Treatment	2006	2007	2008	2007	2008
Monoculture wheat	29.6 *ab*	38.1 *b*	29.4 *b*	37.5 *b*	34.4
Wheat-lucerne	31.0 *a*	41.1 *a*	35.9 *a*	39.8 *ab*	34.5
Wheat-chicory	29.4 *ab*	41.5 *a*	34.5 *a*	40.1 *a*	39.4
Half monoculture wheat	28.0 *b*	39.8 *ab*	31.8 *b*		
l.s.d (P<0.05)	2.37	2.66	2.33	2.31	n.s.
Monoculture lupin		148.9 *a*	129.7 *b*		
Lupin-lucerne		143.2 *ab*	126.7 *b*		
Lupin-chicory		136.4 *b*	127.9 *b*		
Half monoculture lupin		148.9 *a*	139.7 *a*		
l.s.d (P<0.05)		12.34	6.08		
Monoculture canola		3.6	3.0		
Canola-lucerne		3.5	3.0		
Canola-chicory		3.4	3.0		
l.s.d (P<0.05)		n.s.	n.s.		

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Grains per head, spikelets per head and grains per spikelet

There were no significant differences in grains per head between the wheat treatments at site 1 in both years (Table 4-13). There were significant differences at site 2 in both years, with the intercrops producing more grain per head ($P<0.05$) than the monoculture wheat in 2007 (Table 4-13). In 2008, the monoculture wheat produced more grains per head ($P<0.05$) than the wheat-chicory intercrop (Table 4-13).

The wheat-lucerne intercrop produced significantly more spikelets ($P<0.05$) than the monoculture wheat at site 2 in 2007, and both intercrops produced more grains per spikelet ($P<0.05$) than the wheat monoculture (Table 4-14). In 2008 at site 2, the monoculture wheat produced more spikelets ($P<0.05$) than the wheat-chicory intercrop, which also produced fewer grains per spikelet ($P<0.05$) than the other treatments (Table 4-14 and Table 4-15). Site 1 in 2007 had significantly less monoculture wheat spikelets per head, compared to all other treatments (Table 4-14). The number of grains per head was lower for monoculture wheat, but this difference was not significant (Table 4-14). There was no significant difference in the spikelets produced per head for any of the site 1 treatments in 2008. There was however, significantly more grains per spikelet ($P<0.05$) produced by the wheat-lucerne intercrop as compared to the monoculture wheat (Table 4-14 and Table 4-15).

Table 4-13 Wheat grains per head for treatments at site 1 and 2 in 2007-08

	Site 1		Site 2	
Treatment	2007	2008	2007	2008
Monoculture wheat	27.8	25.5	35.7 *b*	31.6 *a*
Wheat-lucerne	39.3	33.9	44.1 *a*	29.0 *ab*
Wheat-chicory	43.1	31.4	44.5 *a*	23.9 *b*
Half monoculture wheat	39.9	33.6		
l.s.d (P<0.05)	n.s.	n.s.	6.14	5.72

Table 4-14 Wheat spikelets per head for treatments at site 1 and 2 in 2007-08

	Site 1		Site 2	
Treatment	2007	2008	2007	2008
Monoculture wheat	13.1 *a*	10.9	14.7 *b*	13.0 *a*
Wheat-lucerne	15.8 *b*	12.4	15.9 *ab*	12.2 *ab*
Wheat-chicory	16.1 *b*	12.5	16.3 *a*	11.3 *b*
Half monoculture wheat	16.5 *b*	12.7		
l.s.d (P<0.05)	0.92	n.s.	1.12	1.44

Table 4-15 Wheat grains per spikelet for treatments at sites 1 and 2 in 2007-08

	Site 1		Site 2	
Treatment	2007	2008	2007	2008
Monoculture wheat	2.1	1.8 *b*	2.4 *b*	2.4 *a*
Wheat-lucerne	2.4	2.6 *a*	2.7 *a*	2.3 *a*
Wheat-chicory	2.6	2.4 *ab*	2.7 *a*	2.0 *b*
Half monoculture wheat	2.4	2.4 *ab*		
l.s.d (P<0.05)	n.s.	0.63	0.25	0.25

Note: Means within each treatment row followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Lupin branches and pods

There was no significant interaction between treatment and order for either number of branches per order or number of pods per branch in 2007 and 2008.

In 2007, there were significantly more branches ($P<0.05$) produced in the half monoculture lupin than the monoculture lupin, lupin-lucerne and lupin-chicory intercrop (Table 4-16). There were more branches ($P<0.05$) produced in the 2nd order than the 1st and 3rd orders in 2007 (Table 4-16)

In 2008, there were no significant differences in the number of branches produced between treatments. There were more branches ($P<0.05$) produced in the 1st and 2nd order than in the 3rd order (Table 4-16).

In 2007, there were more pods per branch ($P<0.05$) in the half monoculture lupin and lupin-chicory intercrop than the monoculture lupin and lupin-lucerne intercrop (Table 4-16). There were also significantly more pods per branch in the 1st and 2nd orders than the main and 3rd order.

There was no significant difference in the number of pods per branch between treatments in 2008 (Table 4-16). In 2008, the 1st order produced more pods per branch ($P<0.05$) than the main and 3rd order, while there were more pods per branch ($P<0.05$) in the 2nd order than the 3rd order (Table 4-16).

Table 4-16 Lupin pod and branch number per order for 2007 and 2008

	Number of branches per order		Number of pods per branch	
Treatment	2007	2008	2007	2008
			Main	Main
Monoculture lupin			6	5
Lupin-lucerne			5	5
Lupin-chicory			5	6
Half monoculture lupin			7	6
	1st Order	1st Order	1st Order	1st Order
Monoculture lupin	4	6	16	17
Lupin-lucerne	4	7	9	20
Lupin-chicory	5	8	18	21
Half monoculture lupin	7	7	27	23
	2nd Order	2nd Order	2nd Order	2nd Order
Monoculture lupin	8	5	14	9
Lupin-lucerne	6	4	10	7
Lupin-chicory	10	6	15	12
Half monoculture lupin	12	8	21	17
	3rd Order	3rd Order	3rd Order	3rd Order
Monoculture lupin	3	1	4	3
Lupin-lucerne	2	2	2	4
Lupin-chicory	3	1	4	2
Half monoculture lupin	6	2	9	4
l.s.d ($P<0.05$) treatment	2.3	2.9	4.6	5.3
l.s.d ($P<0.05$) order	2.0	2.5	4.6	5.3

4.4 Discussion

Intercropping lucerne and chicory with wheat, lupin and canola generally resulted in a reduction of the intercrop grain yield compared to the monoculture crop. These reductions ranged from 0-46% for wheat, 45-74% for lupin and 8-83% for canola, with large variation across seasons for some species. The cereal yield reductions are within the ranges of those reported in previous lucerne/cereal over-cropping studies of 25% (Harris *et al.* 2008a), 6-60% (Egan & Ransom 1996) and 13-63% (Humphries *et al.* 2004).

Row spacing in intercropping

One of the key differences of this trial, compared to previous crop/pasture intercropping trials, is the spatial arrangement of the two species into double alternate rows. As such, it is important to quantify if this reduction in yield and dry matter production is due to the change in spatial design and plant numbers, or a competition for resources by the two intercrop species.

In the experiment described in this thesis, plant populations were maintained on a per row basis, resulting in an expected reduction in the annual crop numbers/m^2 in the intercrop and half monoculture treatments. In 2006, there was a comparison between two target crop numbers, one that maintained the plant populations on a per row basis and other with a higher target plant population. There were no significant differences in yield between these two treatments in either the monoculture wheat or wheat-lucerne intercrop treatments. As a result, in 2007 and 2008 the half monoculture treatments and the intercrop treatments were sown with the same sowing rate per row, resulting in a lower plant number per m^2 than the monoculture treatments. Despite this, wheat yield results in 2006 and 2008 show that the lower plant numbers of the half monoculture achieved the same yield as the monoculture treatments. A positive relationship between plant numbers and yield was only seen in two of nine cases. This indicates that lower seeding rates per hectare in the half monoculture and intercrop treatments were generally not having a significant effect on crop grain yields compared to the monoculture. The low association between plant number and yield is consistent with other seeding rate and plant density studies. It is reported that grain yields increase as plant densities increase and then plateau (Puckridge & Donald 1967). If, however, the seeding rate (Peltzer *et al.* 2009) or plant density (Puckridge & Donald 1967) is too high, then yield is reduced. In addition, yield loss that occurs when using wider row spacing can be reduced by increasing the spread of the seed in the row (Amjad & Anderson 2006). Similarly, from a study on row spacing and seeding rate, Laford and Derksen (1996) suggest seeding rate did not need to be changed with row spacing, due to the lack of interaction found between seeding rate and row spacing. In addition, increasing the seeding rate of crops grown on wide row spacing was not found to increase grain yields (Chen *et al.* 2008).

Since seeding rate and plant numbers appear not to be related to yield in the majority of treatments shown in this chapter, it is important to discuss the possible effect of changing the spatial arrangement to the double row arrangement used in this study. Changing spatial design, generally widening of row spacing, is a concept that has been widely adopted by primary producers, particularly in conservation tillage systems (Peltzer *et al.* 2009). As row spacing is increased, the rectangularity of the arrangement is decreased, providing greater distances between rows of plants. This delays the start of competition between the rows of plants (Midmore 1993). There have been studies into the effects of widening row spacing, on a range of crop species, which have shown both negative effects and no yield reduction (Amjad & Anderson 2006; Lafond 1994; Lafond & Derksen 1996; Tompkins *et al.* 1991).

Wheat yields decreased when row spacing was increased from 320mm to 640mm in 2 out of 3 years (Felton *et al.* 2004). Similarly, wheat yields were higher when grown on 180mm rows, compared to wider rows of 240mm and 360mm in a study that used target plant densities of 50, 100, 150, 200 and 250 plants/m^2 (Amjad & Anderson 2006). Here, a reduction in grain quality also occurred in some cases on wider rows, but not in others. The yield reduction possibly result from a reduction in average plant numbers, due to in-row competition, a result of increased seed numbers per row on the wider row spacing (Amjad & Anderson 2006). Similarly, in a US study, a reduction in wheat yield when grown on wide row spacing (300mm compared to 150mm) was attributed to a reduction in heads per m^2 (Chen *et al.* 2008). In contrast to these yield reductions, yield was not decreased as row spacing was widened from 100mm to 300mm, in both direct-seeded and conventional tillage systems in Canada (Lafond 1994; Lafond & Derksen 1996). There was a reduction in the number of plants and heads on wider rows, but a compensatory increase in the number of grains per head. This is consistent with results from the current study, where there was a higher number of heads per m^2 in the half monoculture treatment compared to the monoculture wheat. Whilst not significant, there was also a trend toward a higher number of grains per head in the half monoculture treatment.

The architecture or rectangularity of spatial design is known to influence grain yield. For example, Kemp (1983) found that at high seeding rates, and subsequently high plant densities, yields were similar for a range of row spacing. However, at lower densities, yield increased as row spacing increased. This led to the conclusion that the practice of reducing rectangularity, at low plant densities increased wheat grain yields due to greater production of tillers per plant (Kemp *et al.* 1983). Similarly, yield reduction on wide rows can be minimised by sowing in May and increasing the spread of seed across the row (Amjad & Anderson 2006). While the wheat results reported here are not conclusive, they do show that reduced plant numbers had a minimal effect on yield in wheat, in two of the three seasons. There was also no significant effect from increasing sowing rates in 2006.

In contrast with the wheat results, there was a negative effect on lupin yield when plant numbers were reduced as a result of maintaining seeding rate per row. The reduction in lupin grain yield between the half monoculture and monoculture treatments of 11 to 31% was greater than the 7% yield reduction found in wider row spaced lupin studies conducted in the 1980s, where fertiliser placement disadvantaged the wider rows (Perry *et al.* 1998). Subsequent studies on wider row spaced lupin conducted in the 1990s, with better fertiliser placement, showed wider row spacing in lupin resulted in an increase in mean yield of 3 to 4% (Jarvis 1992). The high lupin yield reduction seen in this study between the monoculture and half monoculture treatments indicates that the reduction in seeding rate per hectare resulted in the half monoculture lupin plant numbers falling outside of the optimum range for yield.

Assessing the effects of competition

The effect of competition in this study can be assessed by comparing results from the half monoculture treatments and the intercrop treatments. These treatments were sown at the same rates and on the same row design. It is expected that if there is no competition occurring between the two intercrop species, then yield results will not differ between the half monoculture and intercrop treatments. However, grain and dry matter yields were reduced in the lucerne intercrops compared to the half monoculture wheat and lupin treatments. While the grain and dry matter yields in some years tended to be lower in the chicory intercrops, they were often not significantly different from the half monoculture treatments. This indicates lucerne growing as an intercrop competes with the crop for resources required for growth and yield during the growing season. It also shows that chicory is a less competitive intercrop species than lucerne in this study.
In this study, spatial design and sowing rate were factors in reducing intercropping yields; however there also appears to be an additional impact of intercrop competition, particularly when lucerne is used as the intercrop species.

Competition for resources – wheat

Competition for resources, when plants are growing together, is measured by a reduction in a measurable trait of the plants, such as grain yield, grain protein content, tiller numbers and more. Using an understanding of plant physiology, resource use and previous studies on competition, this study investigates the components of yield and grain quality in order to better understand the reductions in intercrop yield found in this, and previous, intercropping studies.

Early competition

Wheat plant establishment numbers did not differ between the half monoculture and intercrop treatments. This indicates that lucerne and chicory were not competing for resources with the establishing wheat crop. Tillering is another measure of yield determination and there were no differences seen in tiller numbers taken early (GS31) in the season. This is in contrast to a previous wheat-lucerne over-cropping study where wheat grain yield was affected by a reduction in tiller numbers (taken around GS31), heads and biomass compared to the monoculture treatment (Harris *et al.* 2008a). Competition studies between wheat and weed species have also shown that reduction in wheat yield is often due to a reduction in the number of tillers produced (Gill & Blacklow 1984; Gill *et al.* 1987; Martin *et al.* 1987; McNamara 1976).

Biomass was also measured at GS31 and there was no difference in biomass production between the wheat-chicory intercrop and the half monoculture wheat in any year. This, combined with the plant number and tillering results, indicates that the chicory component of the intercrop was not competing with the wheat crop for resources early in the growing season. For the wheat-lucerne intercrop, there was a reduction in biomass of the wheat-lucerne intercrop seen in one season, and no reduction in the other. This indicates early season competition may have occurred in at least one year. These results contrast with those of previous wheat-lucerne over-cropping studies that have reported early reductions in biomass production, and these authors conclude that early season competition for resources, light and nutrients, are the most likely cause of the grain yield reductions reported (Harris *et al.* 2008a; Humphries *et al.* 2004). Possibly, the contrast in results may be due to the difference in row design of this study compared to previous over-cropping studies.

Mid season competition

There was no difference in wheat biomass measured at wheat anthesis (GS65) between the half monoculture wheat and the wheat-chicory intercrop. There was a reduction in biomass of the wheat-lucerne and the half monoculture wheat only in one season. There were differences in the number of heads per m^2 measured in the 2008 season. The numbers of wheat heads were lower in both the intercrop treatments, compared to the half monoculture treatment. This indicates a loss of head-bearing tillers in the time between tiller and maturity. In a separate study, the reduction in the number of heads per m^2, due to a reduction in tiller numbers, as well as the early death of potentially head-bearing tillers, was attributed to competition between wheat and a weed species, *Bromus diandrus* (great brome) (Gill & Blacklow 1984). Similarly, wheat yield loss occurring prior to grain fill, due to a reduction in the number of heads per m^2 and number of grains per head, was a result of competition from great brome (Gill *et al.* 1987). This suggests that for this current study, the intercrops began competing for resources between tillering and anthesis, resulting in a reduction in the number of head-bearing tillers. Here, the number of wheat heads in the wheat-lucerne intercrop was lower than that of the wheat-chicory intercrop, supporting the previous statement that lucerne appears to compete more strongly than chicory does, with the wheat component of the intercrop.

Late competition

Seasonal conditions post anthesis determines number of grains set, (Sofield *et al.* 1977) protein, (Mason & Madin 1996) and grain weight (Gill & Blacklow 1984). Protein and grain weight can be reduced if there is competition for water during grain fill (Gill & Blacklow 1984; Mason & Madin 1996).

In this current study, there was generally no difference in the number of grains per head between the intercrop and monoculture treatments. Grain weights were either unaffected by intercropping or were higher for intercropped wheat compared to monoculture wheat. Protein levels were also generally unaffected by intercropping, with wheat intercrops only having lower protein than the monoculture wheat at one site in one year. This indicates there was limited competition for resources post anthesis between the wheat and pasture components of the intercrop.

Dry matter measured at maturity (GS95) showed there was no difference in production between the half monoculture wheat and the wheat-chicory intercrop. In one season, there was a reduction in dry matter at maturity between the half monoculture wheat and the wheat-lucerne intercrop. This yield reduction was measured at GS31 and continued to maturity. These outcomes indicate again that the greatest effect of intercrop competition on yield and grain quality of wheat occurred prior to anthesis (GS65) and maturity (GS95).

Competition for resources – lupin

Two of the key components of lupin grain yield are number of branches per plant and pod number per branch (Supasilapa *et al.* 1992).

In this study, there were more branches produced in the half monoculture treatment than the lupin-lucerne and lupin-chicory intercrop in the 2007 season, indicating competition was affecting this component of lupin yield in the intercrop treatments. In this season the half monoculture lupin and lupin-chicory intercrop also produced more pods per branch than the lupin-lucerne intercrop. This shows the yield components were more greatly affected by competition in the lupin-lucerne intercrop compared to the lupin-chicory intercrop.

In 2008, which had more favourable in-growing season rainfall, there was no difference branching numbers between treatments.

In both seasons there was a difference in the branch numbers and pods per branch depending on the branching order. In 2007, there were more branches and pods per branch in the 1st and 2nd orders compared to the 3rd order. In contrast in 2008, a more favourable season, there were more branches in the 2nd order compared to the 1st and 3rd orders and more pods per branch in the 2nd order compared to the 3rd order. These results are supported by studies on weed and lupin competition. Competition between capeweed (*Arctotheca calendula*), annual ryegrass (*Lolium rigidum)* and lupin, caused a reduction in lupin lateral branch pod numbers (Allen 1977). Competition between annual ryegrass and lupin was observed later in the growing season where grain yields were reduced due to few pods being produced on the lateral branches (Arnold *et al.* 1985). Similarly, lupin yield reductions due to a reduction in the number of branches per plant and pods per branch, was a result of competition between great brome and lupin (Supasilapa *et al.* 1992). As competition increased due to higher weed numbers, yield reductions were higher (Arnold *et al.* 1985; Supasilapa *et al.* 1992) due to a decrease in the number of branches and pods per plant (Supasilapa *et al.* 1992).

Lupin dry matter in the half monoculture and intercrop treatments did not differ in early September. However, dry matter in October was lower in the wheat-lucerne intercrop compared to the half monoculture treatment. There was no reduction in dry matter production in the wheat-chicory intercrop. The wheat-lucerne intercrop dry matter reductions also occurred in December. A reduction in biomass at maturity of the wheat-chicory intercrop was only measured in 2007. Similarly, the presence of ryegrass did not cause a reduction in lupin biomass until early spring, and the effect was still evident at harvest (Arnold *et al.* 1985). In addition to biomass reductions at maturity, the reduction in 1000 grain weights of the intercrops, compared to the half monoculture lupin, indicates competition affected grain fill.

These results indicate that the intercrop competition that affected lupin grain yield was occurring mid-season and continued until maturity, as the severity of yield reductions appears dependent on seasonal conditions.

The lower lupin grain yield of the lucerne intercrop was due to a difference in the number of lupin branches and pods. In one season, the lupin-lucerne intercrop had a lower number of branches than the half monoculture lupin, and fewer pods per branch then the half monoculture and lupin-chicory intercrop. This supports the conclusion that lucerne is competing more strongly for resources than chicory, resulting in greater yield reductions.

Summary

Timing of competition and seasonal conditions has a significant impact on subsequent performance of the grain component of the intercrop. In wheat, the competition affecting crop performance occurred after cereal first node and prior to anthesis and grain fill. A minority of treatments indicated that early competition was impacting on grain yields. In these treatments, yield reductions were greater than later season competition. In lupin, competition began to affect the components of yield and dry matter in October, and continued to maturity. In addition to a reduction in grain yields from competition, there is an additional negative impact of changing the spatial arrangement and/or seeding rate when intercropping, especially for lupin. This effect, in the case of wheat, is related to seasonal conditions, and in more favourable growing seasons, the effect is reduced or negated.

The choice of intercrop pasture species had an impact on how greatly grain yields were affected. Lucerne and chicory appear to differ in the level of competitiveness for resources, and also in the timing of this competition, with lucerne being more competitive than chicory. The effect of competition will be further explored in chapter 5, with a focus on the effect of competition on the pasture species, and productivity of intercropping as a whole system.

Chapter 5. Intercropping and Pastures

5.1 Introduction

Lucerne is the most widely grown perennial pasture legume species in Australia, and has been the basis of the published over-cropping studies conducted in Australia to date. However, lucerne is not ideally suited to all soil types and growing conditions within the higher rainfall zones of southern Australia, as it can have a low tolerance to low pH soils and waterlogged conditions (Lodge 1991). Thus, there is a need to explore the use of alternative perennial species in intercropping systems, and develop a system suited to more regions within the higher rainfall zones.

Chicory is a perennial pasture species that is increasingly being used in the study region in combination with, and as an alternative to, lucerne. Chicory is suited to the conditions of the higher rainfall zones where lucerne may not be, particularly at sites with lower pH soils and those that are prone to waterlogging (Li *et al.* 2010). Chicory also performs well in neutral pH and alkaline conditions, with dry matter production comparable to that of lucerne (Li *et al.* 2008). Importantly, in the context of this study, and for the development of a system that re-introduces perennials into the landscape, chicory has a rooting depth and water use comparable to that of lucerne. Further, chicory has a similar pattern of drying the soil, with both species able to utilise soil moisture to depth (Hayes *et al.* 2010b). These characteristics indicate chicory may be a suitable species for inclusion in an intercrop.

The study covered in this chapter will compare chicory and lucerne as intercrop component species grown with grain crops wheat, lupin and canola. The productivity and persistency of the two pasture species, when grown in combination with a range of grain crops, will be measured to determine the suitability of chicory as an intercrop species.

Competition between intercrop species can result in yield reductions of the component species (Egan & Ransom 1996; Harris *et al.* 2008a; Humphries *et al.* 2004). However, this reduction in grain yield may not give an indication of the overall productivity of the intercropping system. Over-cropping studies have shown that these cereal-lucerne systems can still be more productive than growing the components as monoculture stands (Harris *et al.* 2008a; Humphries *et al.* 2004). In order to assess the overall productivity of the system, Land Equivalent Ratio (LER) values were calculated for a range of productivity measures. LER values greater than 1, referred to as over-yielding, occurs when the yield of the intercrop exceeds that of its monoculture components (Midmore 1993). This study also focuses on assessing overall productivity of the intercropping system for different crop-pasture combinations. This will provide an understanding of the suitability of this intercropping system and the pasture-crop combinations used for the higher rainfall zones of southern Australia.

5.2 Materials and Methods

A description of the trial site, and the materials and methods, are presented in Chapter 3.

5.3 Results

5.3.1 Pasture dry matter yields

Growing season and annual dry matter production

The monoculture treatments of lucerne and chicory generally produced more dry matter ($P<0.05$) than the intercrops and half monoculture treatments in-growing season (May/June to December), and over the annual growing season of the pasture (June to May). The monoculture treatments did not always produce the highest amount of dry matter during the out-of-growing season period (December to May) after the establishment year. The intercrops and half monoculture treatments often yielded similarly to the monoculture treatments during this period (Table 5-1 and Table 5-2).

Dry matter production was significantly higher in the chicory monoculture, than the lucerne monoculture and intercrop treatments, in the pasture establishment years of 2006 at site 1, and 2007 at site 2. The monoculture treatments tended to produce more dry matter ($P<0.05$), both during and out-of-growing season. Monoculture chicory produced more total dry matter ($P<0.05$) than monoculture lucerne in the establishment years (Table 5-1 and Table 5-2). Annual dry matter production was very low in 2006, due to it being the establishment year of site 1, and also a drought year.

After establishment, the in-growing season dry matter production for the half monoculture treatments was often higher ($P<0.05$) than the intercrops (Table 5-1 and Table 5-2). The exception to this was the lupin intercrops. Out-of-growing season dry matter production was often not significantly different between the monoculture and intercropping treatments (Table 5-1 and Table 5-2).

There were differences in dry matter yield reductions between the two pasture species. Dry matter yield reductions were generally between 50% and 60% for chicory intercropped with wheat and lupin. Lucerne dry matter yields were reduced between 0% and 73% of that of the monoculture canola intercropped with lucerne, with canola-chicory intercrops yield reductions between 14% and 78%. In 2008, the yield reductions were lower than in 2006 and 2007.

Table 5-1 Pasture dry matter yield (kg/ha), in-growing season, out-of-growing season and the annual total at site 1 in 2006-08

Year	Treatment	In-growing season	Out-of-growing season	Annual Total
2006	Monoculture lucerne	670 *ab*	428 *ab*	1098 *b*
	Wheat-lucerne	340 *c*	151 *d*	491 *e*
	Lupin-lucerne	320 *c*	256 *b*	576 *d*
	Half monoculture lucerne	539 *b*	237 *cd*	776 *cd*
	Monoculture chicory	795 *a*	533 *a*	1327 *a*
	Wheat-chicory	245 *c*	174 *cd*	419 *e*
	Lupin-chicory	316 *c*	271 *b*	587 *d*
	Half monoculture chicory	545 *b*	337 *bc*	882 *c*
	l.s.d (P<0.05)	131.2	172.9	207.2
2007	Monoculture lucerne	4872 *a*	1049 *ab*	5920 *a*
	Wheat-lucerne	1251 *cd*	629 *bcd*	1943 *c*
	Lupin-lucerne	1972 *bc*	883 *abc*	2855 *bc*
	Canola-lucerne	740 *d*	566 *c*	1306 *d*
	Half monoculture lucerne	2675 *b*	760 *abcd*	3435 *b*
	Monoculture chicory	5097 *a*	1173 *a*	6270 *a*
	Wheat-chicory	2165 *bc*	931 *abc*	3095 *b*
	Lupin-chicory	2203 *b*	844 *abc*	3046 *b*
	Canola-chicory	1026 *d*	364 *d*	1390 *d*
	l.s.d (P<0.05)	927.6	461.6	1021.6
2008	Monoculture lucerne	6628 *b*	1830 *c*	8458 *b*
	Wheat-lucerne	3488 *d*	2057 *b*	5548 *de*
	Lupin-lucerne	6987 *ab*	3099 *ab*	10086 *ab*
	Canola Lucerne	5312 *b*	1956 *c*	7268 *cd*
	Half monoculture lucerne	9188 *a*	2423 *abc*	11612 *a*
	Monoculture chicory	6296 *bc*	2633 *abc*	8929 *bc*
	Wheat-chicory	1748 *d*	2070 *b*	3818 *e*
	Lupin-chicory	2553 *d*	1755 *c*	4307 *e*
	Canola-chicory	3966 *cd*	3276 *a*	7242 *cd*
	l.s.d (P<0.05)	2386.1	1108.6	2182.0

Table 5-2 Pasture dry matter yield (kg/ha), in-growing season, out-of-growing season and the annual total at site 2 in 2007-08

Year	Treatment	In-growing season	Out-of-growing season	Annual Total
2007	Monoculture lucerne	2924 *b*	530 *ab*	3454 *b*
	Wheat-lucerne	609 *d*	318 *b*	927 *d*
	Monoculture chicory	4838 *a*	733 *a*	5571 *a*
	Wheat-chicory	1919 *c*	407 *b*	2326 *c*
	l.s.d ($P<0.05$)	903.1	246.6	918.7
2008	Monoculture lucerne	6052 *a*	2295 *b*	8347
	Wheat-lucerne	2724 *b*	4613 *a*	7336
	Monoculture chicory	5107 *ab*	3581 *a*	8688
	Wheat-chicory	3017 *b*	3518 *a*	6535
	l.s.d ($P<0.05$)	2430.2	1145.8	n.s.

Note: Means within each treatment column followed by a different letter are significantly different ($P<0.05$)
Not significant = n.s.

Seasonal dry matter production

Lucerne and chicory produced similar amounts of dry matter annually, once established. However, there were differences in the timing of dry matter production (Table 5-3 and Table 5-4). Lucerne produced more dry matter at the start of the season (September) compared to chicory, whereas chicory produced greater dry matter at the end of the season (May) than lucerne (Table 5-3 and Table 5-4).

During the growing season, the half monoculture lucerne often produced greater amounts of dry matter ($P<0.05$) than the intercrop treatments, however there was generally not significant differences in out-of-growing season dry matter production (Table 5-3). The exception was lucerne intercropped with lupin, where lucerne was dry matter production was not significantly different to the half monoculture lucerne (Table 5-3).

In the establishment year of 2006, dry matter production was similar between the half monoculture and monoculture treatments in 3 of the 4 periods (Table 5-3). In 2007, dry matter production of the half monoculture treatment was lower ($P<0.05$) in the majority of measurements than the monoculture treatments (Table 5-3). In 2008, production of the half monoculture treatment was either the same or higher than the monoculture (Table 5-3).

Table 5-3 Pasture dry matter (t/ha) measurements for the 12 month season at site 1 in 2006-08

2006	10/10/2006	7/12/2006	8/03/2007	10/05/2007	
Monoculture lucerne	518 b	670 *a*	313 b	115 bc	
Wheat-lucerne	340 cd	158 b	99 c	52 cd	
Lupin-lucerne	320 cd	188 *b*	189 *bc*	67 cd	
Half monoculture lucerne	421 *bc*	539 *a*	166 c	72 *bdc*	
Monoculture chicory	549 a	795 *a*	326 *a*	207 *a*	
Wheat-chicory	245 d	93 *b*	104 c	70 *bcd*	
Lupin-chicory	316 *cd*	179 *b*	160 c	111 *bc*	
Half monoculture chicory	392 c	545 *a*	213 *abc*	124 a	
l.s.d (P<0.05)	102.9	268.5	127.4	56.2	
2007	2/09/2007	25/10/2007	30/11/2007	27/03/2008	16/05/2008
Monoculture lucerne	2490 *a*	4667 *a*	4872 *a*	835 *a*	214 cd
Wheat-lucerne	1181 *b*	1251 *cd*	1329 *d*	545 *ab*	146 *de*
Lupin-lucerne	1332 *b*	1972 *bc*	2792 *b*	715 *a*	168 *de*
Canola-lucerne	606 d	740 *d*	255 e	463 *ab*	103 e
Half monoculture lucerne	1181 *b*	2549 *b*	2675 *b*	603 *ab*	156 *de*
Monoculture chicory	1001 bc	4903 *a*	5097 *a*	789 *a*	384 a
Wheat-chicory	429 d	2165 cb	1621 cd	568 *ab*	362 *ab*
Lupin-chicory	685 c	2203 *b*	2469 *bc*	564 *ab*	280 bc
Canola-chicory	342 d	1026 d	339 e	272 *b*	92 e
l.s.d (P<0.05)	356.4	935.8	861.3	421.9	101.4

2008 Sowing	10/09/2008	6/11/2008	16/12/2008	26/01/2009	6/05/2009
Monoculture lucerne	2948 c	5730 *b*	6628 *ab*	1675 *bc*	155 c
Wheat-lucerne	4283 *b*	3488 *cd*	3292 c	1905 *bc*	153 c
Lupin-lucerne	5291 *a*	6987 *ab*	7750 *ab*	2970 *a*	129 c
Canola-lucerne	4562 *ab*	5312 *b*	6501 *ab*	1718 *bc*	239 c
Half monoculture lucerne	4000 *b*	8340 *a*	9188 *a*	2269 *abc*	154 c
Monoculture chicory	1177 *d*	4634 *c*	6296 *ab*	1978 *abc*	655 *a*
Wheat-chicory	1101 *d*	1748 d	2836 *c*	1594 *c*	476 *ab*
Lupin-chicory	1406 *d*	2553 *cd*	5157 *bc*	1437 *c*	318 *b*
Canola-chicory	1281 *d*	3966 *cd*	5662 *bc*	2669 *ab*	607 *a*
l.s.d (P<0.05)	978.1	2317.3	4076.0	1024.6	217.9

Note: Measurements taken within the crop growing season (up to and including December) are cumulative. Means within each treatment column followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Table 5-4 Pasture dry matter (t/ha) measurements for the 12 month season at site 2 in 2007-08

2007	2/09/2007	25/10/2007	30/11/2007	27/03/2008	16/05/2008	
Monoculture lucerne	497 *ab*	2733 b	2924 b	363 *ab*	168 *b*	
Wheat-lucerne	218 *c*	609 c	386 d	219 *b*	99 *b*	
Monoculture chicory	700 *a*	4735 *a*	4838 *a*	452 *a*	281 *a*	
Wheat-chicory	331 *b*	1919 *b*	1270 c	292 *ab*	115 *b*	
l.s.d (P<0.05)	254.9	913.8	792.6	165.4	109.0	
2008	18/08/2008	12/11/2008	16/12/2008	26/01/2009	24/04/2009	6/05/2009
Monoculture lucerne	2017 *a*	5486 *a*	6052 *a*	1430 *b*	718 *b*	148 *b*
Wheat-lucerne	1162 *b*	2421 *b*	2724 *b*	2754 *a*	1693 *a*	166 *b*
Monoculture chicory	1323 *b*	4445 *a*	5107 *ab*	2723 *a*	500 *b*	358 *a*
Wheat-chicory	608 *c*	2255 *b*	3017 *b*	2508 *a*	648 *b*	362 *a*
l.s.d (P<0.05)	1175.0	1281.1	2430.2	717.2	613.2	113.4

Note: Measurements taken within the crop growing season (up to and including December) are cumulative. Means within each treatment column followed by a different letter are significantly different (P<0.05) Not significant = n.s.

5.3.2 Pasture plant populations

There was a high establishment rate of lucerne and chicory at both sites; however plant numbers declined dramatically in the establishment year for both lucerne and chicory monocultures and intercrops (Table 5-5 and Table 5-6). Lucerne and chicory plant numbers further declined, at a slower rate, after the initial large decline in the year of establishment. Plant numbers in the lucerne intercrops remained approximately 50% of the monoculture (Figure 5-1). In contrast, the chicory intercrop plant numbers declined to less than 50% of the monoculture. This effect occurred when wheat was the crop component of the intercrop.

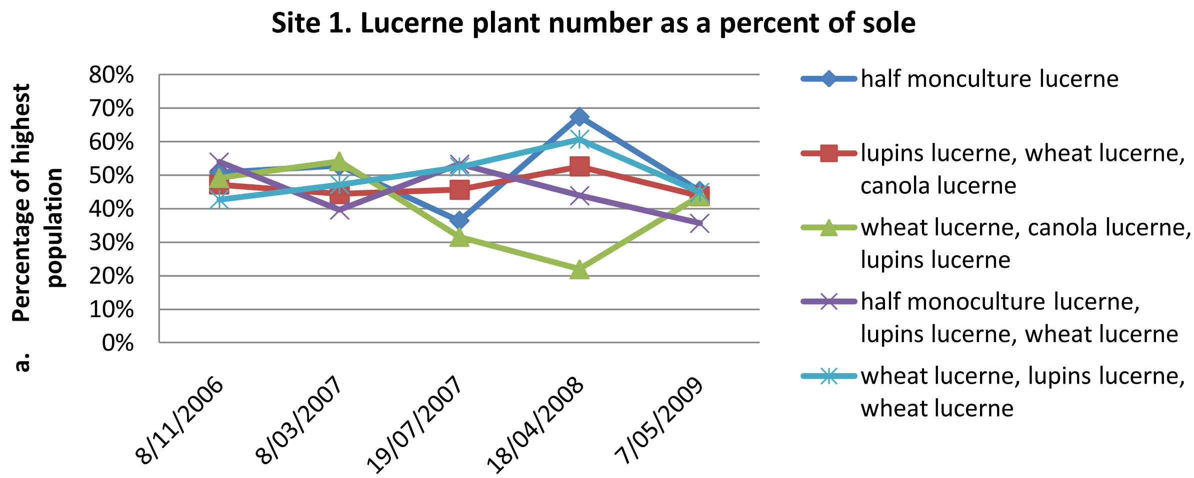
There is an anomaly in chicory counts taken at the start of the 2007 and 2008 seasons where, in most cases, plant numbers increased (Table 5-5 and Table 5-6). This was due to the sampling method of counting each "plant" as visible above the surface. A similar problem was experienced by Hume (1995) and was also due to the development of several stem per plant resulting in multiple crowns, "plants", on the surface (Figure 5-2). Plant densities of chicory were related to annual dry matter yield in the 2007 season at both site 1 (r^2=0.70; P<0.05) and site 2 (r^2=0.79; P<0.05). Lucerne plant densities were also related to annual dry matter yield in 2007 at site 2 (r^2=0.90; P<0.05) (Figure 5-2 and Figure 5-3).

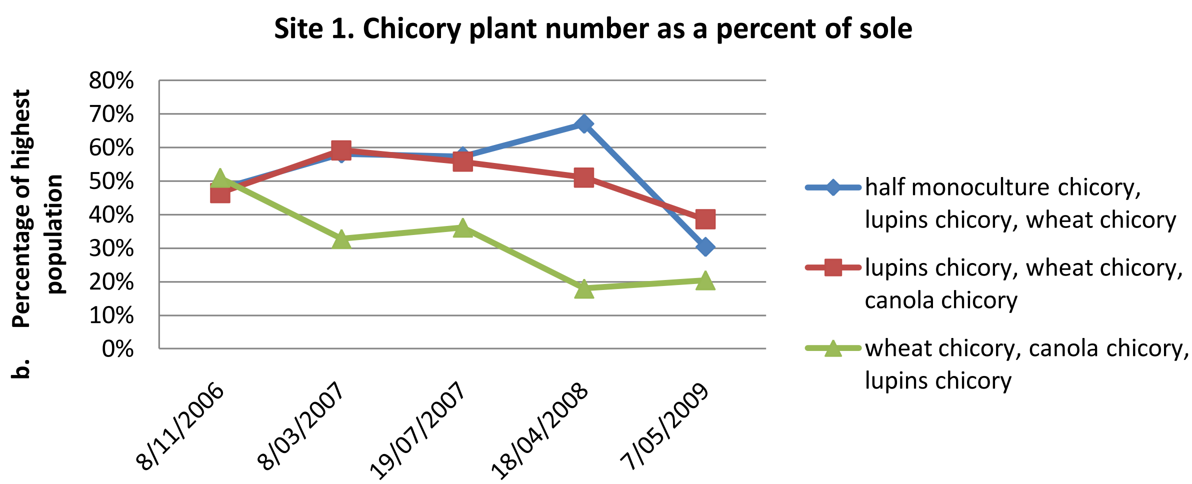
Table 5-5 Pasture plant counts (number of plants/m^2) at site 1

Treatment	8/11/2006	8/03/2007	19/07/2007	18/04/2008	7/05/2009
Monoculture lucerne	334	76	98	74	46
Half monoculture lucerne	170	40	36	50	21
Lupin, wheat, canola with lucerne	158	34	45	39	20
Wheat, canola, lupin with lucerne	164	41	31	16	20
Half lucerne, lupin with lucerne	180	30	52	32	16
Wheat, lupin, wheat with lucerne	143	36	51	45	21
Monoculture chicory	168	71	58	95	94
Half chicory, lupin, wheat with chicory	80	41	33	64	29
Lupin, wheat, canola with chicory	78	42	32	49	36
Wheat, canola, lupin with chicory	86	23	21	17	19

Table 5-6 Pasture plant counts (number of plants/m^2) at site 2

Treatment	19/07/2007	22/07/2008	7/05/2009
Monoculture lucerne	198	91	51
Monoculture chicory	174	109	98
Wheat-lucerne	101	46	27
Wheat-chicory	88	46	49





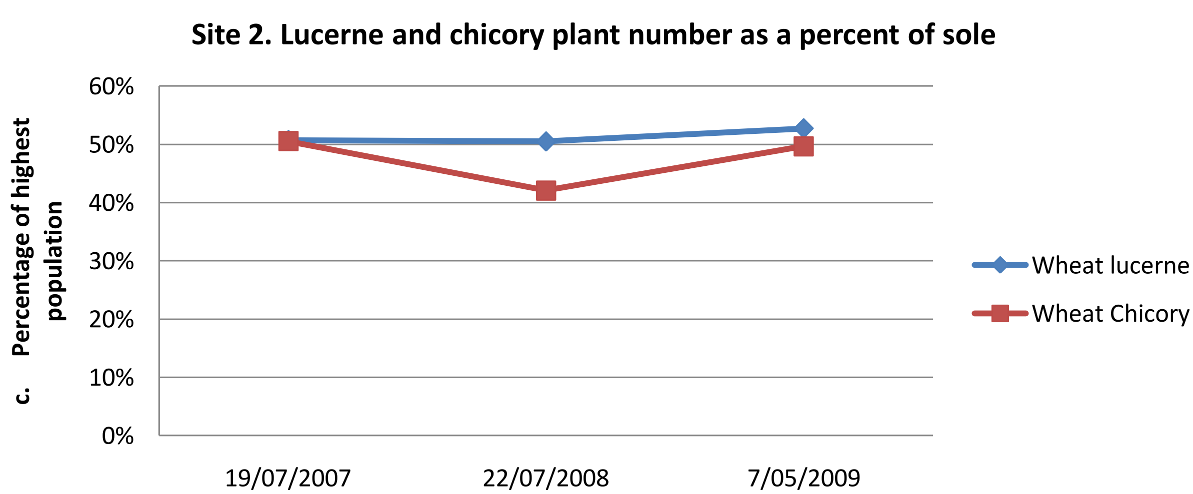


Figure 5-1 Plant numbers as a proportion of monoculture a) site 1 lucerne b) site 1 chicory and c) site 2 lucerne and chicory

Figure 5-2 Chicory plant showing the development of multiple stems per plant giving the appearance of multiple plants

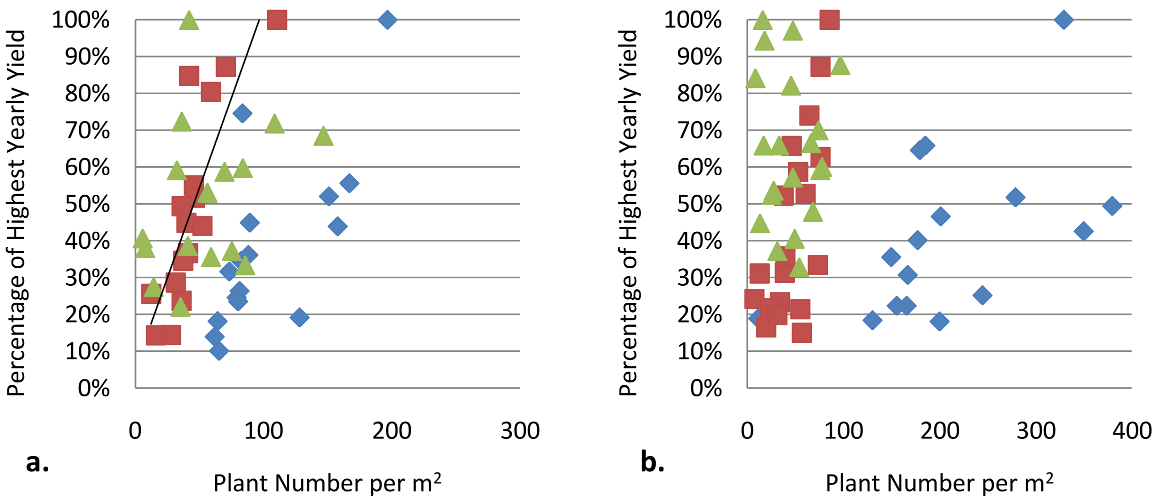


Figure 5-2 Yield and plant number in years ◆ 2006, ■ 2007 and ▲ 2008, site 1 a) chicory b) lucerne

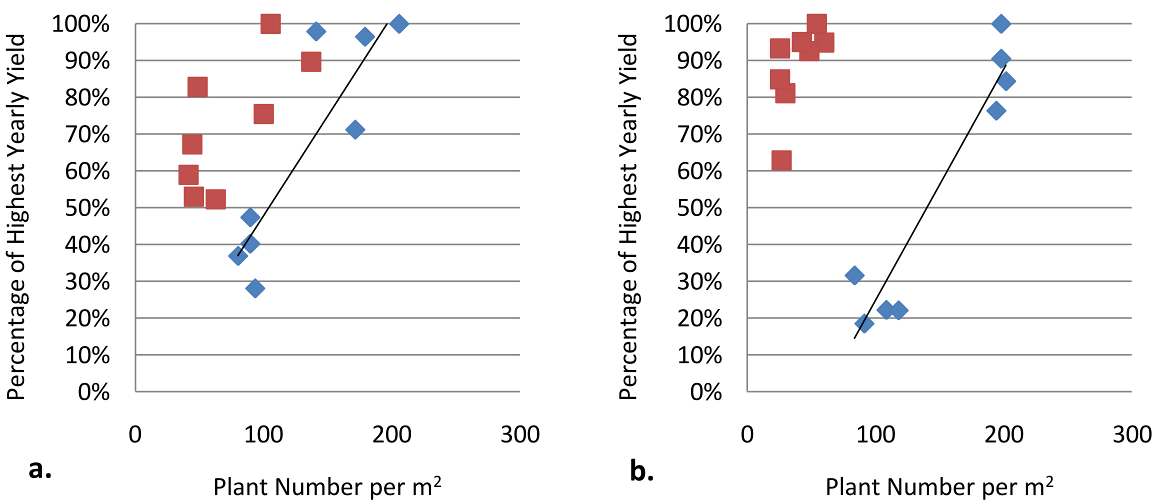


Figure 5-3 Yield and plant numbers in years ◆ 2007 and ■ 2008, site 2 a) chicory b) lucerne

5.3.3 Land Equivalent Ratios (LER)

LER for economically important traits

In 2008, both lucerne and chicory intercrops produced LER values of greater than 1, based on the economically important traits of grain yield and pasture available for livestock grazing (based on out-of-growing season dry matter, and pasture dry matter available at harvest) (Table 5-7). Chicory intercrops produced LER greater than 1 more often than lucerne intercrops (Table 5-7). The amount that each component contributed to overall LER varied between years and treatments (Table 5-7). LER values were low in 2006, due to drought conditions. In this year, lupin did not contribute to the grain component of the LER, as it was not harvested (Table 5-7).

LER for production

A production-based LER of greater than 1 was achieved in all treatments at site 1 on an annual and in-growing season basis in 2008. The exception was the canola-lucerne intercrop during the growing season (Table 5-8). Annual production and growing season LER was also greater than 1 for intercrops at site 2 in 2008 (Table 5-8).

Chicory intercrops produced annual total LER values greater than 1 for site 1 in 2007. In 2007, the only lucerne intercrop to over-yield was wheat-lucerne (Table 5-8). During the establishment year at site 1, 2006, there was only one treatment to produce a LER of greater than 1 and that was wheat-lucerne intercrop at site 1.

In 2006 and 2007, wheat and canola contributed a greater amount of dry matter to the intercrop combination than either lucerne or chicory. Lupin generally contributed equal or less dry matter than the pasture species in these two seasons (Table 5-8). In 2008, the results are different, with the lucerne pastures contributing similar or greater dry matter to the combined intercrop LER value.

Irrespective of season or species, chicory contributed 30-40% of production when intercropped with wheat or lupin (Table 5-8). Canola intercrops vary greatly over the two seasons. In 2007, it was the dominant contributor to LER, but in 2008, canola's dry matter contribution to LER was low. Lucerne was the greater contributor to LER, when grown with lupin, in all seasons (Table 5-8).

Table 5-7 Crop grain yield and pasture dry matter yield (amount available for livestock consumption) expressed as Land Equivalent Ratio (LER) at site 1 and site 2 in years 2006-08

Treatment	Grain component	Pasture component	LER
Site 1, 2006			
Wheat-lucerne	0.52	0.28	**0.80**
Wheat-chicory	0.74	0.20	**0.94**
Lupin-lucerne	0.00	0.40	**0.40**
Lupin-chicory	0.00	0.34	**0.34**
Site 1, 2007			
Wheat-lucerne	0.56	0.34	**0.90**
Wheat-chicory	0.59	0.41	**0.99**
Lupin-lucerne	0.26	0.62	**0.88**
Lupin-chicory	0.52	0.94	**1.45**
Canola-lucerne	0.81	0.14	**0.95**
Canola-chicory	0.92	0.11	**1.03**
Site 1, 2008			
Wheat-lucerne	0.68	0.63	**1.32**
Wheat-chicory	1.03	0.55	**1.58**
Lupin-lucerne	0.28	1.28	**1.56**
Lupin-chicory	0.55	0.77	**1.32**
Canola-lucerne	0.28	1.00	**1.28**
Canola-chicory	0.17	1.00	**1.18**
Site 2, 2007			
Wheat-lucerne	0.80	0.20	**1.01**
Wheat-chicory	0.81	0.31	**1.12**
Site 2, 2008			
Wheat-lucerne	0.54	0.88	**1.42**
Wheat-chicory	0.58	0.75	**1.33**

Table 5-8 Crop and pasture dry matter yields, in-growing season and annual total, expressed as Land Equivalent Ratio (LER) at site 1 and site 2 in years 2006-08

	LER Growing Season			LER Annual Total		
Treatment	Grain component	Pasture component	LER	Grain component	Pasture component	LER
Site 1, 2006						
Wheat-lucerne	0.60	0.51	**1.11**	0.60	0.45	**1.05**
Wheat-chicory	0.59	0.31	**0.90**	0.59	0.32	**0.90**
Lupin-lucerne	0.46	0.48	**0.94**	0.46	0.52	**0.99**
Lupin-chicory	0.52	0.40	**0.92**	0.52	0.44	**0.96**
Site 1, 2007						
Wheat-lucerne	0.79	0.26	**1.05**	0.79	0.33	**1.12**
Wheat-chicory	0.85	0.42	**1.27**	0.85	0.49	**1.34**
Lupin-lucerne	0.23	0.40	**0.64**	0.23	0.48	**0.71**
Lupin-chicory	0.53	0.43	**0.96**	0.53	0.49	**1.01**
Canola-lucerne	0.77	0.15	**0.92**	0.77	0.22	**0.99**
Canola-chicory	0.86	0.20	**1.06**	0.86	0.22	**1.08**
Site 1, 2008						
Wheat-lucerne	0.56	0.53	**1.09**	0.56	0.66	**1.22**
Wheat-chicory	0.92	0.28	**1.19**	0.92	0.43	**1.34**
Lupin-lucerne	0.47	1.05	**1.53**	0.47	1.19	**1.66**
Lupin-chicory	0.77	0.41	**1.18**	0.77	0.48	**1.25**
Canola-lucerne	0.15	0.80	**0.95**	0.15	0.86	**1.01**
Canola-chicory	0.46	0.63	**1.09**	0.46	0.81	**1.27**
Site 2, 2007						
Wheat-lucerne	0.72	0.21	**0.92**	0.72	0.27	**0.98**
Wheat-chicory	0.53	0.40	**0.93**	0.53	0.42	**0.95**
Site 2, 2008						
Wheat-lucerne	0.59	0.45	**1.04**	0.59	0.84	**1.47**
Wheat-chicory	0.41	0.59	**1.00**	0.41	0.66	**1.16**

5.4 Discussion

Intercropping the perennial pastures, lucerne and chicory with a range of grain crops had a varied impact on dry matter production of the pasture species. Intercrop dry matter yield reductions, as a percent of the monoculture, ranged from nil to 78% for lucerne and 19% to 78% for chicory. This is consistent with the 71% yield reduction reported in an over-cropping wheat-lucerne study (Harris *et al.* 2007). While there were reductions in pasture dry matter production, LER values show intercropping could still be more productive than the monoculture components. This also occurs in lucerne-cereal over-cropping (Harris *et al.* 2007; Humphries *et al.* 2004).

Chicory as an intercrop species

Once established, lucerne and chicory produced similar amounts of annual dry matter. However, chicory was more productive than lucerne in the pasture establishment year.

Annual production of established lucerne and chicory did not differ, however there were differences in the timing of dry matter production throughout the season. Lucerne was more productive at the start of the season, during the winter period, with chicory more productive at the end of the season, during the autumn period. These seasonal differences are supported by studies on lucerne and chicory production. Lucerne production is greatest during spring and summer (Brown *et al.* 2005; Dolling *et al.* 2005a), and least during autumn (Dolling *et al.* 2005a). By contrast, chicory is virtually winter dormant (Hume *et al.* 1995), producing minimal dry matter during this period (Hayes *et al.* 2010a) and is most productive during late spring and summer (Hume *et al.* 1995; Li *et al.* 1997a). These differences in seasonal growth between the two species indicate lucerne is more likely to be competitive for resources than chicory during the growing season, particularly early in the growing season due to the growth of the lucerne during this period, which overlaps with the grain crop for resource requirements.

Differences in production, and therefore resource use, during the annual growing season are an important consideration of an intercropping system. When selecting intercropping species, the aim is to select two species with growth and resource requirements as dissimilar as possible (Fukai & Trenbath 1993). In this current study, it appears that low winter activity is a desirable trait for reducing competition of the intercrop pasture species. This benefit is also found in wheat-lucerne over-cropping, where using lucerne varieties with greater winter dormancy reduced the grain yield penalty (Egan & Ransom 1996).

Seasonal dry matter production showed the chicory variety used in this study was more winter dormant than the lucerne variety. High winter dormancy of chicory has been reported previously (Hume *et al.* 1995). By contrast, the winter dormancy of lucerne varies greatly between varieties. Lucerne dormancy is classified by a winter activity rating from 1 to 10. Aurora, the lucerne variety used in this study, has a winter activity rating of 6, indicating low to moderate winter production (Humphries *et al.* 2004). This lucerne rating system enables producers to select varieties best suited to their climatic conditions. However, in an intercropping system, it may also be a useful tool for selecting varieties with a low winter activity, which therefore may be better suited to intercropping.

Productivity of the system, and the duration of productivity of the pasture component of the intercrop, will influence the potential for both lucerne and chicory as intercrop species. The duration of a lucerne pasture phase in a cropping system, with the aim to dry the soil profile, is suggested to be between 2 and 5 years (Angus *et al.* 2001; Ridley *et al.* 2001). Using this as a guideline, pasture intercrop species should be expected to persist productively for 2-5 years in intercrop.

The life of a lucerne stand will vary depending on the variety selected and the management practice. Under some conditions, a lucerne stand could persist for up to 20 years, with 3-7 years being more common (Lodge 1991). Here, lucerne plant numbers declined over the three years of the study in both the monoculture and intercrop treatments, and the decline was unaffected by intercropping. Plant numbers were between 16 and 46 plants per m^2 at the beginning of the fourth season. These plant numbers are within the range reported in over-cropping lucerne studies, where lucerne is still productive (Harris *et al.* 2007; Humphries *et al.* 2004).

The persistence of chicory has been shown to be less than that of lucerne (Hayes *et al.* 2010a). Pasture trials indicate chicory will continue to be productive for three to four years before declining to unproductive levels (Li *et al.* 1997a, 1997b). When appropriately grazed and given adequate nutrition, chicory persistence is improved, persisting into the fifth year however, production at this stage can be low (Alemseged *et al.* 2003). The crop-pasture intercropping system allows for short grazing and long rest periods, as recommended in these studies to improve persistence of chicory. Chicory is deemed to be unproductive if plant numbers are below 25 plants/m^2 (with six or more shoots per plant), or 150 shoots/m^2 (Li *et al.* 1997a). Chicory plant numbers in this study were still above this target level at the beginning of the fourth season, suggesting that intercropped chicory will persist into the fourth season.

These results indicate that both intercropped lucerne and chicory would fit into a 3-5 year pasture-crop rotation. However, removal of the species at the end of such a rotation does require consideration. Removal of lucerne has been documented as being difficult, with producers responding in a survey that they were unsatisfied with the 80% removal levels achieved (Davies & Peoples 2003). There is little information available on removing chicory, but as it has been reported to naturally decline to unproductive levels after 3 to 4 years, it is unlikely to have adverse effects on a subsequent crop rotation. Due to difficulties with adequate lucerne removal, a lucerne intercrop might be better suited to a longer-term rotation compared to a shorter-term intercrop rotation, which would be better suited to chicory.

Overall, the dry matter yield and persistence of chicory, in addition to being less competitive than lucerne when intercropped, indicates its suitability as a shorter-term pasture species in an intercrop system.

Plant densities and spatial design

In order to gain an understanding of the cause of yield reductions in intercropping, plant densities and spatial design were observed in this study.

As with the grain crops, the intercrop pastures were sown on a double alternate row arrangement, with seeding rates maintained per row. This resulted in a reduction in plant numbers per m^2 for the intercrops and half monoculture treatments, compared to the monoculture treatment.

There were differences in dry matter yield between the monoculture and half monoculture treatments, indicating an effect of plant density or changing spatial arrangement. Despite lower plant density in half monoculture and intercrops, there was generally a low correlation with dry matter yield, except in the 2007 season. In this season, chicory plant numbers increased at both sites, and lucerne numbers at one site, which increased dry matter production. This indicates that the lower plant densities were impacting on production in one of the three seasons of this study.

Pasture dry matter production appears to also be related to seasonal conditions. In less favourable seasons, monoculture lucerne was more productive than half monoculture lucerne. In contrast, half monoculture lucerne was more productive than monoculture lucerne in the more favourable season.

These results show there was a negative effect on pasture dry matter production due to changes in plant densities and spatial arrangements. However, this reduction in yield appears to be reduced or reversed in more favourable seasons, as was also found in the grain component of wheat intercrops (Chapter 4). This seasonal effect was also observed in an over-cropping study, which found that there was a strong relationship between growing season rainfall and increased production of the companion crop (Harris *et al.* 2007). Cenpukdee and Fukai (1992) also reported that differences in growing season conditions affected competition of the two intercrop species.

Intercrop competition

Annual and in-growing season production for lucerne and chicory was generally greater for the monoculture treatments compared to the intercrop treatments. With some of these differences attributed to plant densities and changing spatial arrangement, competition was also investigated in this study. The half monoculture and intercrop treatments were sown in the same row design at the same seeding rate; therefore differences in production between these treatments indicate competition between the intercrop species.

Dry matter production was often significantly different between the half monoculture treatment and the intercrops for in-growing season production. This suggests intercrop competition for resources was occurring in the growing season. Out-of-growing season, which is after the removal of the grain crops and therefore this potential competition, the dry matter production measured was often similar between the monoculture, half monoculture and intercrops. However, this did depend on the intercrop species and how competitive it was in the growing season. Where grain crops were very dominant, there was an ongoing effect on the pasture plants of reduced out-of-growing season dry matter.

Species combinations of the crop-pasture intercrop also had an impact on dry matter production of the pasture. Wheat and canola had the greatest impact on pasture dry matter production, and lupin the least. When lupin was grown in intercrop with lucerne, there was no reduction in lucerne production compared to the half monoculture lucerne. This is consistent with research focusing on crop and weed competition, which found lupin to be a poor competitor, while wheat and canola were stronger competitors (Lemerle *et al.* 1995; Lutman *et al.* 1994).

There were also differences in the timing of competition affecting dry matter production of the intercrop pasture. For chicory, competition was occurring by the time the first pasture measurement was taken. However, lucerne competition was often not evident until the second pasture measurement. Fukai and Trenbath (1993) stated that, at some point in the growing season, the intercrop components will compete with each other for resources. Generally, the dominant species is the one which grows faster than the other, leading to this dominance. This supports the conclusion that the difference in the competitive nature of lucerne compared to chicory is due to lucerne's early season vigour. Similarly, competition early in the growing season contributed to crop yield reductions in wheat-lucerne over-cropping (Harris *et al.* 2008a). Competition for resources between the grain crop and pasture species affected dry matter production of both lucerne and chicory grown in intercrop. Lucerne is a more competitive intercrop species than chicory, supporting the conclusions reached in Chapter 4, and it is likely this is due to early vigour of the lucerne during the winter period.

Productivity of Intercropping

Land Equivalent Ratio (LER) assesses overall productivity of an intercropping system. In-growing season dry matter LER gives an indication of comparative resource use of the intercrop compared to the monoculture components, when both component species are actively growing. Wheat intercrops generally over-yielded, indicating high in-season resource use. In all cases, wheat was a greater contributor to intercrop LER than the pasture component. By contrast, lupin intercrops only over-yielded in the more favourable season of 2008, with the lupin's contribution to LER generally similar to that of the pasture species. This supports the conclusion that wheat grown in intercrop is a stronger competitor than lupin.

The annual total LER showed, with the exception of drought conditions, that chicory intercrops are able to utilise resources throughout the year, resulting in over-yielding. By comparison lucerne intercrops only over-yielded in 2008. This suggests that greater resource use and competition of lucerne intercrops during the growing season, affected out-of-growing season resource use, resulting in lucerne intercrops being less likely to over-yield annually than chicory intercrops. This is supported by the finding that prolonged competition between two grain intercrop species resulted in LER values of less than 1, indicating an inefficient system (Cendekdee & Fukai 1992). The difference in resource use between lucerne and chicory is likely to be a reflection of the difference in-season growth of the two species. Chicory appears to increase the efficiency of the intercrop by competing with the crop less during the growing season, and utilising resources available during the out-of-growing season period.

The difference in resource use of lucerne and chicory intercrops was also reflected in the economically-based LER values (crop grain yield and pasture dry matter available for stock consumption). In the more favourable season of 2008, all intercrop combinations were more productive than the monoculture component species. However, only chicory intercrops over-yielded in the below average rainfall year of 2007. Similarly, LER values greater than 1, based on economic traits, were reported in a lucerne-wheat companion cropping study (Humphries *et al.* 2004).

Summary

This study shows chicory is well suited to intercropping. This is due to greater winter dormancy of the species when compared to lucerne, resulting in lower growth early in-growing season, presumably reducing its competitiveness with the crop for resources. There were also differences between the two pasture species in regard to resource use and/or timing of demand for resources.

Intercropping grain crops with perennial pasture species, lucerne and chicory, generally resulted in a reduction in pasture and crop yields (Chapter 4). However, in average rainfall conditions, as experienced in 2 of the 3 years of this study, all the intercrop combinations over-yielded based on economic and productive traits. Intercropping can therefore be more productive than growing the component species as monoculture stands, in this environment. A greater incidence of over-yielding by chicory intercrops indicates chicory was better suited to intercropping than lucerne, due to chicory's lower competitiveness with the crop component.

Overall, a pasture-crop intercropping system using alternative crop and pasture species grown in combination and rotation appears well-suited to the higher rainfall zones, given average growing season conditions.

The differences in competition for resources between the intercrop species will be further explored in Chapter 6, focusing on the source of intercrop competition.

Chapter 6. Intercropping competition for resources: Light and Water

6.1 Introduction

Intercropping studies have shown that competition for resources including light, water and nutrients, can result in yield reductions in the component species (Cendekdee & Fukai 1992; Millar & Badgery 2009; Morris & Garrity 1993b). Previous cereal-lucerne over-cropping studies report both early and late season competition causing yield reductions of the over-cropped components (Egan & Ransom 1996; Harris *et al.* 2008a; Humphries *et al.* 2004). Competition for N and light prior to stem elongation of wheat resulted in a reduction in tillers, heads and biomass, in a wheat-lucerne situation (Harris *et al.* 2008a). Similarly, where there was a 50% reduction in early wheat biomass with wheat over-cropped with lucerne, this was reported to be due to competition for light and/or nutrients, particularly N (Humphries *et al.* 2004). In contrast, competition between cereal-lucerne over-crops was found most likely to have occurred post cereal anthesis (Egan & Ransom 1996).

The ability of plants to compete for resources is determined by management, the environment and the plant genotype. Management influences include row spacing, sowing date and plant density (Sadras & Calderini 2009). The effect of environmental factors varies depending on the level of plant adaptation, and these factors include climatic conditions, soil pH and nutrient levels (Sadras & Calderini 2009). Plant traits such as seedling vigour, canopy structure, root growth and resource use efficiency determine a plant's ability to compete for resources (Sadras & Calderini 2009).

Limiting competition in intercropping through species selection, plant population management, geometry and row spacing can minimise yield reductions caused by competition (Keating & Carberry 1993; Midmore 1993). While the practice of intercropping generally results in a reduction in production of one or both of the plant species, changing components of the system can reduce competition effects. In an over-cropping study, the use of a more winter dormant variety of lucerne improved the Land Equivalent Ratio of the system (Humphries *et al.* 2004). Understanding the timing and source of intercrop competition may enable improvements to be made through agronomic manipulation of intercropping systems, with the outcome of improving productivity and limiting yield reductions.

Although there was slight seasonal variation, conclusions from the crop and pasture data in Chapter 4 & 5 indicate that competition for resources affected production between wheat growth stages cereal first node

(September) and maturity (November). This chapter will examine water measurements and surrogate light measurements in the form of Leaf Area Index (LAI) and plant height, with the aim of developing better understanding of the source of intercrop competition that affects crop and pasture yield.

6.2 Materials and Methods

A description of the trial site, and the materials and methods, are presented in Chapter 3.

6.3 Results

6.3.1 Soil moisture and root depth

There were significant differences in the way different intercrop combinations utilised water. Despite these differences, there was a consistent drying trend that occurred in September for all monoculture and intercrop combinations. This comparative data is described below, arranged for the two depths and season and site.

Soil Moisture: site 1

In 2007, there were significant differences between treatments in soil moisture at 0-15cm, becoming most evident at measurements taken on 27/9/2007 (Figure 6-1). At this measurement, the monoculture pastures lucerne and chicory had higher soil moisture ($P<0.05$) than all other treatments. Monoculture wheat was drier than wheat-chicory and wheat-lucerne intercrops at this measurement (Figure 6-1).

The lupin-chicory intercrop was consistently drier than the lupin-lucerne intercrop at all measurements, with the exception of 28/7/2007 (Figure 6-1). The lupin-chicory intercrop also had lower soil moisture ($P<0.05$) than monoculture lupin at the final measurement on 27/9/2007.

Soil moisture at 0-35cm in 2007 showed similar patterns to soil moisture at 0-15cm. The lupin-chicory intercrop had lower soil moisture ($P<0.05$) than the lupin-lucerne intercrop at all time points (Figure 6-2).

Soil moisture measured under the wheat-chicory intercrop was drier ($P<0.05$) than under monoculture wheat for the first three measurements, but there was no significant difference in soil moisture at the last measurement (Figure 6-2).

The canola-chicory intercrops had higher soil moisture (P<0.05) than the monoculture canola in two of the measurements and, whilst not significant, showed a wetter trend in the other two readings (Figure 6-2).
Soil moisture under monoculture chicory was higher (P<0.05) than the lupin-chicory intercrop for the final three measurements in this season (Figure 6-2). Monoculture chicory had higher soil moisture (P<0.05) than the wheat-chicory intercrop for the final two measurements and was also greater (P<0.05) than the canola-chicory intercrop at the final measurement (Figure 6-2).
The monoculture pastures had higher soil moisture (P<0.05) than the monoculture canola for the final two measurements (Figure 6-2). In the final measurement, taken on 27/9/2007, soil moisture was higher (P<0.05) for monoculture lucerne than for the wheat-lucerne and canola-lucerne intercrops (Figure 6-2).

In 2008, monoculture lupin had a lower soil moisture (P<0.05) at 0-15cm than the lupin-chicory intercrop in the 4 measurements taken from 28/7/2008 to 20/10/2008 (Figure 6-3). The monoculture lupin was only drier (P<0.05) than the lupin-lucerne intercrop on 29/9/2008. The lupin-chicory intercrop had a higher soil moisture (P<0.05) than the lupin-lucerne intercrop on 27/8/2008 (Figure 6-3).
The wheat-lucerne intercrop had higher soil moisture (P<0.05) compared to the wheat-chicory intercrop for all measurements taken from 27/8/2008 until the end of the growing season (Figure 6-3).
Soil moisture under the monoculture pastures was higher (P<0.05) than the monoculture lupin on 27/8/2008 and 29/9/2009 (Figure 6-3). Monoculture lucerne also had higher soil moisture (P<0.05) than the monoculture chicory, all the monoculture crops and the intercrops on 29/9/2008 and 20/10/2008 (Figure 6-3). Measurements were also higher (P<0.05) than the monoculture chicory on 8/12/2008.
Monoculture chicory had higher soil moisture (P<0.05) than the wheat-chicory intercrop on 27/8/2008 and 29/9/2008, and measurements were also higher (P<0.05) for the canola-chicory intercrop on 27/8/2008 (Figure 6-3).

The lupin-chicory intercrop had consistently higher soil moisture (P<0.05) at 0-35cm than monoculture lupin and the lupin-lucerne intercrop for all measurements, with the exception of the final measurement for monoculture lupin in 2008 (Figure 6-4 and Table 6-1).
Soil moisture under the wheat-lucerne intercrop was higher (P<0.05) than the wheat-chicory intercrop for all measurements, in addition to being higher (P<0.05) than the monoculture wheat on 29/9/2008 (Figure 6-4 and Table 6-1).
Monoculture chicory had higher soil moisture (P<0.05) than the wheat-chicory intercrops for all measurements (Figure 6-4 and Table 6-1). Soil moisture for monoculture chicory was also higher (P<0.05) than the canola-chicory intercrop in the two early measurements and on 24/11/2008. It was also higher (P<0.05) than that of the monoculture canola and wheat for readings taken from 29/9/2008 until the final

measurement for monoculture wheat, and on 24/11/2008 for monoculture canola (Figure 6-4 and Table 6-1).

Monoculture lucerne had higher soil moisture ($P<0.05$) than monoculture lupin, monoculture wheat and the lupin-lucerne intercrop on 29/9/2008 and 20/10/2008 (Figure 6-4 and Table 6-1). Measurements were also higher ($P<0.05$) than the monoculture canola and canola-lucerne intercrop on 29/9/2008.

Soil moisture: site 2 results

In 2007, there were no significant differences treatments in the early measurement of soil moisture at 0-15cm (Figure 6-5). Monoculture chicory had higher soil moisture ($P<0.05$) than the wheat-chicory intercrop for the three measurements taken on 10/7/2007, 28/7/2007 and 14/9/2007 (Figure 6-5). Measurements were also higher ($P<0.05$), 5mm and 13mm, than monoculture lucerne on the 28/7/2007 and 14/9/2007 respectively, and monoculture wheat on the 14/9/2007.

There was no treatment by date effect for the 0-35cm depth in 2007. However, there was a treatment effect with monoculture chicory having higher ($P<0.05$) soil moisture than all other treatments, with soil moisture 13mm higher ($P<0.05$) than monoculture lucerne (Figure 6-6).

In 2008, monoculture chicory had higher ($P<0.05$) soil moisture, 10mm, 11mm and 4mm, than monoculture lucerne for measurements at 0-15cm on 23/6/2008, 30/9/2008 and 26/11/2008 respectively (Figure 6-7). They were also higher ($P<0.05$) than the wheat-chicory intercrop on 23/6/2008 and 30/9/2008. Soil moisture under the wheat-lucerne intercrop was higher ($P<0.05$) than the monoculture components on 30/9/2008 (Figure 6-7).

As with the 15cm depth, monoculture chicory had higher soil moisture ($P<0.05$), 18mm to 32mm, at 0-35cm than monoculture lucerne and the wheat-chicory intercrop from 23/6/2008 to 26/11/2008 (Figure 6-8).

Rooting depth

Rooting depth was not directly measured in this study. However, observations of lucerne and chicory rooting depth were made during soil coring for all lucerne and chicory treatments in December 2008. It was observed that roots for both species extended beyond the 90cm maximum core depth.

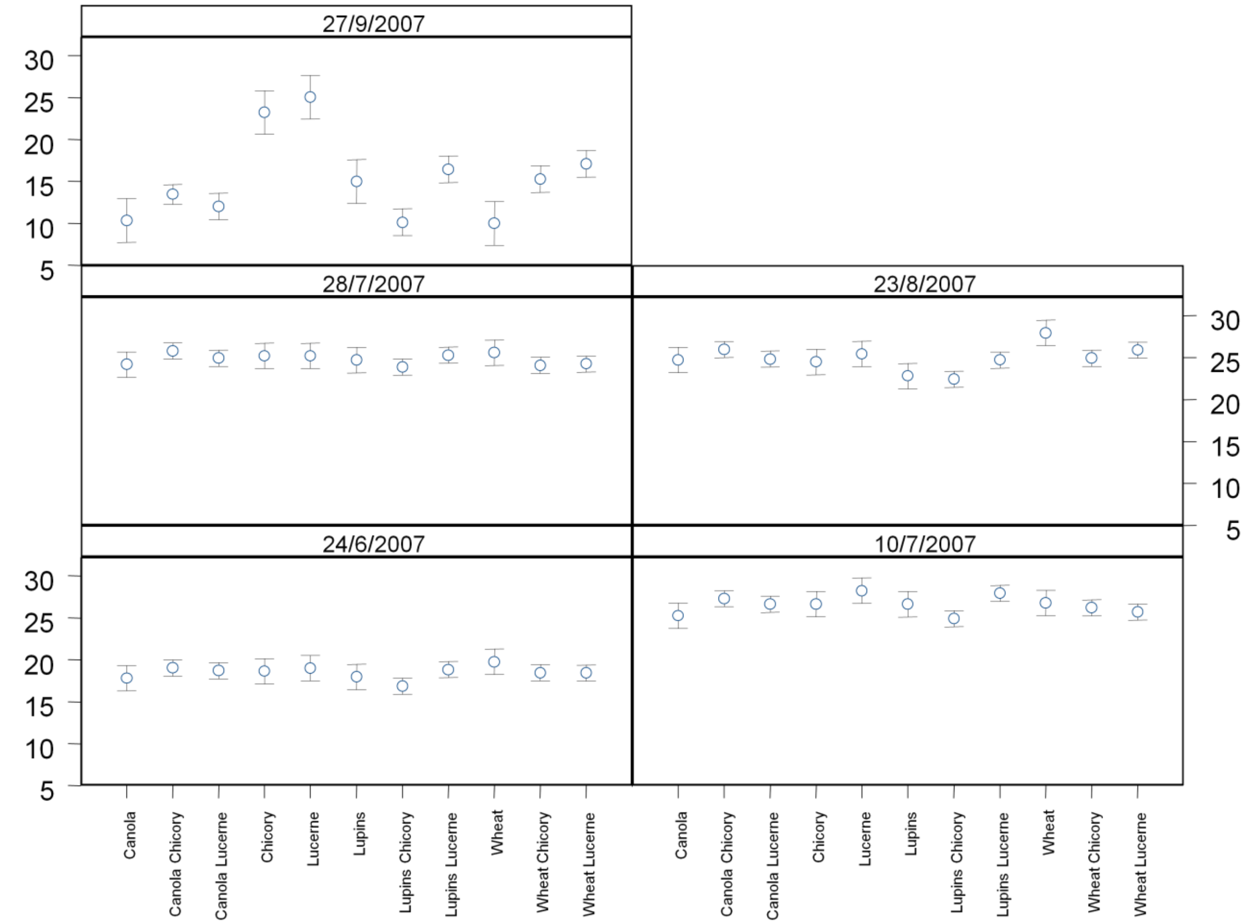


Figure 6-1 Soil moisture (Volumetric Water Content (%)) between 0-15cm at site 1 on 5 dates in 2007

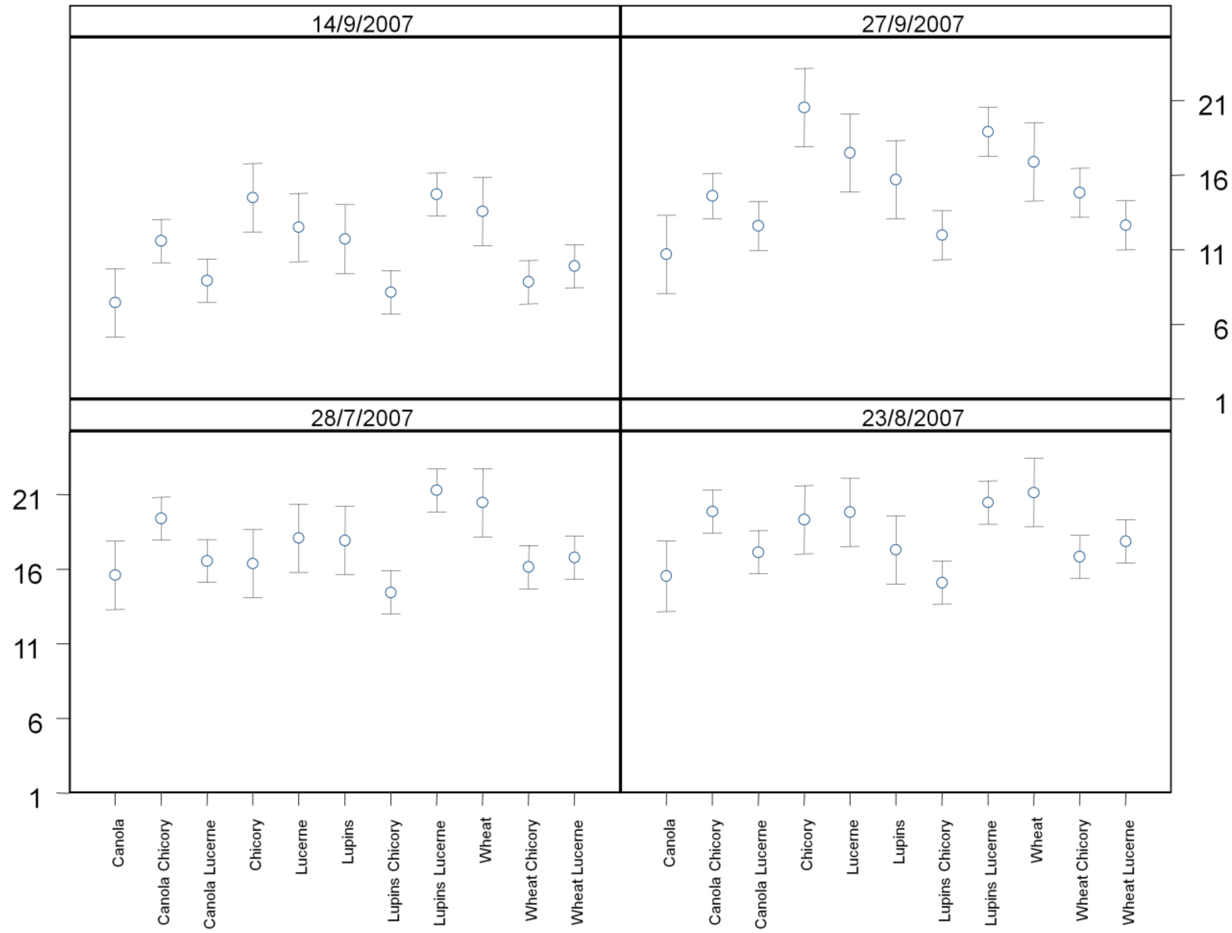


Figure 6-2 Soil moisture (Volumetric Water Content (%)) between 0-35cm at site 1 on 4 dates in 2007

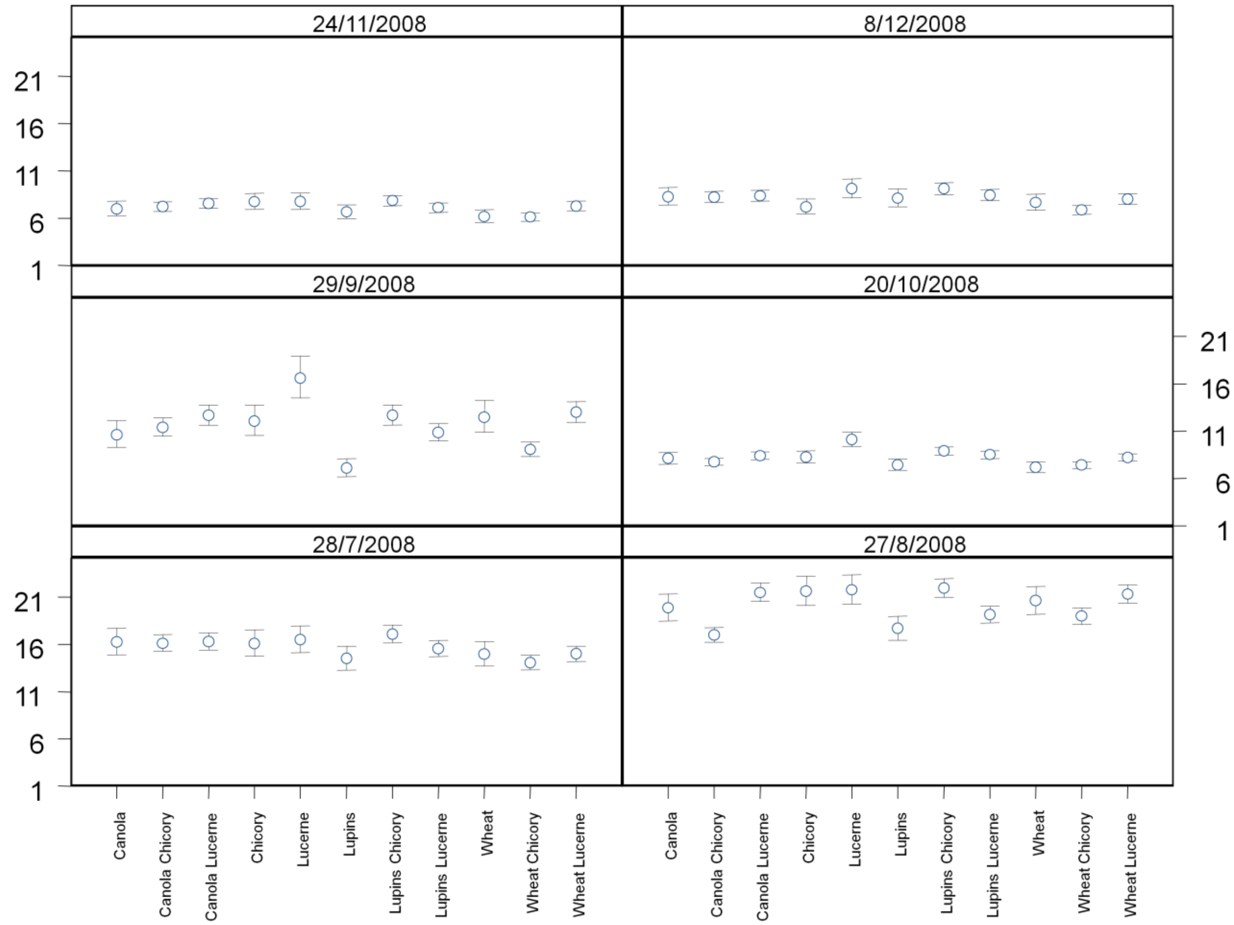


Figure 6-3 Soil moisture (Volumetric Water Content (%)) between 0-15cm at site 1 on 6 dates in 2008

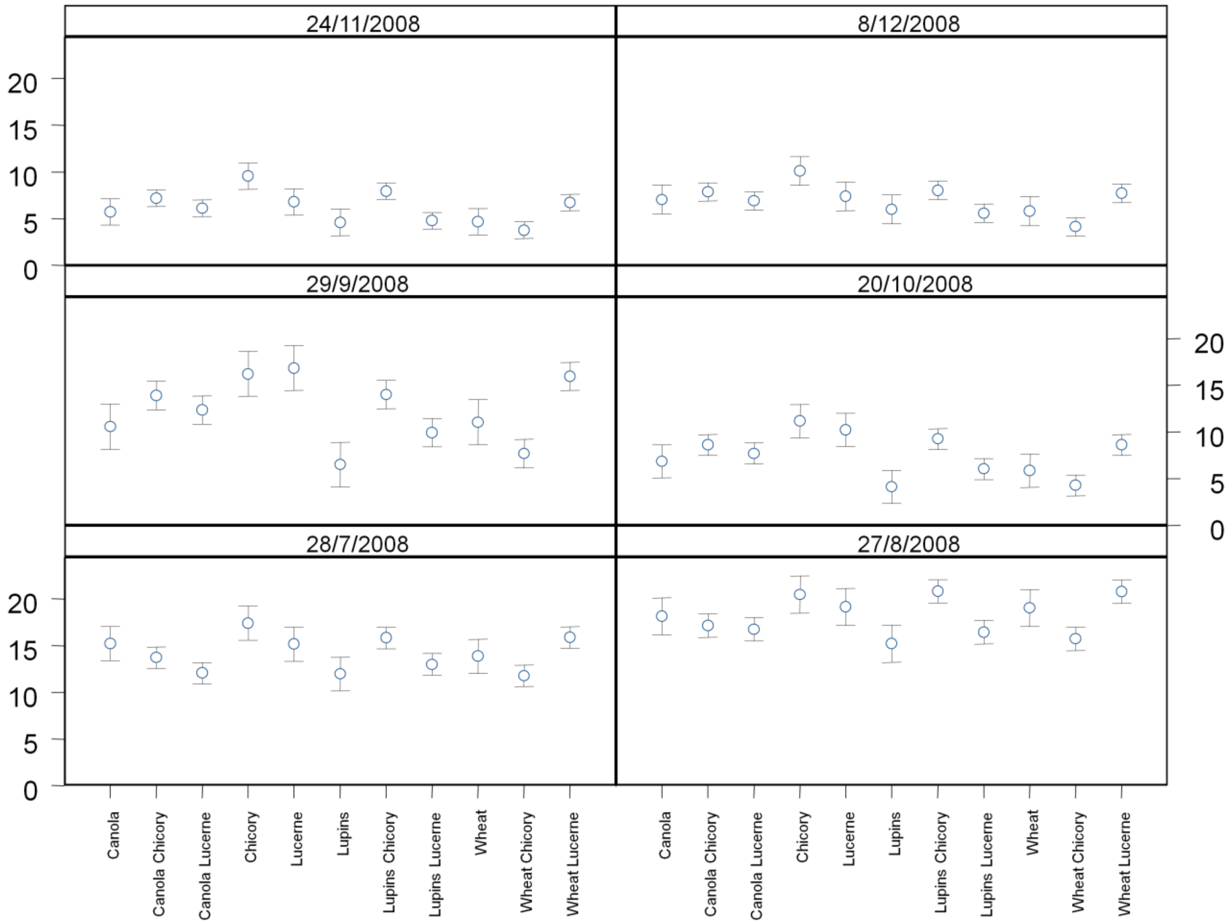


Figure 6-4 Soil moisture (Volumetric Water Content (%)) between 0-35cm at site 1 on 6 dates in 2008

Table 6-1 Soil moisture (mm) between 0-35cm at site 1 from 28/7/2008 to 20/10/2008

Treatment	28/07/2008	27/08/2008	29/09/2008	20/10/2008
Chicory	61	72	57	39
Lucerne	53	67	59	36
Lupin	42	53	23	15
Wheat	49	67	39	21
Wheat-chicory	41	55	27	15
Wheat-lucerne	46	58	35	21
Lupin-chicory	55	73	49	33
Lupin-lucerne	46	58	35	21

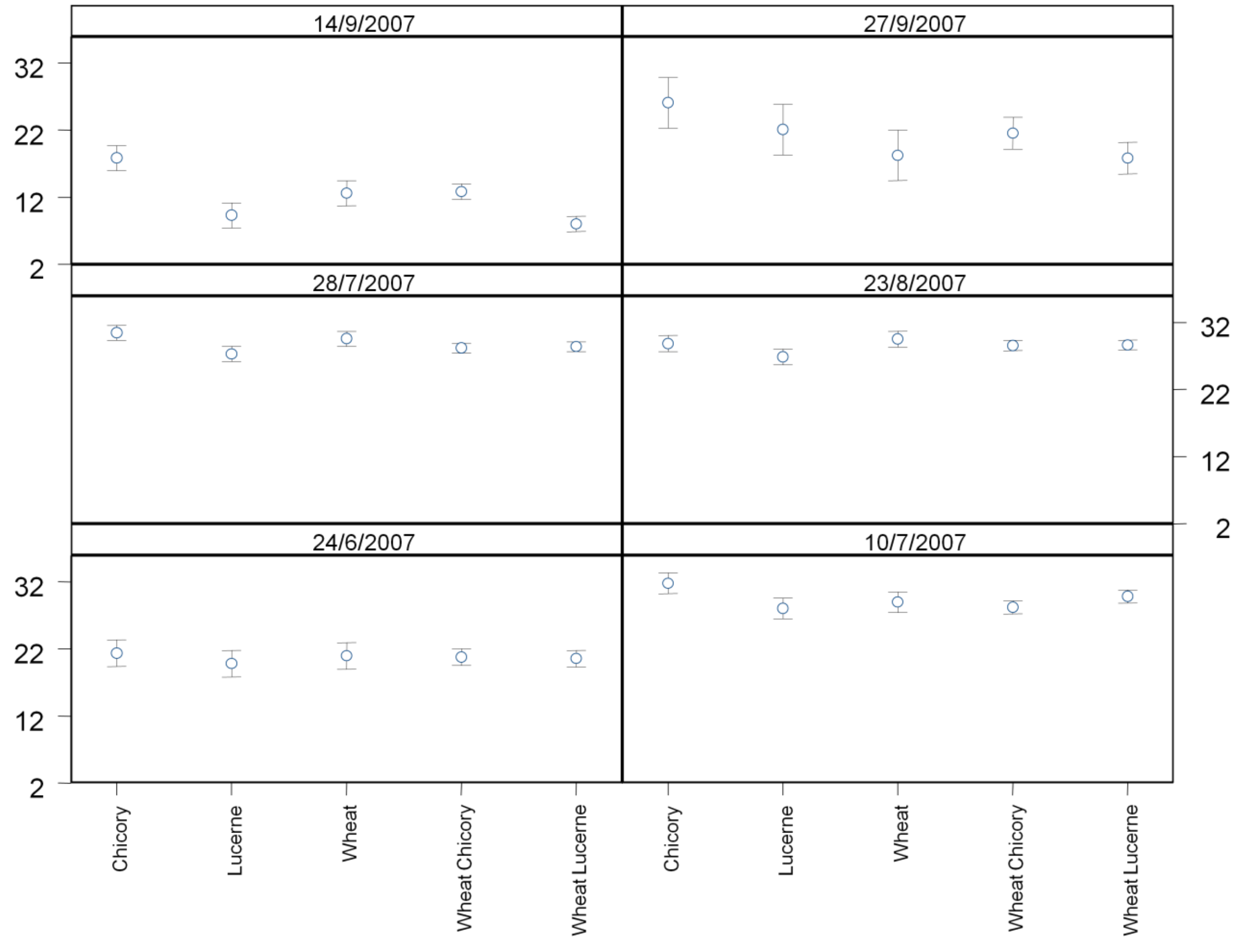


Figure 6-5 Soil moisture (Volumetric Water Content (%)) between 0-15cm at site 2 on 6 dates in 2007

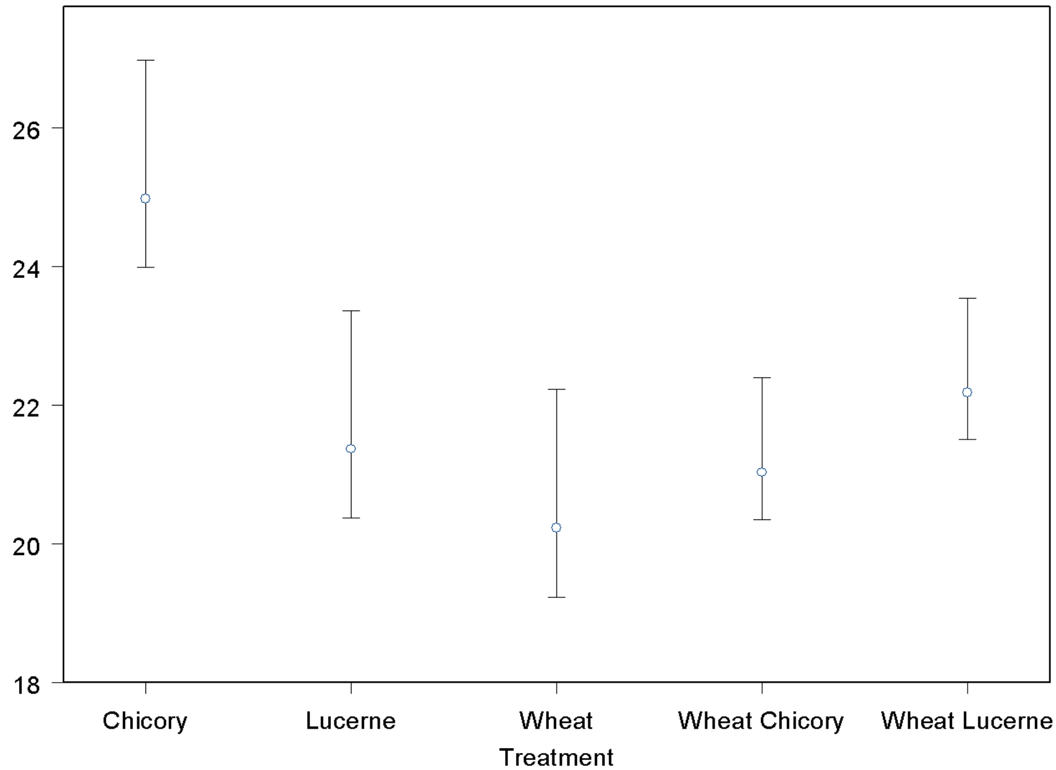


Figure 6-6 Soil moisture treatment effect (Volumetric Water Content (%)) between 0-35cm at site 2 in 2007

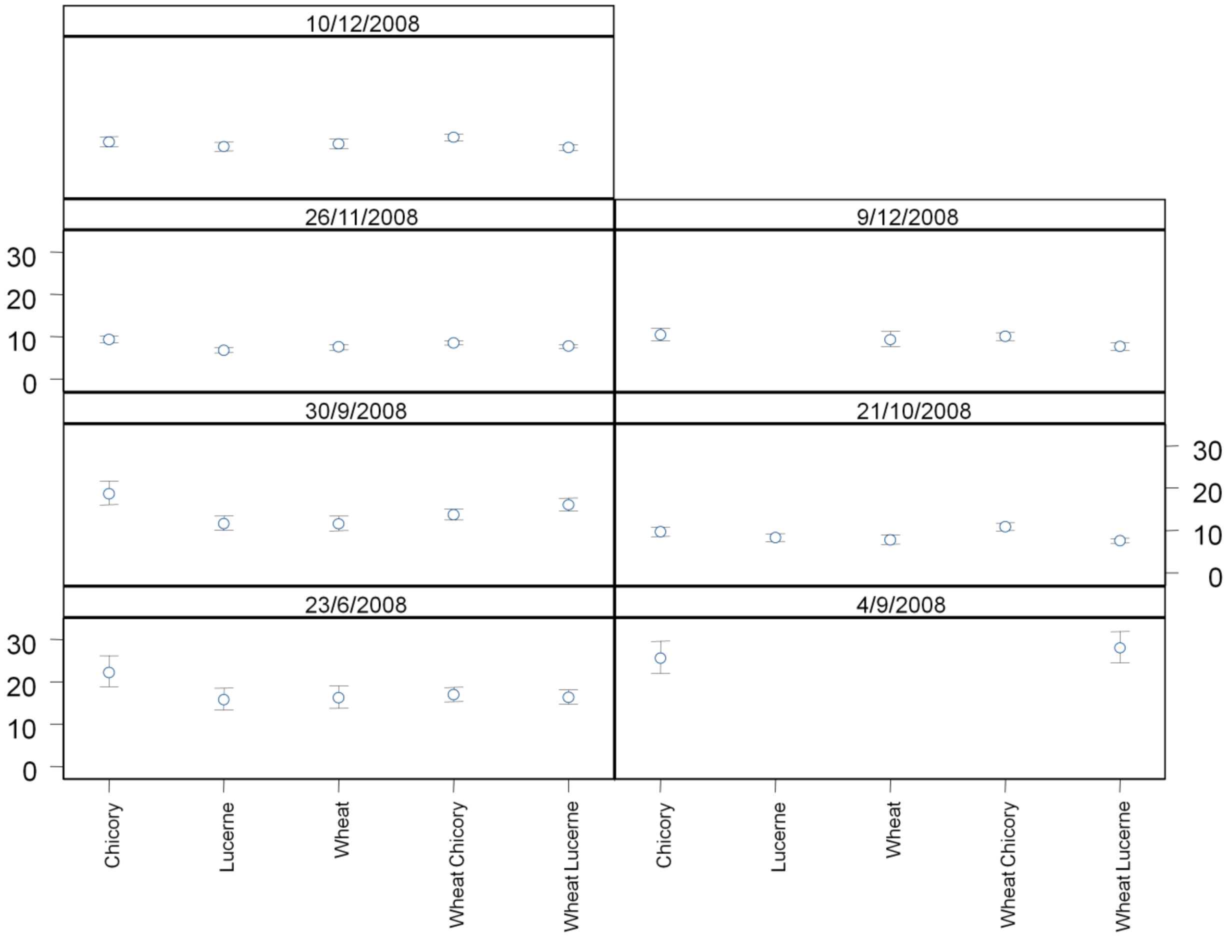


Figure 6-7 Soil moisture (Volumetric Water Content (%)) between 0-15cm at site 2 for 7 dates in 2008

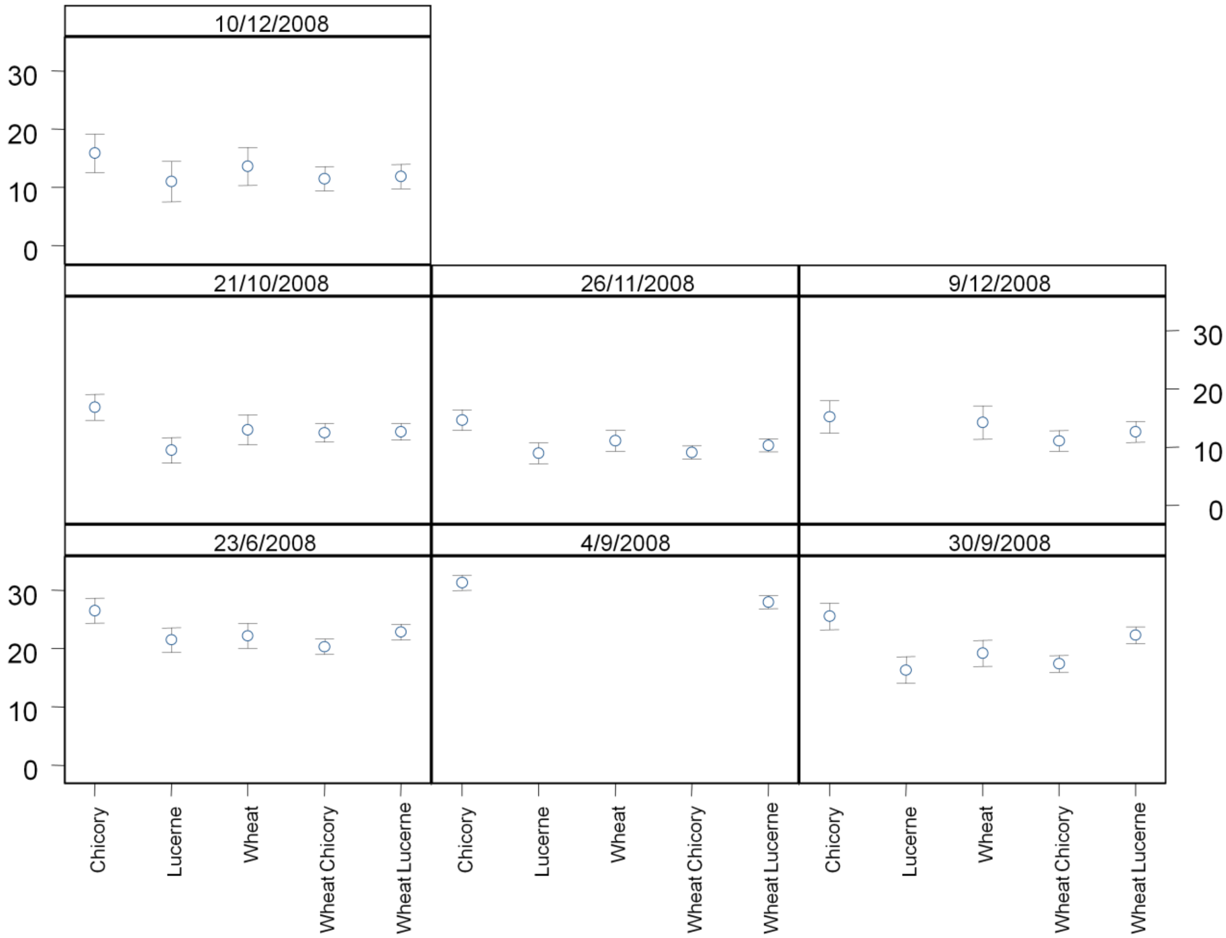


Figure 6-8 Soil moisture (Volumetric Water Content (%)) between 0-35cm at site 2 for 7 dates in 2008

6.3.2 *Leaf Area Index (LAI)*

At site 1, LAI measured in July 2006 and 2007 was low for all treatments, and generally there were no significant differences in LAI between treatments (Table 6-2, Table 6-3 and Table 6-4). There were no significant differences in LAI measured in December 2006, with the exception of the lupin-lucerne which had a lower LAI ($P<0.05$) than the half monoculture lucerne and wheat-lucerne intercrop (Table 6-2).

The wheat-lucerne intercrop and both lupin intercrops had higher LAI ($P<0.05$) than the half monoculture crops in September 2007; however they were not significantly different from the monoculture crops (Table 6-3).

There was a higher LAI ($P<0.05$) in the canola-chicory intercrop compared to monoculture chicory in 2007. There were also visual effects of shading on lucerne and chicory when grown in intercrop with canola in 2007 (Table 6-3). The results from site 2 showed no significant differences in LAI between treatments in 2007 (Figure 6-9).

Table 6-2 Leaf Area Index (LAI) over time at site 1 in 2006

Analysis Group	Treatment	20/10/2006	29/10/2006	12/12/2006
Pastures	Monoculture chicory	1.32	3.44	2.57
	Half monoculture chicory	1.61	2.93	2.32
	Wheat-chicory	1.52	2.36	1.92
	Lupin-chicory	1.16	2.91	2.50
	l.s.d (P<0.05)	n.s.	n.s.	n.s.
	Monoculture lucerne	1.14 *b*	3.46	1.81 *ab*
	Half monoculture lucerne	1.40 *ab*	2.26	2.37 *a*
	Wheat-lucerne	1.60 *a*	2.89	2.10 *a*
	Lupin-lucerne	1.33 *ab*	3.38	1.44 *b*
	l.s.d (P<0.05)	0.440	n.s.	0.623
Crops	Monoculture wheat	1.87 *a*	3.42 *a*	2.93
	Half monoculture wheat	1.29 *b*	3.39 *a*	2.46
	Wheat-lucerne	1.6 *ab*	2.89 *b*	2.10
	Wheat-chicory	1.52 *b*	2.36 *ab*	1.92
	l.s.d (P<0.05)	0.324	1.022	n.s.
	Monoculture lupin	0.89	3.19	2.36
	Half monoculture lupin	1.17	3.50	2.17
	Lupin-lucerne	1.33	3.38	1.44
	Lupin-chicory	1.16	2.91	2.50
	l.s.d (P<0.05)	n.s.	n.s.	n.s.

Note: LAI figures for the intercrop treatments (reading a representation of the whole plot) are the same in the crop and pasture sections, with the analysis undertaken separately for crops and pastures.

Means within each treatment column followed by a different letter are significantly different (P<0.05) Not significant = n.s.

Table 6-3 Leaf Area Index (LAI) over time at site 1 in 2007

Analysis Group	Treatment	12/07/2007	28/07/2007	19/09/2007
Pastures	Monoculture chicory	0.01 *b*	0.64	3.78
	Wheat-chicory	0.02 *ab*	0.75	2.84
	Lupin-chicory	0.02 *ab*	0.59	4.03
	Canola-chicory	0.05 *a*	0.85	2.93
	l.s.d (P<0.05)	0.028	n.s.	n.s.
	Monoculture lucerne	0.01	0.43 *ab*	3.84
	Half monoculture lucerne	0.01	0.05 *b*	3.33
	Wheat-lucerne	0.02	0.89 *a*	3.88
	Lupin-lucerne	0.01	0.44 *ab*	4.07
	Canola-lucerne	0.00	0.38 *ab*	3.58
	l.s.d (P<0.05)	n.s.	0.663	n.s.
Crops	Monoculture wheat	0.01	0.53	4.38 *a*
	Half monoculture wheat	0.01	0.58	2.40 *b*
	Wheat-lucerne	0.02	0.89	3.89 *a*
	Wheat-chicory	0.02	0.75	2.84 *b*
	l.s.d (P<0.05)	n.s.	n.s.	0.892
	Monoculture lupin	0.01	0.89 *a*	3.74 *ab*
	Half monoculture lupin	0.01	0.02 *b*	2.93 *b*
	Lupin-lucerne	0.01	0.44 *ab*	4.07 *a*
	Lupin-chicory	0.02	0.59 *ab*	4.03 *a*
	l.s.d (P<0.05)	n.s.	0.842	0.600
	Monoculture canola	0.01 *ab*	0.66	3.91
	Canola-lucerne	0.00 *b*	0.38	3.58
	Canola-chicory	0.05 *a*	0.85	2.93
	l.s.d (P<0.05)	0.045	n.s.	n.s.

Note: LAI figures for the intercrop treatments (reading a representation of the whole plot) are the same in the crop and pasture sections, with the analysis undertaken separately for crops and pastures.

Means within each treatment column followed by a different letter are significantly different ($P<0.05$) Not significant = n.s.

Figure 6-9 Shading effects in canola-chicory intercrop in September 2007.

Table 6-4 Leaf Area Index (LAI) over time at site 2 in 2007

Analysis Group	Treatment	12/07/2007	29/07/2007	19/09/2007
Pastures	Monoculture chicory	0.00	0.74	3.41
	Wheat-chicory	0.01	0.74	3.22
	l.s.d (P<0.05)	n.s.	n.s.	n.s.
	Monoculture lucerne	0.01	0.77	2.38
	Wheat-lucerne	0.01	0.95	3.12
	l.s.d (P<0.05)	n.s.	n.s.	n.s.
Crops	Monoculture wheat	0.00	0.92	3.55
	Wheat-lucerne	0.01	0.95	3.12
	Wheat-chicory	0.01	0.73	3.21
	l.s.d (P<0.05)	n.s.	n.s.	n.s.

Note: LAI figures for the intercrop treatments (reading a representation of the whole plot) are the same in the crop and pasture sections, with the analysis undertaken separately for crops and pastures.

Means within each treatment column followed by a different letter are significantly different (P<0.05) Not significant = n.s.

6.3.3 *Plant height*

Crop component

There was generally no significant difference in crop plant heights in 2006 (Table 6-5). In 2008, wheat intercropped with lucerne was shorter ($P<0.05$) than the half monoculture treatment in September and December (Table 6-5). Canola intercropped with both chicory and lucerne was shorter ($P<0.05$) than monoculture canola in December 2008 (Table 6-5). There were no significant differences in either canola or lupin plant height in September 2008 (Table 6-5).

Pasture component

The mid season plant height of the pasture in the wheat-lucerne and wheat-chicory intercrops was generally higher ($P<0.05$) than that of the monoculture lucerne and chicory respectively (Table 6-7 and Table 6-8). In contrast, chicory intercropped with lupin had a lower ($P<0.05$) plant height than that of monoculture chicory (Table 6-7). The 2008 mid season results show canola-chicory intercrop plant height is not significantly different from monoculture chicory (Table 6-7). The wheat-chicory intercrop height was higher ($P<0.05$) than that of monoculture chicory. In contrast, the lupin-chicory intercrop plant height was lower ($P<0.05$) than monoculture chicory (Table 6-7). End of season results show that chicory grown with canola was taller ($P<0.05$) than monoculture chicory. In contrast, the wheat-chicory intercrop was shorter than the monoculture chicory (Table 6-7).

Table 6-5 Plant height (cm) of monoculture and intercrop grain crops at site 1 in 2006 and 2008

	2006	2008	
Treatment	Mid season (2/10/2006)	Mid season (5/09/2008)	End season (11/12/2008)
Monoculture wheat	29	53 *a*	85 *b*
Half monoculture wheat	30	54 *a*	91 *a*
Wheat-lucerne	29	48 *b*	85 *b*
Wheat-chicory	30	55 *a*	86 *ab*
l.s.d (P<0.05)	n.s.	2.3	5.2
Monoculture lupin	10 *b*	18	69 *a*
Half monoculture lupin	12 *a*	21	68 *a*
Lupin-lucerne	10 ab	22	65 *ab*
Lupin-chicory	10 ab	18	60 *b*
l.s.d (P<0.05)	2.0	n.s.	6.6
Monoculture canola		25	119 *a*
Canola-lucerne		21	100 *b*
Canola-chicory		18	102 *b*
l.s.d (P<0.05)		n.s.	8.3

Table 6-6 Plant height (cm) of monoculture and intercrop grain crops at site 2 in 2008

Treatment	Mid season (7/09/2008)	End season (11/12/2008)
Monoculture wheat	49	89 *a*
Half monoculture wheat		
Wheat-lucerne	49	84 *ab*
Wheat-chicory	45	81 *b*
l.s.d (P<0.05)	n.s.	5.5

Note: Means within each treatment column followed by a different letter are significantly different (P<0.05)

Not significant = n.s.

Table 6-7 Plant height (cm) of monoculture and intercrop pastures at site 1 in 2006 and 2008

	2006	2008	
Treatment	Mid season (2/10/2006)	Mid season (5/09/2008)	Mid season (11/12/2008)
Monoculture chicory	7	10 *b*	57 *b*
Half monoculture chicory	8		
Wheat-chicory	7	16 *a*	35 *c*
Lupin-chicory	8	7 *c*	52 *b*
Canola-chicory		10 *b*	68 *a*
l.s.d (P<0.05)	n.s.	2.1	18.4
Monoculture lucerne	7 *b*	27 *b*	64 *b*
Half monoculture lucerne	9 *a*	33 *ab*	74 *a*
Wheat-lucerne	9 *a*	37 *a*	72 *ab*
Lupin-lucerne	9 *a*	32 *ab*	74 *a*
Canola-lucerne		33 *ab*	71 *ab*
l.s.d (P<0.05)	1.6	6.1	8.4

Table 6-8 Plant height (cm) of monoculture and intercrop pastures at site 2 in 2008

Treatment	Mid season (7/09/2008)	End season (11/12/2008)
Monoculture chicory	10 *b*	39
Wheat-chicory	16 *a*	49
l.s.d (P<0.05)	4.4	n.s.
Monoculture lucerne	35	67
Wheat-lucerne	37	70
l.s.d (P<0.05)	n.s.	n.s.

Note: Means within each treatment column followed by a different letter are significantly different (P<0.05)

Not significant = n.s.

6.4 Discussion

Soil moisture, light and nutrients are potential sources of intercrop resource competition that can cause reduced yields in one or more of the component species (Midmore 1993). In this study there were consistent differences in soil moisture associated with intercrop combinations compared to the monoculture components, indicating differences in patterns of water use. Soil moisture levels varied depending on the crop and pasture component combination. There were also some differences in Leaf Area Index (LAI) and plant height between intercrop combinations and the individual components. This discussion will focus on resource competition and how it affects grain and pasture yields of the intercrops.

Plant water use of monocultures in duplex soils

The crop and pasture species and combinations used in this study created different levels of access to soil moisture. These differences are likely to be a result of variations in root growth and resource capture. As such, it is important to consider the impact of site soil type on the performance of the species used in this study.

The properties of duplex soils are well reported, including their constraints on plant growth (Belford *et al.* 1992; Dracup *et al.* 1992). A texture change of greater than 1.5 between the acidic sandy loam A horizon and the alkaline clay B horizon, provides not only a physical barrier to root growth, but for species sensitive to high pH, their roots are unlikely to penetrate into the clay layer (Belford *et al.* 1992).

The roots of lupin are more sensitive to the pH of the alkaline clay layer (Dracup *et al.* 1992). As a result, it is likely the root growth of lupin was restricted once reaching the B horizon, thus resulting in it only utilising resources within the A horizon. If, by contrast, the wheat and canola had some access to the B horizon, this would have resulted in the observed differences in soil water use of the monoculture crops. This suggestion is supported by previous cropping studies on duplex soils, which have shown the maximum rooting depth of wheat and lupin is differentially affected, when compared to growing these species in soils of uniform texture (Hamblin & Tennant 1987). The root growth of wheat, canola and lupin is restricted into the clay B horizon of duplex soils. In a Western Australian situation, this resulted in less than 5% of soil water being extracted from this layer (Gregory 1998). There are also differences in the rooting depth of these species when grown on duplex soils. On a duplex soil with an A horizon depth of 70cm, wheat had a maximum rooting depth of 120cm and lupin 90cm (Hamblin & Tennant 1987). Rooting depths of 80cm->80cm for wheat, 60cm for lupin and 60-80cm for canola, is reported, in soil with a depth to the clay layer of 40cm (Gregory 1998).

In addition, it has also been shown that lupin has a greater requirement for soil moisture later in the season compared to wheat (White 1990). Given the dry seasons experienced in this current study, this could also have contributed to the greater yield reductions for lupin intercrops, as the overlap in resource requirements of the crop and pasture species would have been increased.

While wheat and canola root growth is restricted in duplex soils, lupin root growth appears to be more greatly affected. Restricted soil moisture availability, and the likely increased requirement for soil moisture late in the growing season of lupin resulting in greater grain yield reductions for lupin compared to that of wheat and canola.

There were no differences in soil moisture measured under monoculture lucerne and chicory at one site. However, there were differences measured at both 0-15cm and 0-35cm depths in all years at the other site. These differences ranged from an average of 9-13mm for 0-15cm depth and 13-25mm for 0-35cm depth. This indicates greater water use of lucerne, compared to chicory, within the A horizon. Despite these differences, the water use pattern was similar for the two pasture species.

While there were differences in water use of the pasture species, and it is likely that they were accessing water from the measured part of the soil profile, both species used less water during the growing season compared to the monoculture crops. Average additional water available under the monoculture pastures compared to the average of monoculture crops, ranged from 2-6mm at 0-15cm depth and 8-25mm at 0-35cm depth (July-October 2008). When soil cores were taken, chicory and lucerne roots were observed to extend beyond the core depth of 90cm. It is therefore likely that both species were accessing soil moisture from within the clay subsoil. Similarly, it has been reported that after initial establishment of lucerne and chicory (when they were reliant on soil moisture in the 0-75cm layer), the plants became more reliant on soil moisture found below 75cm (Hayes *et al.* 2010b).

Lucerne root growth can be reduced when grown in soils with clay subsoils (Dolling *et al.* 2003). Notwithstanding the possible slowing of lucerne root growth associated with subsoil constraints, lucerne can still extract soil moisture to depths of 1.5m on duplex soils (Latta *et al.* 2002). Impediments to root growth of chicory grown on duplex soils have not been described, but in a comparative study, chicory extracted water to depths of 1.9m, compared to lucerne, which extracted water to a depth of 2.3m (Brown *et al.* 2005).

Chicory also has a similar soil drying pattern to lucerne, measured to a depth of 170cm (Hayes *et al.* 2010b). These studies suggest chicory will have a similar root growth and soil drying pattern to that of lucerne in duplex soils.

Plant water use of intercrops

Intercrops differed in the way they accessed soil moisture, depending on both the crop and pasture component of the intercrop. When wheat was grown with lucerne (0-35cm depth), an additional 9-22mm of soil water was measured, compared to lupin grown with lucerne in the July to October period. However, when wheat was grown with chicory, there was a soil water deficit of 14-22mm compared to lupin grown with chicory in this same period.

Intercrop water use was also influenced by crop type. There were differences in soil moisture between monoculture lupin and lupin grown in intercrop. Within the July to October period, monoculture lupin was 13-26mm drier than the lupin-chicory intercrop, and 4-12mm drier than the lupin-lucerne intercrop, for 0-35cm depth. There were also differences between monoculture wheat soil moisture and that of intercropped wheat. Monoculture wheat had 6-12mm more soil water than the wheat-chicory intercrop (July to October) and 3-9mm for the wheat-lucerne intercrop (July to September). In contrast, there was generally no significant difference between soil moisture of the monoculture or intercropped canola. This indicates the differences in competition, and that capture of the water resource is dependent on both the crop and pasture species of the intercrop.

Plant competition for soil moisture

This study focused on soil moisture use within the A horizon, as this the part of the soil profile in which roots of the intercrops were expected to compete for resources. The results from Chapters 4 and 5 show competition resulted in yield reductions of both intercrop components. It was concluded that competition affecting crop performance occurred between September (cereal first node) and November (maturity) (Chapter 4), whilst for pastures, the effects of competition occurred by September for chicory and October for lucerne (Chapter 5).

This period of competition coincides with the period of moisture decline noted in this study, commencing in September/October. This was also the period of stem elongation (GS30-39) in the wheat. In the wheat intercrop treatments, there were no significant differences in the number of tillers per plant, yet there were fewer heads per m^2 (Chapter 4). Tiller decline in wheat was higher in the lucerne intercrop than chicory intercrop. This suggests competition for water during the stem elongation period, resulting in a greater loss of tillers in the intercrop treatments. This reduction in tiller number is consistent with the understanding of tiller retention. Most tiller loss is reported during stem elongation and head emergence growth stages (Davidson & Chevalier 1990). It was also reported that there was a greater loss of tillers in non-irrigated treatments than irrigated treatments during these growth stages, indicating the importance of soil water to tiller retention.

Lupin intercrop yield determinants were also affected during this same time (October). The greatest impact on yield determinants occurred during the floral phase of development, when branch number and pods per branch are determined.

These results suggest competition for water resulted in yield reductions, and was likely affected by lower than long-term average in-growing season rainfall experienced during the study period. Similarly, reductions in both grain and dry matter yields of the intercrop components were observed in a wheat-lucerne over-cropping study (Humphries *et al.* 2004). While there was no effect of lucerne competition for soil moisture (0-100cm) in one year, in a subsequent year when soil moisture became limiting and rainfall was low (October), there was a reduction in the biomass and grain yield of the wheat component, which was attributed to competition for water (Humphries *et al.* 2004). Additionally, there was a strong positive relationship between growing season rainfall and increases in over-cropping grain yield (Harris *et al.* 2007).

The pasture component of the intercrop was found to affect yields of the crop component of the intercrop. In wheat and lupin intercrops, yield reductions were least when the pasture component was chicory. The chicory monoculture was found to be more likely to have higher soil moisture than the intercrops, ranging from 6-49mm in the July to October period, for 0-35cm depth measurements. However, monoculture lucerne had higher soil moisture than the intercrops only in the September to October period, of 3-24mm. This suggests that chicory growing in intercrop is not likely to be competing as strongly for soil moisture as lucerne grown in intercrop. These results indicate that lower water use by chicory when intercropped, enables greater soil moisture access by the grain component of the intercrop. Consequently, there was higher dry matter production and grain yields of chicory intercrops compared to lucerne intercrops (Chapter 3).

Plant competition for light

Competition for light in over-cropping studies has been shown as a likely source of grain yield reductions (Harris *et al.* 2008a; Humphries *et al.* 2004).

Plant height was generally not negatively affected by intercropping in this study. Overall, plants grew taller when grown as an intercrop compared to their height when grown as monocultures. This is due to the ability of plants to change their canopy structure in response to the presence of another species (Keating *et al.* 2003).

There was also little evidence in LAI measurements to suggest competition for light in the majority of treatments. However, wheat-lucerne intercrop biomass (at first node) and wheat plant height results, in 2008, suggested there may have been some competition for light affecting yield in this season. There was also anecdotal evidence of competition for light between intercropped canola and the two pastures in 2007. In these two cases, which suggested there was a yield reduction as a result of light competition, there was an early reduction in the dry matter production of the suppressed species, and a minimal reduction in the dry matter production of the dominant species. This is supported by the understanding that competition for light would result in a slight reduction in dry matter production of the dominant species and a moderate reduction in dry matter produced by the suppressed species (Donald 1997). Previous intercropping studies have also shown this effect of shading by a dominant species (Cendekdee & Fukai 1992; Mariotti *et al.* 2009). Tall cassava varieties grown with soybean affected soybean yield, due to early growth of the cassava reducing solar radiation available to the soybean (Cendekdee & Fukai 1992). Likewise, competition for light resulted in reductions in cereal and lupin dry matter when intercropped with vetch, whilst dry matter production of vetch is unaffected (Mariotti *et al.* 2009).

Over-cropping studies have shown competition for light affects early season growth and early yield determinants, such as tiller number (Harris *et al.* 2008a; Humphries *et al.* 2004). In this current study, there were two cases where light competition may have resulted in yield reductions. Overall, the results did not show strong trends for early light competition and dry matter reductions, as indicated in previous over-cropping cereal-lucerne studies (Harris *et al.* 2008a; Humphries *et al.* 2004).

The low incidence of light competition in this study was likely due to the spatial design, and the influence this had on light interception. It has been shown that where a double alternate row design is used, the effects of shading are reduced (Chen *et al.* 2004; Mohta & De 1980). The yield of the suppressed species, soyabean, was found to improve when it was intercropped in a double row arrangement with *Zea mays* (maize) or *Sorghum bicolor* (sorghum), while yields of dominant species, maize and sorghum, were not affected by row spacing (Mohta & De 1980). In addition, pea yield (the suppressed species) was improved when row designs moved from a mixed row arrangement to a separated row arrangement (Chen *et al.* 2004).

These studies support the suggestion that early competition for light was generally reduced, due to the double row arrangement used in this study.

Summary

In this study, soil moisture became limiting during September/October. As soil moisture declined during these months, intercrop competition for water affected crop yield components and dry matter production of the crop and pasture species. The impact of intra-plant competition depended on both the pasture and crop component of the intercrop. There was a greater yield reduction in lupin grown in intercrop compared to wheat and canola, due to a likely restriction in lupin root growth, therefore resource capture was confined to the A horizon. Consequently, lupin was a poorer competitor compared to wheat and canola.

Yield reductions in the intercrop grain component were not as high in the chicory intercrops as in the lucerne intercrops (Chapter 4), and this is likely due to lower water use by chicory in the A horizon compared to that by lucerne, enabling greater access to soil water by the grain component of the intercrop.

There did appear to be some effect of competition for light in two of the intercrop combinations in one season, but generally light competition did not appear to affect the majority of intercrop combinations in this study. This is likely due to the similar height of the intercrop species and the ability of the component species to change their canopy structure when intercropped using a double alternate row arrangement. The results show that competition for water was the main contributor to yield reductions in this study.

Chapter 7. Effect of grazing on intercrop production

7.1 Introduction

While intercropping can increase overall system productivity, yield reductions of the grain component may make this system more suitable to a situation not reliant on grain production (Harris *et al.* 2007). As such, this part of the study has focused on the development of the intercropping system primarily for benefits to a grazing system in a mixed farming situation.

In order to increase the value of intercropping in a livestock system, there may be an opportunity to graze the intercrop early in the season, thereby increasing dry matter utilisation for grazing purposes. Grazing of cereal crops is a practice increasingly being adopted in southern Australia (Kelman & Dove 2009), as it provides an opportunity to fill the winter feed gap of the livestock enterprise on mixed farming properties.

Research has shown both negative and positive responses in grain yield when grazing wheat (McMullen & Virgona 2009; Virgona *et al.* 2006). Longer durations of grazing had a negative impact on grain yields of a grazed crop (Virgona *et al.* 2006). Yields were reduced when crops were grazed for 51 days however there was no impact on crop yield when grazed for 15 days. Seasonal conditions also appear to influence the impact that grazing has on grain yields. Yield reductions occurred when wheat was grazed after 'jointing' in one season. However, in another season, there was no reduction even when grazed after the 'flag leaf' stage (Worrell *et al.* 1992). This is supported by a study that reports that successful grazing of dual-purpose crops is reliant on factors including species selection, sowing date, time of grazing and stocking rate at grazing (Kelman & Dove 2009). To minimise the impact of grazing on grain yields, it is recommended that grazing does not continue beyond stem elongation (Kelman & Dove 2009; Winter & Thompson 1987). While grazing has been shown in some cases to reduce grain yields, the economic benefits can be improved compared to un-grazed treatments (Kelman & Dove 2007; Kirkegaard *et al.* 2008). However, there are no published studies on the effects of grazing crop-pasture intercrops.

The aim of this study, conducted in one season, is to determine if early sheep grazing of crop-pasture intercrops would impact on grain and biomass yields. In addition, the effect of grazing on productivity of the intercropping system will be assessed using LER as the indicator. The investigation of livestock grazing preferences, based on dry matter measurements, aims to provide an insight into whether this could affect the outcome of grazing intercrops.

Competition for soil moisture was found to affect yield and yield components of un-grazed intercrops (Chapter 6). This chapter will describe the role of grazing in determining if, under a grazing treatment, the sources or effects of resource competition differ from un-grazed treatments.

7.2 Materials and Methods

A description of the trial site, and the materials and methods, are presented in Chapter 3.

Grazing methodology

The grazing trial was conducted in 2008 at, site 2, on 2nd year pasture stands.

Ten sheep were randomly selected from a flock of Merino wethers (~12 months of age at selection). The sheep used had been previously exposed to the feed types in the experiment to prevent selective grazing due to lack of familiarity with a feed type. These sheep were weighed and condition scored (Department of Agriculture and Food Western Australia 2006; Jefferies 1961). Only sheep with a condition score of 3 or greater were used, ensuring the sheep were of the same weight and condition. Plots were grazed in August, January and February.

For the August grazing, the sheep were placed in three small "paddocks" (Figure 7-1). Paddocks 1 and 2 were ~400m^2 and had 4 sheep placed in each of the two paddocks, Paddock 3 was 200m^2 and had 2 sheep placed in it. The stocking rate was 100 sheep/ha (100 DSE/ha). Each paddock contained a water trough. In January and February the "paddock" fences were removed and sheep grazed the site as a whole. Sheep numbers were increased to 20 in order to maintain the same stocking rate (100 DSE/ha) as the August grazing.

Sheep were checked daily and when one of the following occurred all sheep were removed: Available feed reached between 500-1000kgDM/ha; wheat plants reached growth stage 30 (Zadoks *et al.* 1974); or the animals showed any signs of distress. For each grazing, sheep were removed due to available feed reducing to between 500-1000kgDM/ha.

The August grazing started on 11/8/2008 and concluded on 18/8/2008. Dry matter measurements were taken on 13/8/2008, 15/8/2008 and 18/8/2008. January grazing started on 26/1/2009 and concluded on

31/01/2009, with dry matter measurements taken at these two times. February grazing started on 23/2/2009 and concluded on 3/3/2009, with dry matter measurements taken on these two dates.

The herbage taken at each sampling time was sorted into species, then dried and weighed.

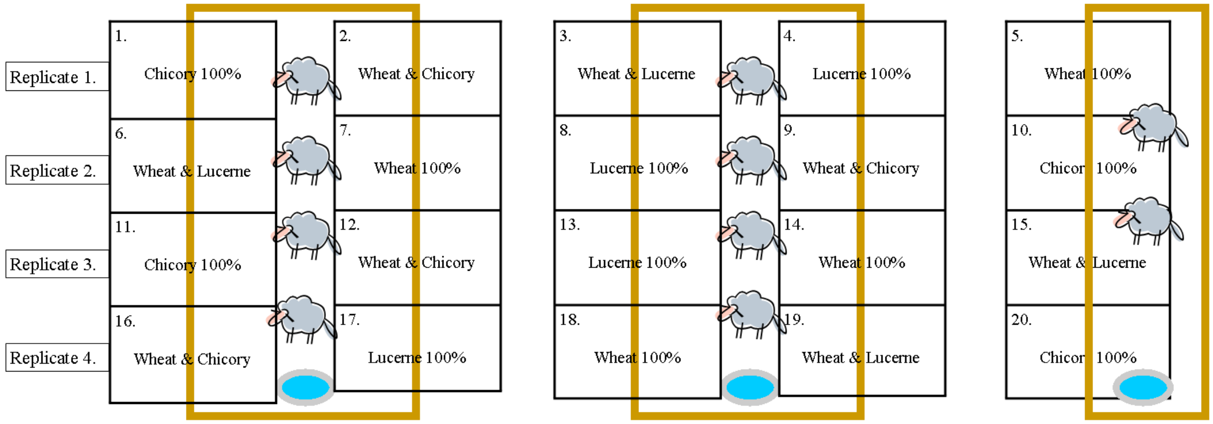


Figure 7-1 The grazing trial site showing paddock divisions (brown) under the grazing treatments, the number of sheep and watering points in August at site 2 in 2008

7.3 Results

7.3.1 Crop grain yields

There was no significant interaction between treatment and grazing.

Grain yields for the grazed monoculture wheat and wheat intercrops were significantly lower ($P<0.05$) than that of the un-grazed treatments (Table 7-1). Monoculture wheat had higher grain yields ($P<0.05$) than the intercrops (Table 7-1). The intercrop yields were not significantly different from each other (Table 7-1).

The percentage of the monoculture grain yield did not differ between grazing treatments for the wheat-chicory intercrop. By contrast, the percent of monoculture grain yield was lower in the grazed wheat-lucerne intercrop compared to the un-grazed treatment (Table 7-1)

Table 7-1 Wheat grain yield (t/ha) of grazed and un-grazed monoculture and intercrop treatments

Treatment		Grazed	Percent of Monoculture	Un-grazed	Percent of Monoculture
Monoculture wheat		3.10		4.59	
Wheat-lucerne		1.48	48%	2.48	54%
Wheat-chicory		1.76	57%	2.65	58%
l.s.d (P<0.05)	Treatment		0.542		
	Grazing		0.442		

7.3.2 Crop dry matter production

Crop dry matter production was higher ($P<0.05$) in the monoculture wheat than in the lucerne and chicory intercrops (Table 7-2).

There was a significant interaction between treatment and grazing in November (Table 7-2). The dry matter production was higher ($P<0.05$) in the un-grazed treatment for monoculture wheat and wheat-lucerne intercrop than the grazed treatment, while the dry matter production was lower ($P<0.05$) in the un-grazed compared to grazed treatments for wheat-chicory intercrop (Table 7-2). In contrast there was no significant interaction between treatment and grazing in December (Table 7-2). In December, dry matter production was higher ($P<0.05$) in the un-grazed treatment compared to the grazed treatment (Table 7-2).

There were no significant interaction effect between treatment and grazing in November and December for cumulative dry matter production, which included dry matter removed by grazing (Table 7-3). Cumulative dry matter production was higher ($P<0.05$) in the monoculture wheat then the intercrops (Table 7-3). In December, there was more cumulative dry matter produced by the un-grazed treatment compared to the grazed treatments (Table 7-3).

There was a positive relationship between crop dry matter at anthesis (r^2=0.67 and r^2=0.74; $P<0.05$) and maturity (r^2=0.87 and r^2=0.79; $P<0.05$), and between grain yield of both the grazed and un-grazed treatments (Figure 7-2).

Table 7-2 Wheat dry matter (kg/ha) production of grazed and un-grazed treatments for each collection point during the crop growing season

Treatment and Date	Grazed	Un-grazed	l.s.d (P<0.05 Treatment	l.s.d (P<0.05) Grazing	l.s.d (P<0.05) Treatment.Grazing
18/08/2008					
Monoculture wheat		1618	519.7		
Wheat-lucerne		971			
Wheat-chicory		777			
12/11/2008					
Monoculture wheat	9646	12848	1705.0	1392.1	2411.2
Wheat-lucerne	4348	7623			
Wheat-chicory	5989	5299			
16/12/2008					
Monoculture wheat	9734	12501	1313.0	1072.0	
Wheat-lucerne	4504	8545			
Wheat-chicory	4264	7827			

Table 7-3 Cumulative (including dry matter removed by grazing) wheat dry matter (kg/ha) production of grazed and un-grazed treatments for each collection point during the crop growing season

Treatment and Date	Grazed	Un-grazed	l.s.d (P<0.05 Treatment	l.s.d (P<0.05) Grazing
18/08/2008				
Monoculture wheat		1618	286.3	
Wheat-lucerne		971		
Wheat-chicory		777		
12/11/2008				
Monoculture wheat	11199	12848	1729.9	1412.5
Wheat-lucerne	5242	7623		
Wheat-chicory	6654	5299		
16/12/2008				
Monoculture wheat	11287	12501	1305.1	1065.6
Wheat-lucerne	5398	8545		
Wheat-chicory	4929	7827		

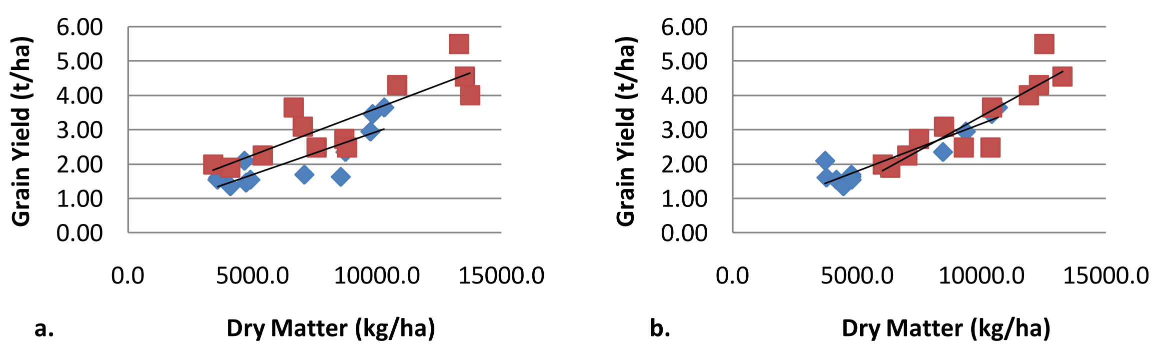


Figure 7-2 Wheat crop dry matter and yield at (a) anthesis (b) maturity and wheat grain yield for ◆ grazed and ■ un-grazed treatments

7.3.3 Grain quality

There was no significant interaction between treatment and grazing for either screenings or protein.

There were significantly higher screenings in the grazed treatment than the un-grazed treatments. There was no significant difference in screenings between monoculture wheat and wheat-lucerne intercrop (Table 7-4). In contrast, the wheat-chicory intercrop had lower screenings (P<0.05) than the monoculture wheat and wheat-lucerne intercrop (Table 7-4).

Protein did not differ significantly between the grazed and un-grazed treatments. The wheat-chicory intercrop had lower protein (P<0.05) than the wheat monoculture and wheat-lucerne intercrop (Table 7-4).

Table 7-4 Wheat screenings (%) and protein (%) for grazed and un-grazed monoculture and intercrop treatments

	Monoculture wheat	Wheat lucerne	Wheat chicory	l.s.d (P<0.05) Treatment	l.s.d (P<0.05) Grazing
Screenings					
Grazed	2.6	4.2	1.4	0.87	0.71
Un-grazed	2.3	2.2	1.1		
Protein					
Grazed	12.56	13.17	10.38	1.432	1.170
Un-grazed	12.69	11.66	10.45		

7.3.4 Grain yield components

There was no significant interaction between treatment and grazing for grain yield components.

Tillers

There was no significant difference between the grazed and un-grazed treatments for tiller numbers (Table 7-5). There was also no significant difference between treatments for the number of tillers produced per plant (Table 7-5).

Heads/m^2

There were no significant differences in heads per m^2 between grazed and un-grazed treatments (Table 7-5). The lucerne and chicory intercrops had less heads per m^2 ($P<0.05$) than the monoculture wheat (Table 7-5).

1000 grain weights

There was no significant difference between the grazed and un-grazed treatments for TGW (Table 7-5). The wheat-chicory intercrop had higher TGW ($P<0.05$) than the wheat monoculture and wheat-lucerne intercrop (Table 7-5). The TGW of the wheat-lucerne intercrop and monoculture wheat were not significantly different from each other (Table 7-5). No relationship was found between grain weight and grain yield (Figure 7-3).

Grains/head, spikelets/head and grains/spikelet

Grains per head and spikelets per head were lower ($P<0.05$) in the grazed treatments than in the un-grazed treatments (Table 7-5).

The wheat-chicory intercrops had fewer grains per head ($P<0.05$) than the monoculture wheat and wheat-lucerne intercrop (Table 7-5). The wheat-chicory intercrop also had less spikelets per head ($P<0.05$) than monoculture wheat (Table 7-5). There were more grains per spikelet in the un-grazed treatment than the grazed treatment. The wheat-chicory intercrop had fewer grains per spikelet than the monoculture wheat and wheat-lucerne intercrop (Table 7-5).

Heads/m^2 and grains/m^2

There were positive relationships between both heads/m^2 ($r^2=0.64$ and $r^2=0.58$; $P<0.05$) and grains/m^2 ($r^2=0.69$ and $r^2=0.67$) with grain yield for grazed and un-grazed treatments, but there was not with TGW (Figure 7-3).

Table 7-5 Wheat grain yield components including, tillers, heads/m^2, 1000 grain weight (g), grains/head, spikelets/head and grains/spikelet, for grazed and un-grazed treatments

	Monoculture wheat	Wheat-lucerne	Wheat-chicory	l.s.d (P<0.05) Treatment	l.s.d (P<0.05) Grazing
Tillers					
Grazed	5	4	3	1.00	0.80
Un-grazed	4	4	4		
Heads per m^2					
Grazed	356	176	217	51.5	63.1
Un-grazed	407	217	177		
1000 Grain Weight					
Grazed	34.9	30.5	38.7	3.23	2.63
Un-grazed	34.4	34.5	39.3		
Grains per head					
Grazed	25	23	20	3.4	2.7
Un-grazed	32	29	24		
Spikelets per head					
Grazed	11	11	10	0.9	0.8
Un-grazed	13	12	11		
Grains per spikelet					
Grazed	2.13	2.04	1.89	0.057	0.047
Un-grazed	2.36	2.25	2.05		

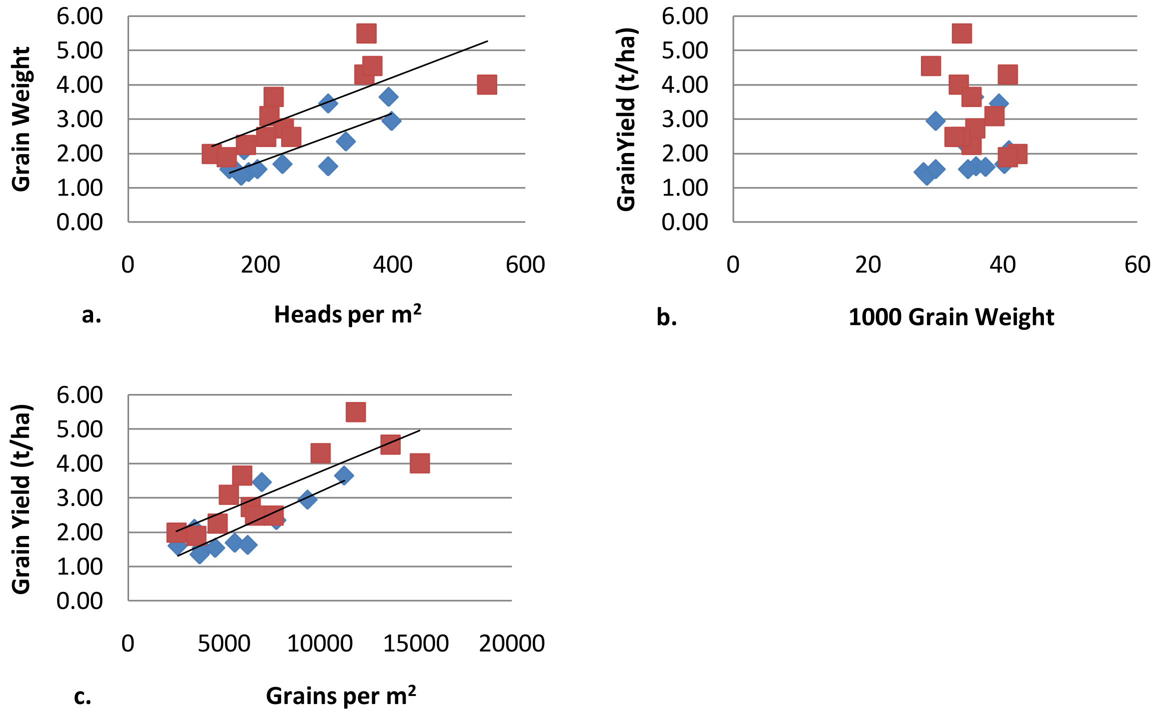


Figure 7-3 Wheat grain yield (t/ha) and (a) Heads per m^2 (b) TGW (c) Grains per m^2. Grazed wheat = ◆ Un-grazed wheat = ■

7.3.5 Pasture dry matter yields

Seasonal and annual totals

There was no significant interaction between treatment and grazing for seasonal or annual totals. There was no significant difference between grazed and un-grazed treatments for in-growing season, out-growing season or annual dry matter production (Table 7-6).

Monoculture lucerne and chicory produced more dry matter (P<0.05) within the growing season than the intercrop treatments did (Table 7-6). Monoculture lucerne had lower (P<0.05) out-of-growing season dry matter production than monoculture chicory, and the intercrops (Table 7-6). There was no significant difference of grazing or treatment for annual dry matter production (Table 7-6).

Cumulative production

There was no significant interaction between treatment and grazing for any of the measurement points for cumulative dry matter production. There was also no effect of grazing on cumulative dry matter production at any measurement point.

Monoculture lucerne produced more dry matter (P<0.05) than the intercrop and monoculture chicory when measured on 18/8/2008 (Table 7-7). Monoculture chicory produced more dry matter (P<0.05) than the lucerne and chicory intercrops in August (Table 7-7). Monoculture lucerne produced more dry matter in November (P<0.05) than monoculture chicory and the intercrops, with the intercrops having lower production (P<0.05) than the monoculture chicory (Table 7-7). In December, the monoculture lucerne and chicory produced more dry matter (P<0.05) then the intercrops (Table 7-7). Dry matter production measured in January was higher in the monoculture chicory and both intercrops than the monoculture lucerne (Table 7-7). The wheat-lucerne intercrop had higher dry matter (P<0.05) when measured in February than the wheat-chicory intercrop and both monoculture treatments (Table 7-7). Dry matter production in March was higher (P<0.05) in both the monoculture chicory and chicory intercrop compared to the monoculture lucerne and lucerne intercrop (Table 7-7).

Table 7-6 Seasonal and annual dry matter production of grazed and un-grazed pasture treatments

Treatment	Grazed	Un-grazed	l.s.d (P<0.05) Treatment	l.s.d (P<0.05) Grazing
In-Growing Season				
Monoculture lucerne	6052		1546.8	1089.5
Wheat-lucerne	3039	2724		
Monoculture chicory	5107			
Wheat-chicory	3402	3017		
Out-Growing Season				
Monoculture lucerne	2295		658.5	465.6
Wheat-lucerne	3484	4613		
Monoculture chicory	3581			
Wheat-chicory	4295	3518		
Annual Production				
Monoculture lucerne	8347		1470.2	1039.6
Wheat-lucerne	6524	7336		
Monoculture chicory	8688			
Wheat-chicory	7698	6535		

Table 7-7 Dry matter measurements for grazed and un-grazed treatments, taken for the 2008 season

Date	Treatment	Grazed	Un-grazed	l.s.d (P<0.05) Treatment	l.s.d (P<0.05) Grazing
18/08/2008	Mono lucerne		2017	432.3	
	Wheat-lucerne		1162		
	Mono chicory		1323		
	Wheat-chicory		608		
12/11/2008	Mono lucerne	5486		940.6	665.1
	Wheat-lucerne	3473	2421		
	Mono chicory	4445			
	Wheat-chicory	2532	2255		
16/12/2008	Mono lucerne	6052		1540.8	1089.5
	Wheat-lucerne	3039	2724		
	Mono chicory	5107			
	Wheat-chicory	3402	3017		
26/01/2009	Mono lucerne	1430		513.5	363.1
	Wheat-lucerne	1887	2754		
	Mono chicory	2723			
	Wheat-chicory	2577	2508		
24/02/2009	Mono lucerne	718		536.1	379.1
	Wheat-lucerne	1431	1693		
	Mono chicory	500			
	Wheat-chicory	1265	648		
6/05/2009	Mono lucerne	148		89.6	63.4
	Wheat-lucerne	166	166		
	Mono chicory	358			
	Wheat-chicory	454	362		

Note: Mono = monoculture

7.3.6 Species selection

August

After the first period of grazing, there were lower intakes (P<0.05) of the chicory component of the wheat-chicory intercrop compared to the monoculture wheat, the lucerne component of the wheat-lucerne intercrop, and the wheat component of the two intercrops (Table 7-8). There was also less dry matter removed (P<0.05) in the monoculture lucerne, compared to the monoculture wheat.

Following the second period of grazing, there was the same effect of lower consumption (P<0.05) of the chicory grown intercrop, compared with monoculture wheat and all other wheat intercrop components (Table 7-8). There was also greater removal of dry matter (P<0.05) of wheat intercropped with chicory and monoculture wheat, compared to monoculture chicory (Table 7-8). Similarly, there was lower intake (P<0.05) of monoculture lucerne compared to the wheat component of the wheat-lucerne intercrop, and monoculture wheat (Table 7-8).

Similarly, after the third (final) measurement, there was lower consumption (P<0.05) of chicory grown in intercrop with wheat, compared to monoculture wheat and both components of the wheat-lucerne intercrop (Table 7-8). Dry matter removal was lower (P<0.05) in the monoculture lucerne, compared to monoculture wheat and both components of the wheat-lucerne intercrop (Table 7-8). There was also a lower intake (P<0.05) of monoculture chicory, compared to the wheat component of the wheat-chicory intercrop (Table 7-8).

January

There was lower intake (P<0.05) of the monoculture lucerne compared to monoculture chicory and the lucerne grown in intercrop with wheat (Table 7-8).

February

In February, sheep grazed the site evenly to cutting height; therefore there are no significant intake differences between species.

Table 7-8 Grazing preferences (amount consumed of each species) show as a proportion of the starting value dry matter for each grazing

				Wheat-lucerne		Wheat-chicory		
Date	Monoculture lucerne	Monoculture chicory	Monoculture wheat	Wheat	Lucerne	Wheat	Chicory	l.s.d (P<0.05)
August								
1st: 13/08/2008	0.15	0.26	0.5	0.47	0.39	0.38	0.05	0.324
2nd: 15/08/2008	0.43	0.28	0.74	0.77	0.58	0.72	0.22	0.228
3rd: 18/8/2008	0.81	0.68	0.96	0.92	0.96	0.86	0.72	0.141
January								
31/01/2009	-0.65	0.51			0.31		0.04	0.705

7.3.7 Soil moisture

Soil moisture to a 15cm depth in grazed treatments

The treatment by grazing comparison shows lower soil moisture (2mm; $P<0.05$) at a 0-15cm depth in the grazed wheat-chicory intercrop treatment than the un-grazed treatment (Figure 7-4). In contrast, the wheat-lucerne intercrop had higher soil moisture (4mm; $P<0.05$) in the grazed treatment than the un-grazed (Figure 7-4). There was no significant difference in soil moisture of the monoculture treatments for this analysis.

The date by treatment comparison for grazed treatments shows that on 30/9/2008 and 26/11/2008, monoculture chicory had higher soil moisture ($P<0.05$) than the monoculture crops; and monoculture chicory was also higher ($P<0.05$) than the wheat-chicory intercrop on 30/9/2008 (Figure 7-5).

Soil moisture to a 35cm depth in grazed treatments

There was no treatment by grazing effect at 35cm (Appendix 4).

The date by treatment comparison for grazed treatments at 0-35cm shows monoculture chicory consistently had higher soil moisture ($P<0.05$) than the wheat-chicory intercrop (Figure 7-6). Monoculture chicory also had higher soil moisture ($P<0.05$) compared to monoculture lucerne throughout the season, and higher than the monoculture wheat on 30/9/2008 and 26/11/2008 (Figure 7-6).

Soil moisture in un-grazed treatments

Summary, full un-grazed results are presented in Chapter 6 (Figure 6-5, Figure 6-6, Figure 6-7 and Figure 6-8).

Monoculture chicory had higher soil moisture ($P<0.05$) at 0-15cm than monoculture lucerne on 23/6/2008, 30/9/2008 and 26/11/2008. Monoculture chicory also had higher soil moisture ($P<0.05$) compared to the wheat-chicory intercrop on 23/6/2008 and 30/9/2008.

The wheat-lucerne intercrop had higher soil moisture ($P<0.05$) at 0-35cm than the monoculture treatments on 30/9/2008. In contrast, soil moisture measured under monoculture chicory was higher ($P<0.05$) than monoculture lucerne and the wheat-chicory intercrop from 23/6/2008 to 26/11/2008.

Figure 7-4 Treatment by grazing soil moisture measurements taken from 0-15cm at Site 2 in 2008

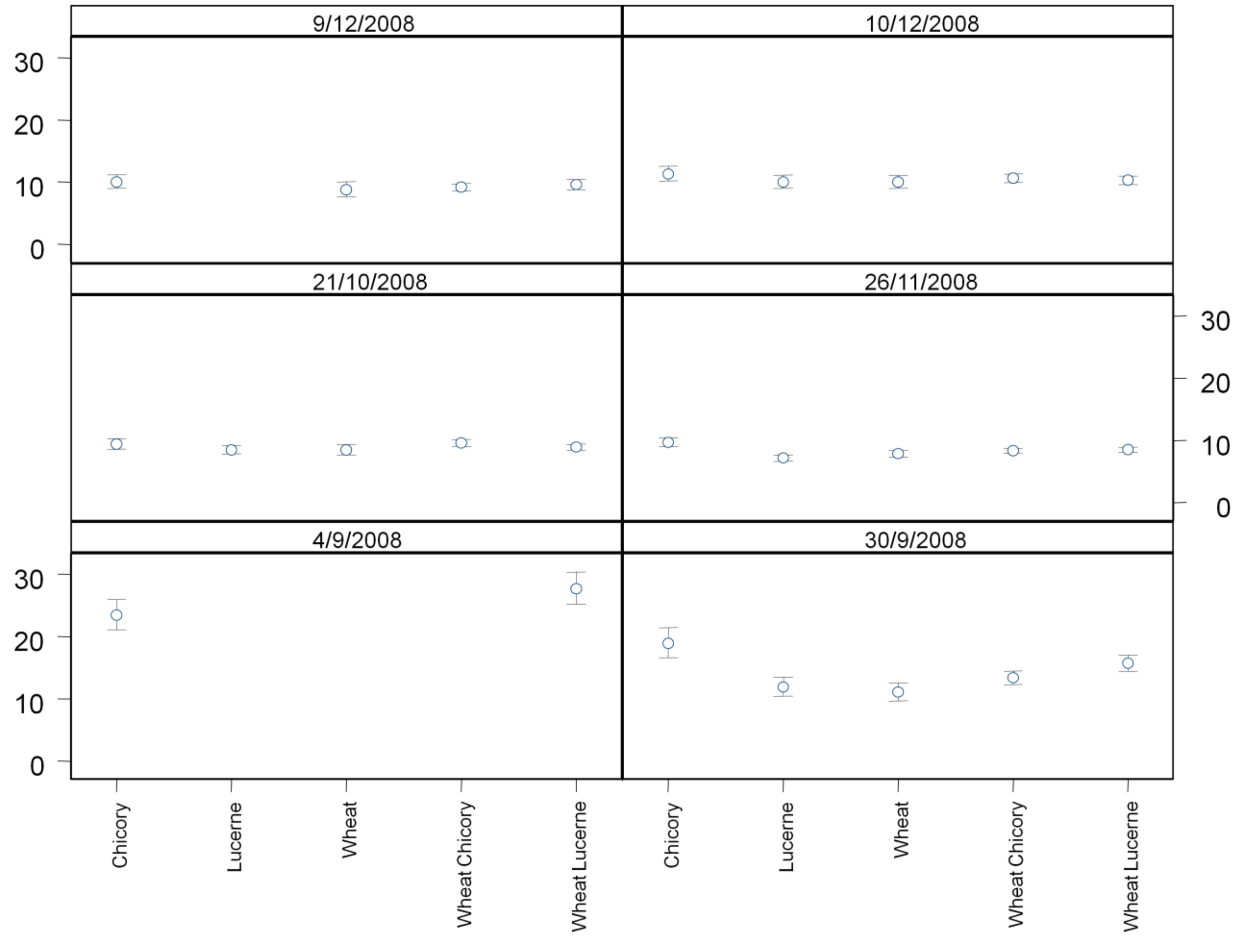


Figure 7-5 Date by treatment soil moisture measurements for grazing treatments, taken from 0-15cm at Site 2 in 2008

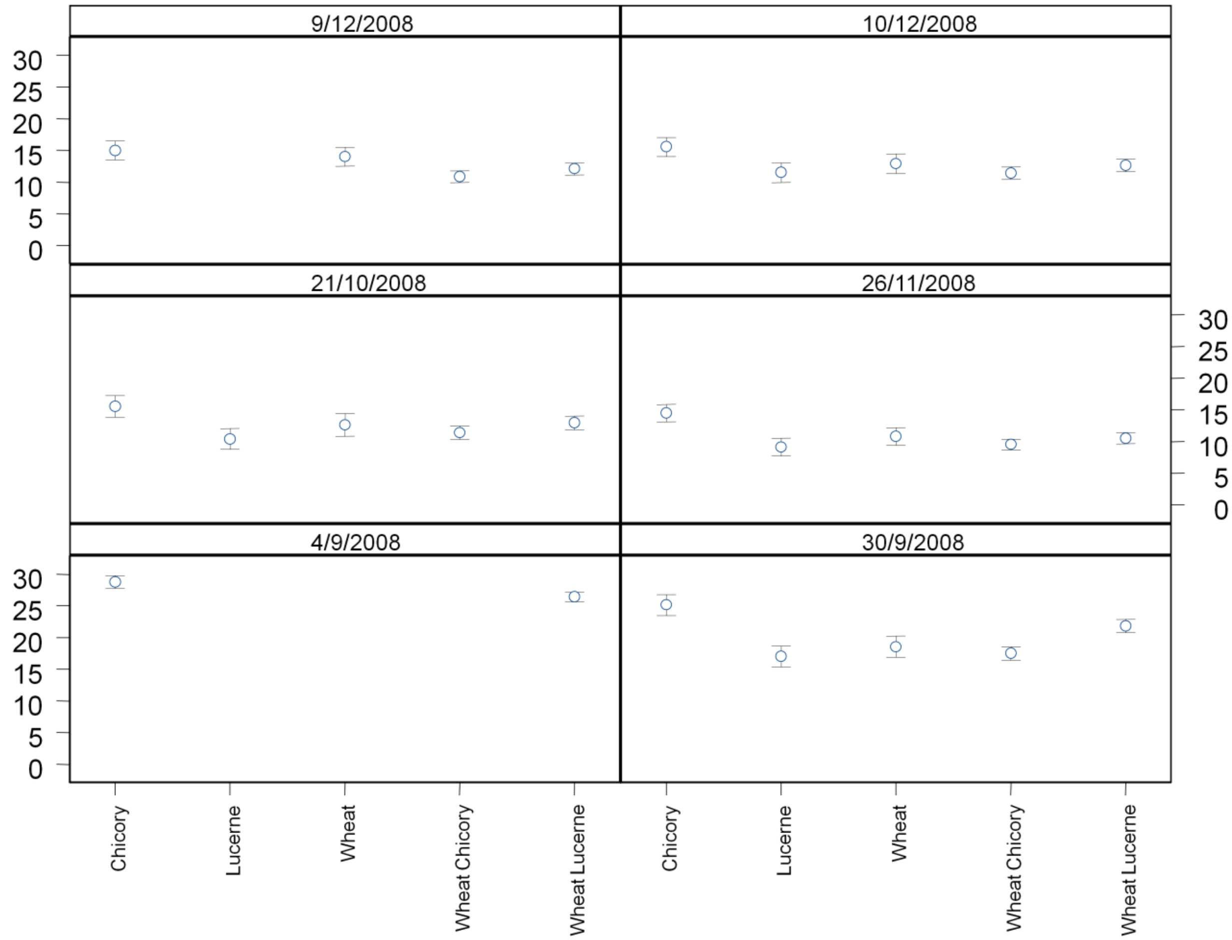


Figure 7-6 Date by treatment soil moisture measurements for grazing treatments, taken from 0-35cm at Site 2 in 2008

7.3.8 Plant height

There was no significant interaction between treatment and grazing for plant height.

Wheat plant height was reduced ($P<0.05$) in the wheat monoculture and intercrop treatments under the grazed treatments, compared to the un-grazed treatments, in September and December (Figure 7-7).

Plant height of the pasture components of the intercrops, and that of the pasture monoculture treatments were lower ($P<0.05$) in the grazed treatments compared to the un-grazed treatments when measured in September (Figure 7-8). However, in December there was no difference in plant heights of the pasture species in the grazed and un-grazed treatments (Figure 7-8).

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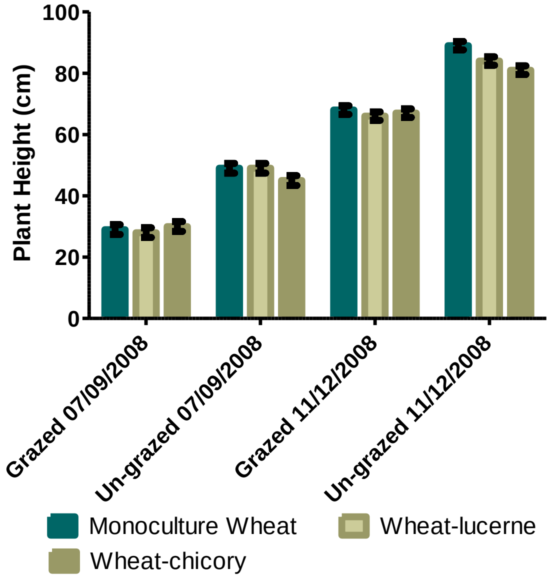

Figure 7-7 Wheat plant height measurements for grazed and un-grazed treatments.

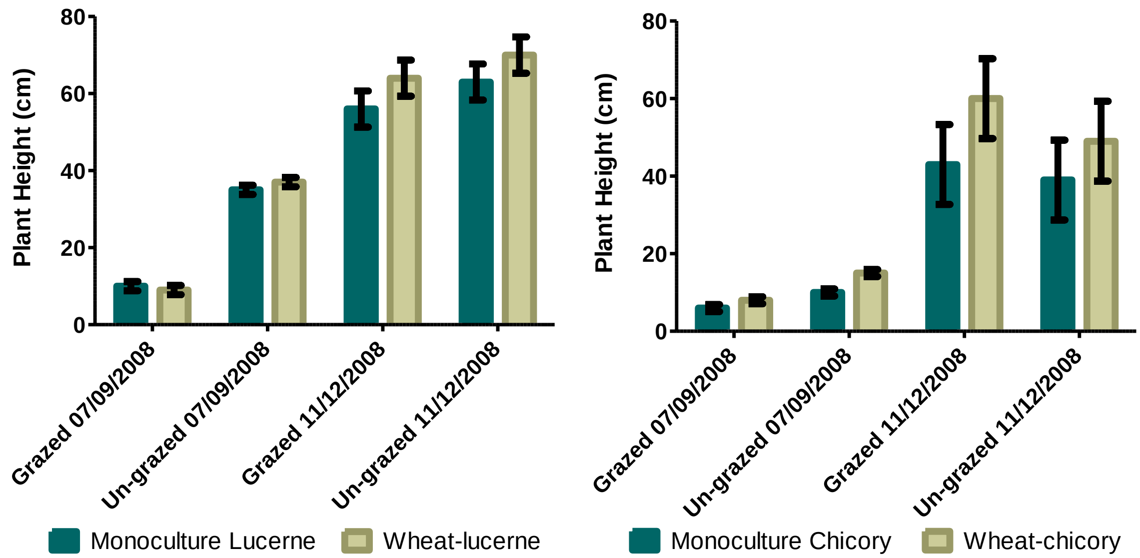

Figure 7-8 Plant height (cm) of (a) lucerne and (b) chicory grazed and un-grazed treatments.

Note: Error bars represent plus and minus the standard error of means.

7.3.9 Land Equivalent Ratios (LER)

Within the growing season, un-grazed intercrops had higher dry matter production LER than grazed intercrops (Table 7-9). The wheat-lucerne intercrop had the highest LER in the un-grazed treatment and the wheat-chicory intercrop had the highest in the grazed treatment (Table 7-9).

The annual total LER was greater than 1.0 for all treatments (Table 7-9). The un-grazed wheat-chicory intercrop and grazed wheat-lucerne intercrop had the highest annual LER, followed by the grazed wheat-lucerne intercrop and un-grazed wheat-chicory intercrop (Table 7-9).

LER based on economic values shows that both grazed lucerne and grazed chicory intercrops had higher LER values than the un-grazed treatments (Table 7-10).

Table 7-9 Growing season and annual total LERs, based on dry matter production, for grazed and un-grazed treatments

	LER Growing Season			LER Annual Total		
Treatment	Wheat component	Pasture component	LER	Wheat component	Pasture component	LER
Grazed						
Wheat-lucerne	0.47	0.50	**0.97**	0.47	0.78	**1.25**
Wheat-chicory	0.59	0.67	**1.26**	0.59	0.89	**1.48**
Un-grazed						
Wheat-lucerne	0.59	0.45	**1.42**	0.59	0.88	**1.47**
Wheat-chicory	0.41	0.59	**1.33**	0.41	0.75	**1.16**

Table 7-10 Economic LERs, based on wheat grain yield and crop and pasture dry matter available for stock consumption (excluding stubble), for grazed and un-grazed treatments

Treatment	Wheat component	Wheat DM component	Pasture component	LER
Grazed				
Wheat-lucerne	0.48	0.58	0.78	**1.83**
Wheat-chicory	0.57	0.43	0.89	**1.88**
Un-grazed				
Wheat-lucerne	0.54		0.88	**1.42**
Wheat-chicory	0.58		0.75	**1.33**

7.4 Discussion

The impact of grazing on crop yield

Grazing of wheat-lucerne and wheat-chicory intercrops resulted in wheat grain yield reductions of 34% for chicory intercrops and 40% for lucerne intercrops. This contrasts with a 32% reduction in the grain yield of grazed monoculture wheat.

Previous cereal grazing studies have reported large variations in the effect of grazing on grain yields, with changes ranging from -27.9 to 29.4% (Virgona *et al.* 2006). The results from this present study are at the most severe range of grain yield reductions reported.

Wheat dry matter measured at anthesis and maturity was generally lower in all grazed treatments. It is likely this reduction in dry matter would mean less assimilates are available during the grain fill period, consequently causing grain yields to be reduced. This assertion is supported by previous wheat grazing studies where reductions in dry matter production at anthesis, due to grazing, gave subsequent reductions in grain yield, highlighting the importance of pre-ear emergence photosynthesis and relocation of assimilates (Dann 1968; Dann *et al.* 1983). This is consistent with information reported on the development of grain dry matter, and the importance of stem assimilates in determining grain yield (Pheloung & Siddique 1991).

When dry matter production of the grazed wheat crop was adjusted to include the sum of dry matter removed by grazing, the overall dry matter production of the grazed wheat crop was still lower than un-grazed treatment. Thus, there was either limited resources post-grazing inhibiting the recovery of grazed monoculture and intercropped wheat, or grazing damaged the reproductive organs of the wheat, resulting in a lower yield potential. Grazing undertaken in this study did not continue past GS30, which is the critical growth stage after which grain yield reductions occur if wheat is grazed during stem elongation (Winter & Thompson 1987; Worrell *et al.* 1992). Additionally, tiller and head numbers/m^2 were unaffected by grazing, so it is unlikely that grazing damaged the plant reproductive meristem.

There was a positive relationship between wheat biomass, at both anthesis and maturity, and grain yield, irrespective of grazing treatment. This relationship has also been reported in a winter wheat grazing study that showed a positive correlation between grain yield and biomass (Winter & Thompson 1987). Similarly, post-grazing dry matter, in addition to the amount of dry matter removed by grazing, was found to be negatively related to grain yield (McMullen & Virgona 2009).

The results show that grazing has both a direct and independent affect on the grain and dry matter yields of the monoculture and intercrop treatments. The reduction in biomass at maturity, due to grazing reducing the amount of non-structural dry matter present at maturity that could contribute to grain fill, is the likely cause of grain yield reduction in this study.

Effect of grazing on crop yield components

Grain yield components provide an insight into the timing of competition (Chapter 5). For both grazed and un-grazed treatments, there was fewer heads/m^2 in the intercrops, compared to monoculture wheat. However, there was no difference in heads/m^2 between grazed and un-grazed treatments. This is also reported in another winter wheat grazing study, where tiller density at heading was not affected by the grazing treatment, but there was a reduction in biomass, LAI and ground cover (Winter & Thompson 1987). In the present study, there was a relationship between both heads/m^2 and grains/m^2, and wheat grain yield. This result is supported by reports that grazing affects grains/head and grains/m^2, which are strongly related to yield (Dann *et al.* 1983; Kelman & Dove 2009; Virgona *et al.* 2006).

The large difference in yield between grazed and un-grazed treatments is likely due to a reduction in the number of grains/head, as a result of less spikelets/head. This assertion is consistent with previous wheat grazing studies. Previous studies have reported that the reduction in yield components is due to stress, particularly water, during critical phases of development. A reduction in yield components was associated with a delay in tiller development, resulting in grain fill of the grazed crop occurring during a period of greater moisture stress than in the un-grazed crop (Dann *et al.* 1983). In the reverse situation, where there are greater seeds/head in the grazed treatment than the un-grazed treatment, this increase is thought to be a reflection of the seasonal conditions at pollination, with greater water stress occurring when the un-grazed treatments were pollinating (Worrell *et al.* 1992). Additionally, under more severe grazing, wheat heads/m^2 and seed weight is negatively affected (Winter & Thompson 1990). These results indicate that additional stress in the current study is likely due to seasonal conditions, grazing conditions, and competition in the intercrops, which causes a reduction in the yield components (grains/head and spikelets/head).

In addition to the reduction in grains/head and spikelets/head due to grazing, TGW was reduced in the grazed wheat-lucerne intercrops, and screenings were also higher. This indicates there was greater competition for resources in the grazed wheat-lucerne intercrop, which continued late into the wheat growing season. Similarly, lower grain weights, in addition to fewer heads, has been observed in grazed winter wheat when the crops were grazed beyond the second-node stage or jointing, depending on the season (Worrell *et al.* 1992). Lower TGW was reported as the main cause of grain yield reductions in a study that simulated grazing through clipping (Dann 1968). Lower TGW was also reported in a wheat grazing study that attributed it to increased stress during grain-fill (Dann *et al.* 1983).

These results show additional stress experienced by the wheat-lucerne intercrop likely due to competition for water post-grazing resulted in a reduction in grain quality not observed in the wheat-chicory intercrop or monoculture wheat.

Reduction in grain yields in this study has been attributed to a reduction in dry matter at anthesis, which reduced assimilates available at grain fill. This indicates that limited resources, particularly water, during the post-grazing period, limited wheat biomass recovery. This assertion is supported by previous dual-purpose grazing studies.

The inability of the wheat crop to recover dry matter after grazing has been suggested, in one instance, to be due to limited water in the post-grazing period (McMullen & Virgona 2009). It is also reported that pre-anthesis plant reserves is the dominant source of assimilates for grain production in un-grazed crops (Virgona *et al.* 2006). This is in contrast to more prolonged grazing treatments where there is a greater reliance on post-anthesis growth, which may be due to many factors including differences in maturity time (Virgona *et al.* 2006). Ranges in the yield response to grazing are attributed to differences in seasonal rainfall, particularly in the post-grazing period, with moisture stress in this period reported to result in limitations to plant growth (Kelman & Dove 2009). Lower growth rates, due to reductions in LAI resulting from soil water limitations, have also been reported (Harrison *et al.* 2008). It is also shown that growth rates of grazed crops did not increase to compensate for the dry matter removed by grazing.

The delay in grazed wheat crop development, as noted in this study, is consistent with reports in previous studies where for every 4-5 days of grazing there is a 1-day delay in the crop reaching anthesis and maturity (Dann *et al.* 1983; Virgona *et al.* 2006; Winter & Thompson 1990). A delay in crop development, associated with reductions in yield, is likely to be due to the crop encountering unfavourable conditions such as water and heat stress later in the season. It is therefore likely that the reduction in grain yields of the wheat intercrops and monoculture wheat was associated with limited water during the post-grazing period.

The impact of grazing on the pasture component of the intercrop

The impact of grazing on the pasture component of a crop-pasture intercrop differed between the two pasture species. Despite this, grazing did not appear to change their relative competitiveness. In both the grazed and un-grazed treatments, there was greater yield reduction in wheat grown with the lucerne compared to that grown with chicory.

Overall, the annual dry matter production of lucerne and chicory was unchanged, irrespective of grazing treatment. There was however, a reduction in dry matter production of lucerne in the out-of-growing season compared to monoculture chicory and both intercrop treatments.

There was no difference in the dry matter production of grazed and un-grazed chicory intercrop during the growing season. This, combined with the reduction in grazed wheat production, indicates there was likely to have been reduced water use during the growing season. A lower relative water use of the wheat-chicory intercrop during the wheat growing season would most likely explain the higher dry matter production of the chicory component outside of the wheat growing season.

The effect of selective grazing

Sheep grazing the intercrop in August consistently showed a selective preference to graze the wheat, grown both in monoculture and intercrop, compared with the lucerne and chicory. Sheep showed the lowest preference for grazing the chicory component of the wheat-chicory intercrop. When the sheep were again introduced to plots in January and February, there appears to be no preferential grazing between the pasture species.

The preference by stock to selectively graze wheat during the growing season may have resulted in a slower recovery of this species post-grazing. Severe grazing using 100 sheep/ha (100 DSE/ha), as was undertaken in this study, is reported to be an important factor in yield reductions in previous studies. A high stocking rate grazing trial reported that the crash grazing technique, short grazing duration at high stocking rates of 240-740 sheep/ha, caused reductions in grain yield (Dann *et al.* 1977). Other studies have reported that longer grazing periods had a greater impact on yield due to slower crop growth rates and LAI recovery, post-grazing (Harrison *et al.* 2008; Virgona *et al.* 2006).

These results suggest that in addition to seasonal conditions, grazing preference and intensity may have influenced yield results.

Soil moisture and plant height of grazed intercrops

In the intercrops the only grazing effects on soil moisture were seen in the 0-15cm depth measurements. There was 2mm less soil moisture in the grazed wheat-chicory intercrop than the un-grazed treatment. In contrast, soil moisture was 4mm higher in the grazed wheat-lucerne intercrop compared to the un-grazed intercrop. The response of the wheat-lucerne intercrop is similar to that reported in previous studies, which found grazed crops used less water than un-grazed crops during the immediate post-grazing period (Harrison *et al.* 2010; Virgona *et al.* 2006). This conservation of water was explained by a reduced leaf area, resulting in less transpiration (Virgona *et al.* 2006). This affect was also reported in a drier year of another study, where soil moisture differences were seen under differing grazing stocking rates (Kelman & Dove 2009). It found higher soil moisture readings during the grazing period, under higher stocking rates, with the effect continuing until grain harvest. As such, the lower soil moisture of the grazed wheat-lucerne intercrop could be a reflection of a difference in recovery rate of the intercrop, post-grazing.

It is also likely that increased competition from lucerne during the post-grazing period as shown by the higher dry matter production of the grazed lucerne intercrop at wheat anthesis further inhibited the ability of the wheat crop to recover leaf area, potentially reducing water use of the wheat component. This is supported by previous studies that showed moisture stress in the post-grazing period limited wheat growth rates (Harrison *et al.* 2008; Kelman & Dove 2009) due to a reduction in leaf area expansion (Harrison *et al.* 2008).

The lucerne and chicory results in this study are similar to those observed in a grazing trial using different grazing pressures. Higher soil moisture readings were reported under higher stocking rates, as was seen in the wheat-lucerne intercrop (Kelman & Dove 2009). In contrast, water use was found to be greater in the low and medium stocking rates compared to the un-grazed treatment, as was seen in the wheat-chicory intercrop. This may be due to differences noted in species selection. A lesser preference to graze the chicory component of the wheat-chicory intercrop may have enabled improved recovery, post-grazing.

Grazing resulted in a reduction in plant heights of the wheat and pastures. The pastures were able to recover during the post-grazing period to be the same height as the un-grazed treatment by wheat maturity. In contrast, the reduction in wheat plant height remained to maturity. This reduction in wheat plant height is also reported in previous studies (Virgona *et al.* 2006; Winter & Thompson 1990; Worrell *et al.* 1992).

Reduction in intercrop wheat plant height, in addition to a reduction in wheat dry matter production, indicates there may have been competition for light in the post-grazing period, resulting in grain yield reductions. This is consistent with previous discussions (Chapter 6) about the effect of shading on the suppressed species, which results in a moderate reduction in dry matter production, while the dominant species only experiences a slight reduction in dry matter production (Donald 1997). More pronounced dry matter reduction in the wheat-lucerne intercrop suggests competition for light may have had a greater negative impact on the wheat component of the wheat-lucerne intercrop, compared to the wheat-chicory intercrop.

The impact of grazing on the productivity of intercropping

While grazing had a significant impact on the performance of the grain component of the intercrop, overall the productivity of the intercropping system was not compromised by grazing. Wheat-lucerne and wheat-chicory intercrops over-yielded under both grazing treatments. The wheat-chicory intercrop in-growing season and annual total LER were increased by grazing, indicating increased resource use both within and out of the growing season. The grazed wheat-chicory intercrop had higher dry matter based LER than the grazed wheat-lucerne intercrop, while the reverse was the case in the un-grazed treatments. These differences suggest resource use of the wheat-lucerne intercrop was compromised by grazing, whilst that of the wheat-chicory intercrop was improved.

Economic LER were increased for both lucerne and chicory intercrops under a grazing treatment due to the additional removal of crop dry matter during the growing season.

Summary

The results from this study show that grazing of intercrops impacts negatively on grain yield. The yield components affected by grazing for all treatments were the number of grains/head and spikelets/head. Additionally, TGW and screenings were affected in the wheat-lucerne intercrop, indicating that competition for resources between the intercrop components continued late into the wheat growing season, which reduced grain quality. Results from previous grazing studies suggests that in more favourable post-grazing seasonal conditions than those experienced in this study, the reduction in yield is likely to be less.

Plant height, soil moisture, grain and dry matter results, show that wheat component of the wheat-lucerne intercrop was unable to recover as well as the wheat-chicory intercrops after grazing. This was due to differences in the competitiveness of the pasture component of the intercrop, for water and possibly also light. This result supports conclusions reached in previous chapters (Chapters 4, 5 and 6), that lucerne is more competitive than chicory when grown in intercrop, which results in higher yield penalties in the lucerne intercrops, compared with the chicory intercrops. Overall, LER results show that, despite the higher yield reductions from grazing, productivity of the intercropping system generally increased due to the additional value of the dry matter removed at grazing.

The productivity of intercropping will be further explored in Chapter 8, focusing on the economic cost/benefit of the system in the higher rainfall zone of southern Australia.

Chapter 8. Intercropping in a farm business

8.1 Introduction

This three-year study has shown that crop-pasture intercropping can increase productivity compared to growing monocultures (Chapter 5). In order to develop a better understanding of the potential of intercropping within the focus region, a longer-term data set across many seasons is ideally required. Computer models can be used to simulate such data in the place of field data. Previous studies have examined the use of the Agricultural Production System Simulator (APSIM) to estimate production outcomes of over-cropping lucerne with grain crops. These studies found APSIM satisfactorily simulated the observed production data from field measurements of over-cropped wheat and canola in established lucerne stands (Harris *et al.* 2008b; Robertson *et al.* 2004).

This chapter will compare observed data from the field experiments conducted as part of this thesis study, with the simulation outputs of APSIM for wheat, lupins and canola grown as monoculture stands and in intercrop with lucerne. The aim is to firstly validate APSIM as a tool to satisfactorily predict yield and dry matter production of the range of crop-pasture combinations used here. If there is agreement between the simulated and observed data, then APSIM will be used to assess the longer-term performance of intercropping in the study region.

The economic benefit/cost of an intercropping system in a farm business has not been explored in any detail in previous cereal-lucerne over-cropping studies. A simple gross margin for one season has been presented in a lucerne over-cropping study (Egan & Ransom 1996). This was based on increased stocking rates of the lucerne component of the system, compared to an annual system, in addition to a long-term gross margin for livestock and cropping. This however, only provides a guide based on regionally averaged production and costs. Another over-cropping study presents economic LER values that show LER>1 could be achieved in a wheat-lucerne over-cropping system (Humphries *et al.* 2004). This is consistent with the economic LER presented in Chapter 5, which showed LER>1 was achieved by a range of intercrop combinations. However, LER assumes the components are of the same economic value, have the same cost of production and are of equal importance to the production systems of the study region.

To gain a better understanding of the economics of an intercropping system in the context of a farming business, this chapter will present a case study comparison of the returns from the monoculture crop, monoculture pasture and range of intercrop combinations, based on actual farm data. It will use outputs from APSIM, in addition to actual historic farm data, to determine the benefit/cost of an intercropping rotation. This more rigorous approach will provide a better understanding of economic implications for the higher rainfall zones of southern Australia, of an intercropping system that integrates crop and livestock components.

8.2 Materials and Methods

APSIM

Datasets and configuration

Field study observations described in Chapter 3 were used to compare the simulated outputs from APSIM 7.1. A soil, based on actual field data collected in 2008 (described in Chapter 3) and soil moisture data, was created using Apsoil, and used for all simulations. Meteorological data used was from Naracoorte (latitude 36.96°S longitude 140.74°E), South Australia, station number 026023.

Simulations

Simulations were configured for monoculture crop species wheat, lupin and canola, in addition to monoculture lucerne. Intercrop simulations were also configured for all crops grown in combination with lucerne. The simulation outputs were grain yield, crop dry matter (at anthesis), pasture dry matter, and crop and pasture plant height. The modules used in the monoculture simulations performed in APSIM 7.1 included: *fertilizer, surface organic matter, wheat, lupin, canola* and *lucerne.* The *canopy* module was used in the intercrop simulations to allow for the attribution of light, water and nitrogen to the competing species. Nitrogen and surface organic matter was reset on a fixed date (1st May) in each year of the simulation. Logic codes were used to control the simulated growth of lucerne during the autumn period (Appendix 5).

The grain crops were sown on a set date each year (18th May), using species, cultivars and sowing densities outlined in Table 8-1. Lucerne was sown on 9/7/2006.

Table 8-1 Species, cultivar and sowing density (plants/m^2) used in APSIM simulations

Species	Cultivar	Sowing Density
Wheat	Whistler	208
Lupin	Belara	50
Canola	Mid	67
Lucerne	Sceptre	100

Economics

Datasets

This study assumes fixed/overhead costs will remain the same irrespective of a monoculture or intercrop system, as there will not be any additional requirement for equipment with the proposed intercropping system. As such, the data is presented as a gross margin analysis that accounts for variation in income and operating expenses of the different systems. All prices and expenses are based on actual farm data (from full farm benchmarking reports) for each year from 2001 to 2008, from the property on which this study was conducted (Nalda Park) (Appendix 5).

Income was calculated for the monoculture crops, wheat, lupin and canola, using yields obtained from APSIM simulations for each of the years 2001-08, and the actual farm prices for those commodities in the corresponding year. Intercrop crop yields were based on the percentage yield reductions from the field trials conducted in 2006-08; they were then adjusted for seasonal conditions in the years 2001-05 and 2007-08. The results were compared to the yield results achieved at Nalda Park in the corresponding year to ensure accuracy. To account for over and under simulation of yield within the APSIM results, gross margins were also calculated on yields that were plus and minus 20% of the simulated or calculated crop and pasture yields.

Expense categories included chemicals, fertiliser, fuel, seed, freight and cartage, and other. The expense categories of seed, fertiliser and freight and cartage, were halved for the intercrops, to accurately represent the lower cost due to the reduction in these input requirements.

The monoculture crops had an additional "grazing penalty" in the form of a supplementary feeding cost. This allows accurate reflection of the difference between the crop and pasture systems. Where a crop is grown in a pasture based system, there is a "cost" of having to supplementary feed stock due to the loss of a feed source. This was done by calculating the amount of grazing days that were lost, i.e. the number of out-of-season grazing days that the monoculture pasture system provides. This was then multiplied by the cost of feeding per day, based on the actual average out of season feeding rate at "Nalda Park" (260g/head/day) by the cost of grain for the corresponding season.

Livestock income was calculated using GrazFeed V4.2.1. Pasture dry matter production based on simulations by APSIM, in addition to calculations based on the dry matter production of the actual field measurements, were used in the GrazFeed program. Intercrop dry matter production was calculated using yield reductions from the trial field measurements, adjusted for seasonal conditions in the years 2001 to 2008. This, in addition to pasture quality measurements taken at grazing periods during the 2008 season (Appendix 5), was used in the GrazFeed simulation to obtain data on livestock weight gain, wool growth and pasture grazing days. GrazFeed predicted wool growth rates that were considerably higher than actual wool growth rates observed on Nalda Park. To account for this difference, GrazFeed wool growth rates were adjusted on a daily basis to reflect a per-head annual wool growth of 4kg clean/head. Income was then based on growth rates, by grazing days, by actual price for both wool and meat. Meat prices were adjusted to reflect seasonality in livestock prices, and were historical over-the-hooks prices for 20-22kg carcase weight lambs, for each year from 2001 to 2008.

Livestock expenses were based on actual livestock expenses per head per day for each of the years from 2001 to 2008.

The livestock gross margin was calculated in two parts, in-growing season and out-of-growing season, with the two added together to produce the annual total gross margin. Intercrop gross margins were calculated by adding the intercrop crop and livestock gross margins for the components of each of the intercrops.

8.3 Results

8.3.1 Comparison of APSIM simulations and actual measurements

Monoculture wheat, lupin and canola

There was good agreement in simulated and observed monoculture wheat, lupin and canola grain yields in the 2007 and 2008 seasons (Table 8-2). There was also agreement between simulated and observed field measurements for dry matter production of monoculture wheat and lupin. In contrast, dry matter production of monoculture canola in the APSIM simulation was approximately half that which was observed in field measurements (Table 8-2). In the drought season of 2006, simulated wheat and lupin grain and dry matter yields were higher than the observed (Table 8-2).

Table 8-2 Monoculture wheat, lupin and canola grain yield (t/ha) and dry matter (kg/ha) comparison between simulation and observation in 2006-08

Measurement	Year		
Monoculture Wheat Yield	2006	2007	2008
Simulated	0.71	3.36	3.88
Observed	0.18	3.33	4.28
Monoculture Wheat Dry Matter			
Simulated	2796	12029	12336
Observed	3459	12509	13769
Monoculture Lupin Yield			
Simulated	0.46	2.14	2.17
Observed	0	1.97	2.05
Monoculture Lupin Dry Matter			
Simulated	3566	8565	8691
Observed	968	8165	8330
Monoculture Canola Yield			
Simulated		1.75	1.82
Observed		1.76	1.43
Monoculture Canola Dry Matter			
Simulated		5825	6088
Observed		10894	12721

Monoculture lucerne

Annual monoculture lucerne dry matter production was higher in the APSIM simulation than observed field measurements in 2006 and 2007, while the reverse occurred in 2008 (Table 8-3). Early season dry matter was lower in the APSIM simulation compared to observations in 2007 and 2008. The simulated lucerne dry matter was then higher than observed for summer measurements in 2006 and 2007. This was also the case in May 2008 (Table 8-3).

Table 8-3 Monoculture lucerne dry matter (kg/ha) comparison between simulation and observation in 2006-08

Monoculture Lucerne Dry Matter						
2006 Season	10/10/2006	7/12/2006	8/03/2007	10/05/2007		Annual Total
Simulated	637	988	708	211		1907
Observed	518	670	313	115		1098
2007 Season	2/09/2007	25/10/2007	30/11/2007	27/03/2008	16/05/2008	Annual Total
Simulated	1309	4113	5959	2247	418	8624
Observed	2490	4667	4872	835	214	5920
2008 Season	10/09/2008	6/11/2008	16/12/2008	26/01/2009	6/05/2009	Annual Total
Simulated	1727	4409	5849	1277	406	7532
Observed	2948	5730	6628	1675	155	8458

Intercrops

There was poor agreement between the APSIM simulation and observed data for intercrop grain yields and grain yield reductions, with the exception of canola in 2007 (Table 8-4). Simulated lupin intercrop grain yields were higher than observed, with a lower than observed grain yield reduction (Table 8-4). Wheat intercrop yields were higher in the simulation than observed in 2006 and 2007, and lower in 2008 (Table 8-4). Crop dry matter production was lower in the simulation for all crops in 2007 and 2008, and higher in 2006 (Table 8-4).

Plant height of wheat, lupin and canola were lower in the APSIM simulation than observed field measurements, with the exceptions of lupin in 2006 and canola in September 2008 (Table 8-5).

There was agreement between simulated and observed measures of plant height of lucerne in all intercrops in 2008. In 2006, simulated lucerne height was lower than that observed in the field (Table 8-5).

In the majority of treatments and years, annual dry matter production of the lucerne intercrops was higher in the simulated than observed measurements. The exceptions were lupin-lucerne and canola-lucerne intercrops in 2008 (Table 8-6). There was good agreement on the annual total biomass reduction in APSIM simulated and observed field measurements for lupin-lucerne intercrops (Table 8-6). The annual total biomass reductions for wheat-lucerne intercrops were lower in the simulation compared to field observations. The simulated annual biomass reductions for canola-lucerne intercrop were close to observed in 2008, but were lower in the simulated compared to observed measurements in 2007 (Table 8-6).

The APSIM simulation under-predicted lucerne growth early in the 2006 season compared to observations, and over-predicted growth later in the season, when lucerne was intercropped with wheat and lupin (Table 8-6). However, the simulated in-growing season biomass was higher than observed in 2007. In contrast, out-of-growing season production was lower in the simulated than observed for all lucerne intercrops, with the exception of wheat-lucerne in March (Table 8-6). Lucerne production for the in-growing season was lower in the simulation than observed in 2008. There was agreement between observed and simulated measurements for out-of-growing season lucerne dry matter production in wheat and canola intercrops in January 2008. The remaining out-of-growing season observations in this season were lower than simulated (Table 8-6).

Table 8-4 Grain yield (t/ha) and crop dry matter (kg/ha) and the percent reduction (%) of the monoculture for wheat, lupin and canola intercropped with lucerne in 2006-08

	Wheat-lucerne			Lupin-lucerne			Canola-lucerne	
Grain Yield	2006	2007	2008	2006	2007	2008	2007	2008
Simulated	0.61	2.74	2.02	0.44	1.42	1.23	1.5	1.5
Observed	0.09	1.87	2.93	0	0.52	0.57	1.43	0.4
Grain Yield Reduction								
Simulated	14%	18%	48%	5%	34%	43%	19%	72%
Observed	50%	44%	32%	n/a	74%	72%	14%	18%
Crop Dry Matter (GS65)								
Simulated	2406	7595	7051	3164	4754	4655	5002	5008
Observed	2082	9944	7771	968	8165	8330	10894	12721
Crop Dry Matter Reduction								
Simulated	14%	37%	43%	11%	44%	46%	14%	18%
Observed	40%	21%	44%	54%	77%	53%	23%	85%

Table 8-5 Wheat, lupin, canola and lucerne plant height (cm) when grown in intercrop in 2006 and 2008

	Wheat-lucerne			Lupin-lucerne			Canola-lucerne	
Grain	2/10/06	5/09/08	11/12/08	2/10/06	5/09/08	11/12/08	5/09/08	11/12/08
Simulated	17	14	58	60	6	59	35	82
Observed	29	48	85	10	18	69	21	100
Lucerne								
Simulated	4	31		0	31		30	
Observed	9	37		9	32		33	

Table 8-6 Lucerne dry matter (kg/ha) and percent reduction (%) of the lucerne monoculture for each measurement date and annual total, when grown in intercrop with wheat, lupin and canola in 2006-08

Lucerne Intercrops												
Wheat-lucerne	10/10/06	%	7/12/06	%	8/03/07	%	10/05/07	%			Annual Total	%
Simulated	41	*94*	84	*91*	1156	*nil*	267	*21*			1507	*21*
Observed	340	*34*	158	*24*	99	*68*	52	*55*			491	*55*
Lupin-lucerne												
Simulated	12.5	*98*	41.8	*96*	615	*13*	194	*92*			850.8	
Observed	320	*38*	188	*72*	189	*40*	67	*42*			576	
Wheat-lucerne	2/09/07	%	25/10/07	%	30/11/07	%	27/03/08	%	16/05/08	%	Annual Total	%
Simulated	1722	*nil*	2307	*44*	3626	*39*	604	*73*	52	*88*	4282	*50*
Observed	1181	*53*	1251	*73*	1329	*73*	545	*35*	146	*32*	1943	*67*
Lupin-lucerne												
Simulated	1718	*nil*	2299	*44*	3703	*38*	577	*74*	48	*89*	4328	*50*
Observed	1332	*47*	1972	*58*	2792	*57*	715	*14*	168	*21*	2855	*52*
Canola-lucerne												
Simulated	1530	*nil*	1819	*56*	3301	*45*	309	*86*	63	*85*	3673	*43*
Observed	606	*76*	740	*84*	255	*95*	463	*55*	103	*52*	1306	*78*
Wheat-lucerne	10/09/08	%	6/11/08	%	16/12/08	%	26/01/09	%	6/05/09	%	Annual Total	%
Simulated	2126	*nil*	3019	*32*	4425	*24*	1498	*nil*	375	*8*	6298	*16*
Observed	4283	*nil*	3488	*39*	3292	*50*	1905	*nil*	153	*19*	5548	*34*
Lupin-lucerne												
Simulated	2124	*nil*	2892	*34*	4008	*31*	1093	*14*	300	*26*	5401	*28*
Observed	5291	*nil*	6987	*nil*	7750	*nil*	2970	*nil*	129	*17*	10086	*nil*

Canola-lucerne												
Simulated	2050	*nil*	2565	*42*	4594	*21*	1707	*nil*	435	*nil*	6736	*11*
Observed	4562	*nil*	5312	*7*	6501	*2*	1718	*nil*	239	*nil*	7268	*14*

8.3.2 Gross margin comparison between monoculture and intercrops

Grain prices had a significant impact on gross margins of the monoculture crops and the intercrops (Figure 8-1, Figure 8-2 and Figure 8-3). Wheat prices were higher in 2002 ($351/t), 2007 ($306/t) and 2008 ($259/t), compared to the 8-year average price of $211. Lupin and canola prices were also higher than average in 2007 and 2008 (Appendix 5).

Wheat

The wheat-lucerne intercrop had higher gross margins in all years than the monoculture lucerne. In half of the seasons assessed, the wheat-lucerne intercrop also had higher returns than monoculture wheat (Figure 8-1). Wheat-chicory intercrops had higher gross margins than monoculture chicory in 4 of the 8 seasons, and achieved higher returns than monoculture wheat in 2 of the 8 seasons (Figure 8-1).

With increased grain and dry matter yields (+20%), there is an increase in the gross margins of the intercrops, compared to the monoculture treatments (Figure 8-1). In contrast, the intercrop performance compared to the monoculture components was reduced when grain and dry matter yields were decreased (-20%) (Figure 8-1). The wheat-lucerne intercrops however, still maintained a higher gross margin than the monoculture wheat in 50% of the seasons (Figure 8-1).

Lupin

Generally, monoculture lupin had the highest gross margin of all the lupin comparison treatments, with the exception of 2001, when the monoculture pastures achieved greater returns than the lupin treatments (Figure 8-2). The lupin-chicory intercrops had a higher gross margin than the monoculture chicory in 7 of the 8 seasons. In contrast, the lupin-lucerne intercrop had a lower return than the monoculture components in all seasons, with the exception of monoculture lucerne in 2008 (Figure 8-2).

As grain and pasture yields increased (+20%), the gross margin of the lupin-chicory intercrop and monoculture lupin improved. The lupin-lucerne intercrop returns were also slightly improved, having higher gross margins than monoculture lucerne in 3 of the 8 seasons (Figure 8-2).

Decreasing the grain and pasture yields (-20%) lowered returns from the intercrops (Figure 8-2). However, the lupin-chicory intercrop still achieved higher returns than the monoculture chicory in 5 of the 8 seasons, whilst the lupin-lucerne intercrops had lower returns than the monoculture components in all seasons (Figure 8-2).

Canola

Canola-chicory intercrops had the highest returns in all seasons for the canola comparisons, followed by the monoculture canola and the canola-lucerne intercrop (Figure 8-3). This ranking of returns remained the same when the grain and pasture yields were increased (+20%) (Figure 8-3). When yields were decreased (-20%), the gross margins ranking was generally not changed, with the exception of 2005, when the gross margin for monoculture lucerne was the same as for monoculture canola (Figure 8-3).

Average Gross Margin comparison

The gross margin averaged over seasons from 2001-2008 (2003-2008 for canola), showed that intercrops had a higher average return than monoculture pastures in all treatments, with the exception of the lupin-lucerne intercrops, which performed poorly in all treatments (Figure 8-4). The wheat-lucerne intercrop had a higher average gross margin than monoculture wheat in 2 of the 3 treatments. The wheat-chicory intercrop had a gross margin similar to that of monoculture wheat in the +20% treatment (Figure 8-4). In the lupin treatments, the monoculture lupin had the highest gross margin, followed by the lupin-chicory intercrop, and then the lupin-lucerne intercrop (Figure 8-4). For the canola treatments, the canola-chicory intercrop had the highest average return followed, by monoculture canola and the canola-lucerne intercrop (Figure 8-4).

Comparison of average gross margins under a crop rotation

Based on a standard two year cereal (wheat), one-year canola and one-year legume (lupin) rotation, the monoculture crop rotation had the highest gross margin for all treatments (Table 8-7). The chicory intercrop rotation was $31 to $49/ha lower than the monoculture crop rotation (Table 8-7). The third-highest gross margin was achieved by the lucerne intercrop rotation, followed by the monoculture pastures, which had lowest gross margins. Monoculture chicory had a slightly lower gross margin than monoculture lucerne (Table 8-7).

Grazing

Grazed monoculture crop and intercrops ha lower gross margins per hectare compared to un-grazed treatments (Figure 8-5). Of the grazed treatments, the wheat-chicory intercrop had the highest return (Figure 8-5). The un-grazed wheat-chicory intercrop had a gross margin comparable to monoculture wheat and lucerne, and was higher than both monoculture chicory and the wheat-lucerne intercrop (Figure 8-5).

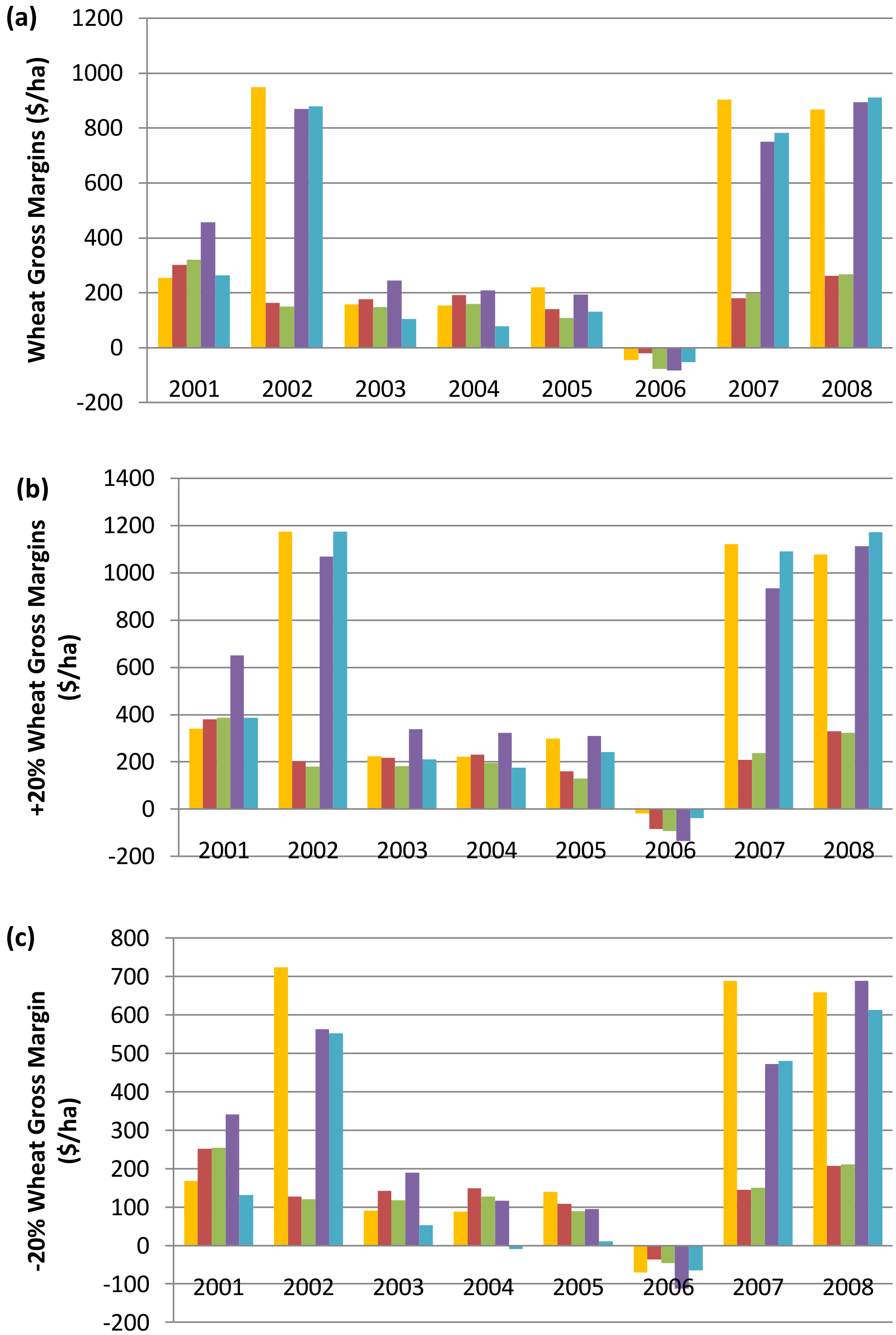

Figure 8-1 (a) Gross margin ($/ha) for wheat intercrops and the monoculture components (b) plus 20% grain and dry matter yields (c) minus 20% grain and dry matter yields.

■ monoculture wheat ■ monoculture lucerne ■ monoculture chicory ■ wheat-lucerne intercrop ■ wheat-chicory intercrop.

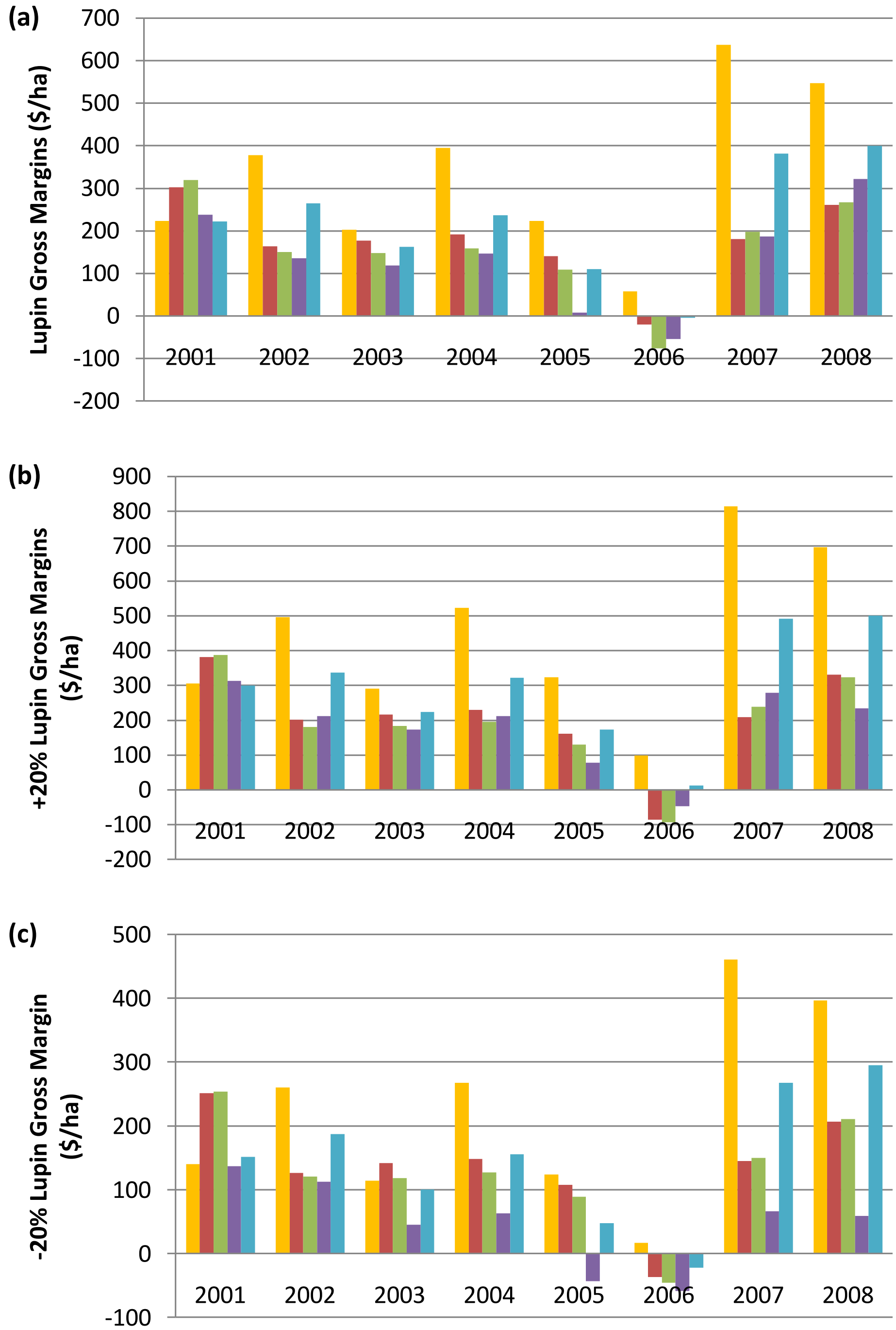

Figure 8-2 Gross margin($/ha) for lupin intercrops and the monoculture components (b) plus 20% grain and dry matter yields (c) minus 20% grain and dry matter yields.

■ monoculture lupin ■ monoculture lucerne ■ monoculture chicory ■ lupin-lucerne intercrop ■ lupin-chicory intercrop.

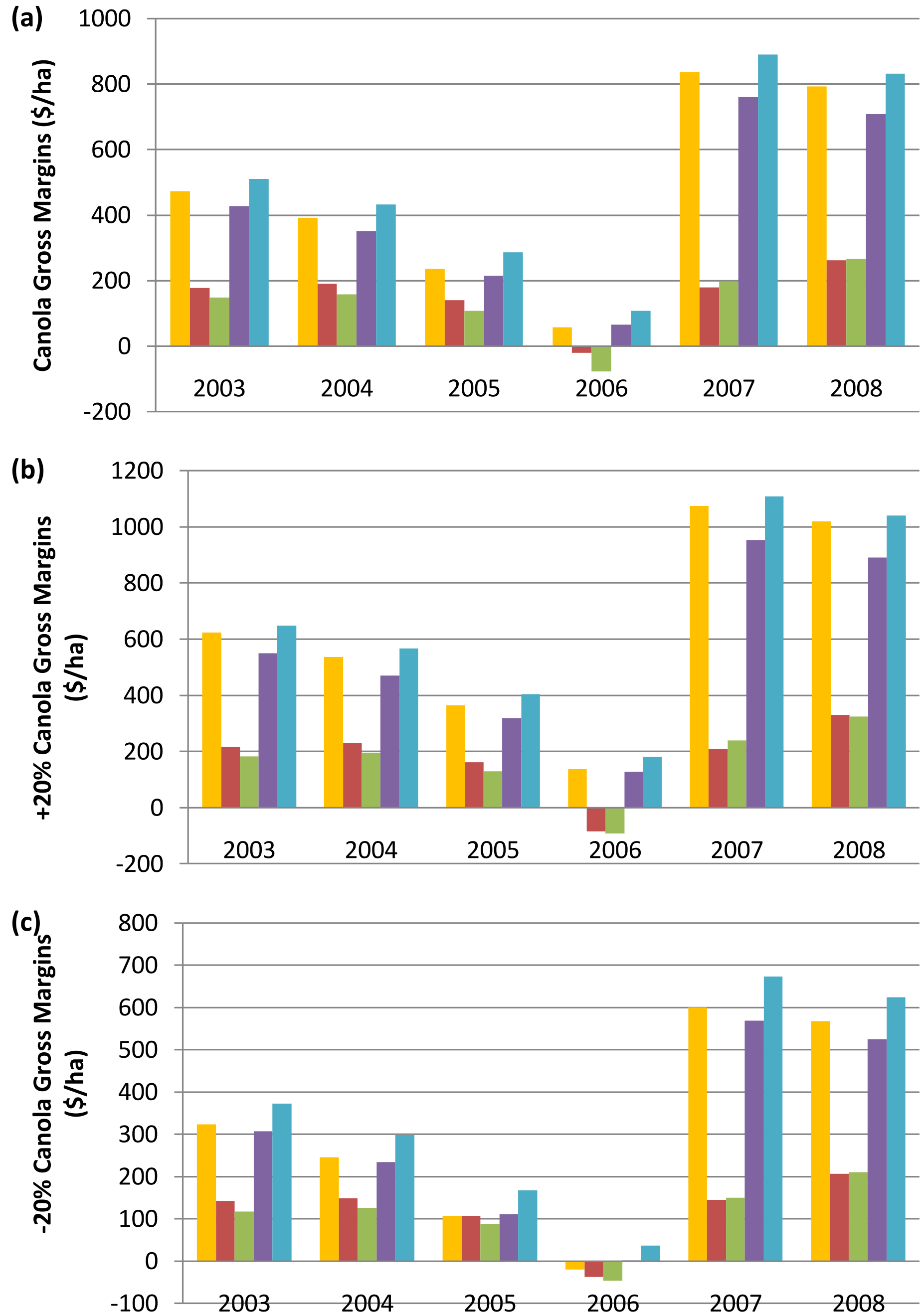

Figure 8-3 Gross margin($/ha) for canola intercrops and the monoculture components (b) plus 20% grain and dry matter yields (c) minus 20% grain and dry matter yields.

■ monoculture canola ■ monoculture lucerne ■ monoculture chicory ■ canola-lucerne intercrop ■ canola-chicory intercrop.

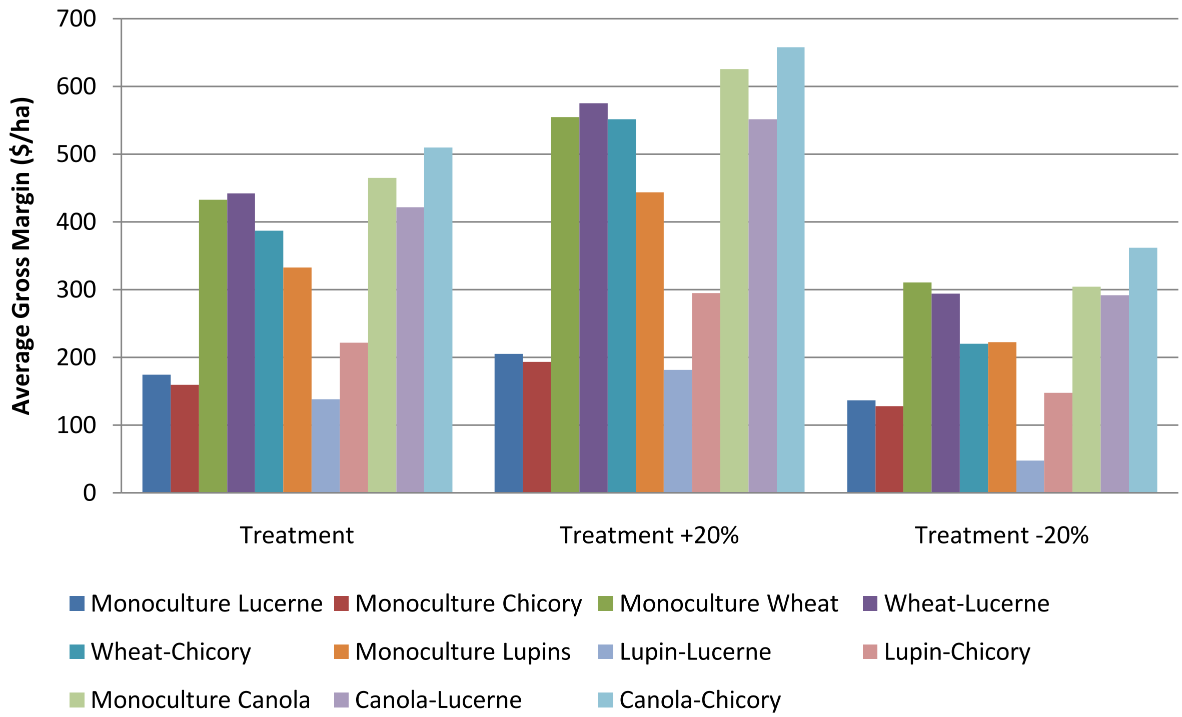

Figure 8-4 Average gross margin ($/ha) for intercrop and monoculture components, plus 20% and minus 20% of the grain and pasture dry matter yield

■ Monoculture lucerne ■ Monoculture chicory ■ Monoculture wheat ■ Wheat-lucerne ■ Wheat-chicory ■ Monoculture lupins ■ Lupin-lucerne ■ Lupin-chicory ■ Monoculture canola ■ Canola-lucerne ■ Canola-chicory

Table 8-7 Average gross margin return of a two year cereal (wheat), one year canola and one year legume (lupin) rotation for monoculture crop and intercrops also compared to the average gross margin of lucerne and chicory

Rotation	Treatment	Treatment +20%	Treatment -20%
Monoculture lucerne	$175	$206	$136
Monoculture chicory	$159	$193	$128
Monoculture crop rotation	$416	$545	$287
Intercrop lucerne rotation	$361	$471	$232
Intercrop chicory rotation	$377	$514	$238

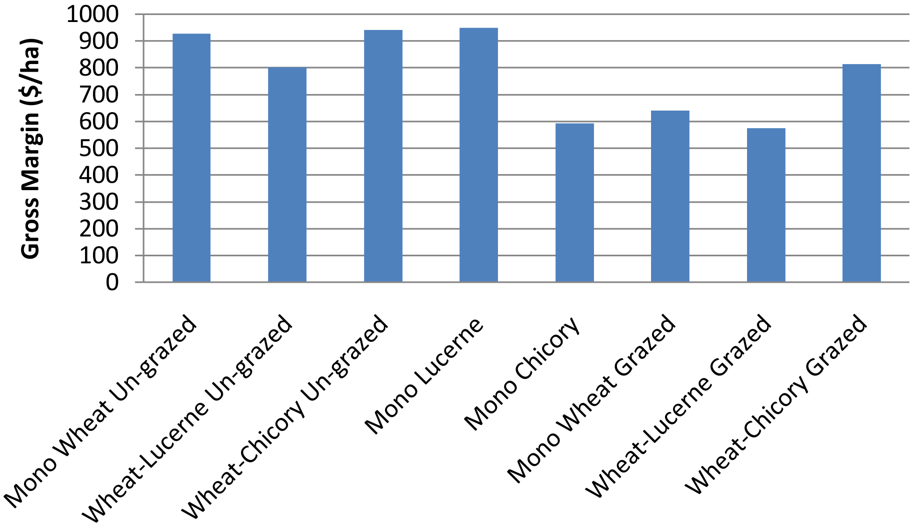

Figure 8-5 Gross margins ($/ha) for Site 2 in 2008, grazed and ungrazed treatments

8.4 Discussion

Using APSIM to model monoculture crop and pasture production

In order to validate an APSIM intercropping simulation, it was important to firstly ensure the program satisfactorily simulated the monoculture components of the intercrop. This also enabled comparison of the crop and pasture yield reductions, as a percent of monoculture, between the APSIM simulation and observed field data.

Overall, APSIM satisfactorily simulated crop grain and dry matter production. There was generally close agreement between the APSIM simulation and observed field data for grain yields of monoculture wheat, lupin and canola. There was also agreement between the simulation and observed dry matter production of wheat and lupin. However, the simulation of canola dry matter was half that of the observed.

These results are consistent with validation studies for wheat, lupin and canola. APSIM satisfactorily estimated wheat and lupin yield and biomass on duplex soils in Western Australia, which are similar to that of the current study (Asseng *et al.* 1998; Farré *et al.* 2004). Harris (2008b) also found wheat biomass to be well simulated, provided that soil N is reset when undertaking a time series. Without resetting, it was found dry matter production was under-estimated in the final crop. The APSIM canola model is also able to simulate the range in canola yields on a variety of Western Australian soil types, including duplex sands. However, APSIM tended to over-estimate early biomass production, particularly for delayed sowings (Farré *et al.* 2002).

Lucerne annual dry matter production was over-simulated by APSIM in two of the three seasons compared to field observations. Generally, this was due to over-estimation of production in the summer months, although there was also an under-estimated lucerne production early in the growing season.

These results are supported by previous studies that have also found that APSIM lucerne tends to have periods of over and under estimation. In one study, APSIM tended to under-estimate lucerne production during the summer/autumn period and over-estimate biomass during spring (Zahid *et al.* 2003). Similarly, APSIM over-estimated lucerne biomass in spring and under-estimated production in summer (Dolling *et al.* 2005b). By reducing radiation use efficiency of APSIM lucerne in autumn and winter, the over-estimation of biomass during the autumn-winter period is reduced. In addition, APSIM generally over-estimated lucerne growth between late autumn and early spring, with the greatest over-estimation of biomass occurring in the autumn/winter period (Dolling *et al.* 2001). The difference between simulated and observed output was suggested to be due to the simulation not accurately predicting radiation utilisation and relocation of carbohydrates, associated with events such as cutting. Similarly, the estimation of biomass was improved when the APSIM lucerne plant module was modified to include total radiation use efficiency, partitioning of biomass to perennial organs, and respiration of perennial organs (Teixeira *et al.* 2010). The original APSIM lucerne module under-predicted biomass early in the growing season, compared to the modified APSIM lucerne module, which accurately simulated early season production and the ongoing season growth of lucerne.

The APSIM lucerne module is also reported to over-estimate autumn growth (Dolling *et al.* 2001; Dolling *et al.* 2005b). In order to overcome this problem, the autumn growth of lucerne in the current study was reduced in the APSIM simulation by including coding to restrict plant growth during the autumn period. This appears to have worked successfully, but could have been the cause of under-estimation in lucerne production during late winter/early spring.

The results of these studies suggest simulation output may be improved for this region with modifications to the APSIM lucerne module for the higher rainfall regions of southern Australia, in addition to a more accurate data set of seasonal soil changes in regards to water and nutrient levels, and plant growth, for validation.

Using APSIM to model intercrop crop and pasture production

When the monoculture crop and lucerne components were used to create an intercrop simulation in APSIM, there was generally poor agreement between observed and simulated intercrop grain yields and grain yield reductions. Grain yields were generally over-estimated, and the grain yield reductions as a percent of the monoculture crop were under-estimated. This is in contrast to a previous grain-lucerne over-cropping APSIM simulation study, which found yields of the APSIM simulation were in agreement with observed field data for wheat and canola (Robertson *et al.* 2004). However, this study also found the percent yield reduction of the simulation to be less than that observed. This is supported by another over-cropping simulation study showing good agreement between simulated and observed wheat grain yields when cereals are over-cropped into lucerne, provided that soil N is reset in the autumn each year (Harris *et al.* 2008b). A possible reason for the need to reset soil N is an over-estimation of lucerne root exploration and subsequent soil N uptake during the summer/autumn period.

The APSIM intercrop simulation generally over-estimated lucerne intercrop dry matter production. As was found with monoculture lucerne, this tended to be due to over-estimation of dry matter production out of the crop growing season, whilst there was under-estimation of growth early in the growing season. The biomass reduction, as a percent of monoculture, showed agreement between observed and simulated measurements for lupin-lucerne intercrops, but was low in the simulated wheat and canola intercrops.

An over-cropping wheat-lucerne simulation study also found lucerne production tended to be higher in the simulation then observed data in the summer/autumn period in some seasons (Harris *et al.* 2008b). Similarly, APSIM simulation of wheat-lucerne over-cropping found an over-estimation of lucerne biomass in autumn (Robertson *et al.* 2004).

These results suggest the under-estimation of lucerne growth early in the growing season of the current study, provided greater partitioning of resources to the grain crop. This would account for the over-estimation of crop grain yields and under-estimation of crop grain yield reductions of the intercrops. Generally, APSIM lucerne validation studies show there is variation in the agreement of data from under-to over-estimation of yield and dry matter for a range of crops in different seasons (Dolling *et al.* 2001; Farré *et al.* 2002; Harris *et al.* 2008b; Robertson *et al.* 2004). It is also expected that there will be some over-estimation of yields when using APSIM, as the field data is subject to limitations that vary season by season, such as pests, disease, soil and nutritional limitations that are not accounted for in this model.

It has been suggested that the scale on which APSIM simulated data is used influences its success in simulating production. If used as a broad indicator of the performance of lucerne within an environment, APSIM is considered satisfactory (Dolling *et al.* 2005b). When taking into account an expected level of variation and over-estimation, these results suggest that APSIM lucerne can successfully simulate a range of lucerne yields at a more general level. This current study and previous studies indicate further work needs to be undertaken to improve the accuracy of APSIM lucerne simulations at a more specific level.

The economics of intercropping

This study has shown that productivity can be increased through the use of an intercropping system (Chapter 5). However, in order for researchers, producers and advisors to make informed decisions regarding changes to systems within a farming business, it is important to have a better understanding of the economic cost/benefit of the new system.

The gross margin returns from the crop and pasture monocultures and intercrops varied greatly across the 8 seasons of the analysis from 2001 to 2008. The highest returns depended on both the crop and pasture component, indicating both have an influence on the economic outcome of the intercropping system.
Lucerne had higher returns than chicory when the two species were grown in intercrop with wheat. In contrast, chicory intercrops had higher gross margins than lucerne intercrops when grown with lupin and canola. Monoculture crops had returns either higher, or comparable to, that of the intercrops, whereas monoculture pastures tended to have lower returns than monoculture crops and intercrops. There may also be a site effect influencing these results. At one site, the wheat-lucerne intercrop had higher gross margins than the wheat-chicory intercrop, but at the other site the reverse was true.

When the gross margins were averaged over time to remove some of the individual season influence and provide a longer-term indication of the performance of the different monoculture and intercrop treatments, the intercrops in all but one combination had a higher average gross margin than the monoculture pastures. The performance of the intercrops compared to the monoculture crops varied depending on the crop species. Monoculture lupins provided higher returns than both intercrops, whereas monoculture wheat and canola had lower gross margins than either the lucerne or chicory intercrop.

The +20% and -20% treatments allowed the assessment of gross margin returns over a range of outcomes, which aims to take out some of the variation in simulated and predicted yields. It also provides an insight into the performance of intercrops under varying conditions. The results show that reducing the yield penalty incurred by competition between the intercrop species, will result in subsequent improvement in performance of the intercrops. Likewise, an increase in yield reductions decreases performance of the intercrops in relation to the component species. This shows the sensitivity of the intercropping systems to changes in crop and pasture yields, due to the effect of season and competition between species.

As continuous use of the same crop species is not a recommended practice for this region (Harris *et al.* 2007), the economics of a commonly used continuous cropping rotation, two years cereal, and one year each of canola and a legume species, was assessed. Monoculture crops had the highest average gross margin return in this rotation, followed by intercropped chicory, then intercropped lucerne. Both intercrops had higher returns than the monoculture pastures.

An interesting outcome is from the chicory intercrops in drought conditions. In all crop-chicory combinations the chicory intercrop tended to have one of the better returns, or lower losses, compared to the lucerne intercrop and the monoculture treatments. This indicates it is a potentially lower-risk system.
The ability of intercrops to capture the benefits of unpredictable upsides in market prices is shown in the gross margin results for this system, in the influence that higher grain prices had on the returns from monoculture crops and intercrops.

The results of this analysis are consistent with the simple gross margin analysis conducted on a summer-active mixed native pasture/wheat over-cropping study. It was found over the three trial years of the study, that generally the highest gross margin was that of monoculture wheat, followed by the over-crop and the monoculture pasture (Millar & Badgery 2009).

Results from the gross margin analysis showed that the economic outcome of intercropping is comparable to returns from monoculture crop and pasture stands, and also provides the ability to capture the upside in both crop and livestock markets prices.

The effect of in-growing season crop grazing on the economics

The grazing of cereal crops improves the economic return of spring grown crops (Kelman & Dove 2007; Kirkegaard *et al.* 2008). In contrast, this one-year study showed that grazing of monoculture crops and intercrops resulted in a lower gross margin return than the comparable un-grazed treatments. This was due to lower than expected crop dry matter at the time of crop grazing, which was inconsistent with all other site and season results in this study (Chapter 7). This can, in part, be attributed to a heavy annual ryegrass (*Lolium rigidum*) infestation at this site, in this one season.

Previous studies of cereal crop grazing have shown that, given appropriate timing and duration of grazing, yield penalties can be avoided (Kirkegaard *et al.* 2008; Virgona *et al.* 2006). As there is no other information available on the effect grazing has on the grain yields of crop-pasture intercrops, it is unknown if the result from this study is an accurate reflection of the impact of grazing. As such, further investigation is required in this area before conclusions can be drawn regarding the practice of early season grazing of intercrops.

Summary

There was generally satisfactory agreement between simulated and observed field measurements for the monoculture grain crops. In contrast, APSIM simulations did not support the observed data for monoculture lucerne production. Subsequently, the intercrops did not generally have close agreement between the simulated and observed results. Improvement in the monoculture lucerne simulation, likely to be through increased accuracy of predictions of radiation utilisation and relocation of carbohydrates to and from the perennial organs, biomass predictions of lucerne should be improved. A more accurate monoculture lucerne simulation should also improve the accuracy of the intercrop simulation. As a number of assumptions were made when using the data sets in this model, accuracy may be further improved by a more detailed data set both at the start of the model run, and also to assess the outputs of the model.

The rotation results validate why there has been a move toward increased cropping in the higher rainfall zones of southern Australia, as monoculture cropping provided higher returns than summer-active perennial pasture species. Intercrops also provided higher returns than monoculture pasture stands, and returns were comparable to that of monoculture crops. Importantly, this shows that producers are able to capture the benefits of higher returns from cropping, while still maintaining a perennial pasture base, through the use of intercropping. There are also indications, particularly for chicory intercrops, that intercropping could be a lower risk system than that of the monoculture components.

The intercropping system provided an economic return comparable with the current system, and increased flexibility. This, in addition to providing the environmental benefits associated with reduced recharge, appears to make intercropping a viable alternative to growing monoculture stands in the higher rainfall zones of southern Australia.

Chapter 9. General Discussion

The principal objective of the study covered in this thesis was to assess the potential of an intercropping system that is based on a double skip row arrangement, using both lucerne and chicory, for the higher rainfall zones of southern Australia. This objective encompassed the thesis hypothesis, that 'Intercropping with a range of crop/perennial pasture intercrops will be more productive than monoculture production in the higher rainfall zones of southern Australia'. Whilst the study was designed to address eight specific questions developed in the literature review, at all times the overarching direction of the study was the development of a holistic system, that is, a system that is profitable, durable and provides positive environmental outcomes. In the context of Australian farming and given the pressures associated with market and climate variability, it is important that this new system improves productivity, whilst not compromising the profitability of farming in the study region, in order for on-farm adoption to be considered by producers.

Based on both economic and productive traits intercropping was generally more productive than growing the components as monoculture stands/swards, despite reductions in the yields of the components.
Economic returns, based on an eight-year gross margin analysis and compiled using APSIM simulation data, calculated data, and actual on-farm costs and income, provided an indication of the advantage/disadvantage of the intercropping system at a farm level in the medium-term. These outcomes potentially will have a significant influence on the on-farm adoption of this system.

The economics of a commonly-used cropping rotation - two years of cereals, and one year each of canola and a legume species, in this case lupin - showed intercropping provided higher gross margin returns compared to monoculture pasture stands. The monoculture crop rotation had a marginally higher average gross margin than the intercrop rotation; a reflection of the favourable returns from cropping compared to livestock during the eight-year study period.

The gross margins demonstrated the ability of intercropping to capture the benefits of higher returns for cropping within the period of the analysis. Likewise, in seasons of higher livestock prices, the benefit would also be captured in this intercropping system. This is a key consideration of the intercropping system, as seasonal fluctuation in markets are unpredictable, and therefore a system that is able to utilise these benefits without the cost of shifting in and out of enterprises is important. Thus this intercropping system has the potential to provide longer-term economic stability and cost savings to mixed farming enterprises.

Whilst the gross margin analysis demonstrated the economic benefits of intercropping, it does not account for benefits such as increased flexibility of the intercropping systems, year-round ground cover, and differing levels of risk of the monocultures and intercrops. Nor does it provide an understanding of how intercropping fits into a whole farm production system. As such, this needs to be investigated in a more reductionist mode to provide a full understanding of the benefits of intercropping in the study region.

APSIM was used in this study with the aim of assessing the longer-term performance of intercropping in the study region, as the program has been shown to be suitable in simulating over-crop production of lucerne grown with cereals and canola (Harris *et al.* 2008b; Robertson *et al.* 2004). While there was satisfactory agreement between APSIM simulated outputs and field data for monoculture grain crops, there was not an agreement between the simulations and field data for monoculture lucerne, which subsequently resulted in poor agreement for the intercrops.

Improvements to the lucerne module have been suggested in previous studies (Dolling *et al.* 2001; Teixeira *et al.* 2010), and these should improve agreement between the simulated and observed monoculture lucerne and intercrop data. This, in addition to the development of a chicory module, will allow modelling to be used for longer-term production simulations in a range of areas within the higher rainfall zones. In addition, it will allow investigation of the outcomes of intercropping in a wider range of environmental conditions; the effects of changing agronomic components of the system; and the ability of intercropping to capitalise on seasonal variations in market prices.

Land Equivalent Ratio (LER) calculations were used in this study to provide a measure of comparative productivity gains/losses of intercropping. The LER values show that the intercropping system can be more productive in comparison to a monoculture system. The summer-active perennial pasture component is able to capture rainfall outside of the annual crop/pasture growing season. This is important in the higher rainfall zones of southern Australia that have a high proportion of rain falling outside of the growing season of annual species, despite being classified as having winter-dominant rainfall. This rainfall is not fully utilised in annual-based systems, and can contribute to environmental problems associated with lower water use. A system that captures out-of-growing-season rainfall and provides high-quality forage for livestock production was shown through LER to not only improve productivity, but environmental outcomes can also be improved. Various studies have established that systems that incorporate an annual and perennial component, such as using a lucerne phase in a cropping rotation or cereal-lucerne over-cropping, can successfully reduce recharge compared to a solely annual-based system (Harris *et al.* 2008a; Hirth *et al.*

2001). This demonstrates that crop-pasture intercropping is able to provide environment benefits of increased water use, in addition to productivity benefits.

The economics and LER values demonstrate the ability of a crop-pasture intercropping system to provide productivity gains and improved environmental outcomes through increased water use, whilst not compromising economic outcomes for producers. Importantly, it demonstrates the suitability of crop-pasture intercropping to mixed farming in the higher rainfall zones of southern Australia.

While intercropping can improve economic and production outcomes, the investigation of competition in this study indicates there are further opportunities to refine the crop-pasture intercropping system. Although there was a negative effect of spatial design or seeding rate noted, this was nil to minimal in more favourable growing conditions with some of the species used in this study. This suggests that further research into the optimal plant number and row design to reduce competition, is required, and may also improve the outcomes of intercropping. In spite of this, the reductions in grain and pasture yields were found to be predominately due to competition between component species.

The impact of competition was dependent on both the pasture and crop components of the intercrop. However, all combinations used in this study over-yielded in more favourable seasons. Therefore the use of chicory as an alternative pasture species to lucerne was able to increase the adaptability of this system to the study region. In fact, chicory appears well-suited to intercropping, with lower grain yield reductions from chicory intercrops, and a greater incidence of over-yielding compared to lucerne intercrops. The difference in the level of competition found in this study between the two species was likely due to the greater winter dormancy of chicory, resulting in lower growth early in the season of chicory, and therefore lowers resource requirements during this period. In addition, differences were observed in the intensity of competition between the two species, suggesting that reducing the early onset of competition in intercropping is important in minimising subsequent reductions in grain yield. Thus improvements to yield outcomes of the intercrop grain component can be achieved through the selection of pasture species/varieties with greater winter dormancy.

The successful use of chicory as an intercropping species increases the adaptability of this system to a greater range of soil types within the study region, and highlights the potential to explore other alternative perennial pasture species that may be suited to intercropping.

Similarly, the successful use of break crop species, canola and lupin, also increases the flexibility of the intercropping system. It reduces the risks associated with continuous cereal rotations, such as pests and disease, enabling longer crop rotations. The success of canola and lupin pasture intercrops highlights the potential to investigate other break crop species that could be using in intercropping.

Competition resulting in grain and pasture yield reductions predominately occurred from mid season (September) to maturity, as a result of competition for water. This is in contrast to results from previous cereal-lucerne over-cropping studies, in which competition affecting yield occurred early in the crop growing season (Harris *et al.* 2008a; Humphries *et al.* 2004).The source of competition was also found to differ from that of the previous studies, where early competition for light and/or nutrients was the likely cause of yield reductions (Harris *et al.* 2008a; Humphries *et al.* 2004).

This difference was likely due to the use of double alternate row spacing in this study. Double alternate row spacing in crop-crop intercropping reduces the onset of early competition and provides greater opportunities for resource capture by less competitive species (Chen *et al.* 2004; Mohta & De 1980). Similarly, this study found that canopy structure did not appear to affect performance of the intercrop, with the exception of canola in one season. The early height advantage obtained by the canola resulted in the dominance of this species, and the subsequent poor performance of the pasture component of the intercrop. This is similar to results reported in crop/crop intercropping studies (Cendekdee & Fukai 1992). These studies found that species selection and row design then become an important consideration of the intercropping system, to improve production of the suppressed species. This indicates the importance of improving species/variety selection and the development of a better understanding of the characteristics that make a species/variety more suited to intercropping.

It has been suggested previously that the use of herbicides to suppress lucerne in a cereal-lucerne over-cropping situation may decrease early competition and increase crop grain yields (Humphries *et al.* 2004). As such, there may be opportunities to further explore suppression through agronomic manipulation, such as herbicide use, seeding rates and grazing, on both the pasture and crop component of an intercropping system where one species is likely to dominate.

The use of double alternate row spacing appears to have been successful in reducing early competition and, as such, provides the inference to further investigate different row spacings in pasture-crop intercropping, as a means of reducing competition. The adoption of guidance seeding technologies and precision agriculture provides the ability to sow on alternate row spacing and to accurately re-sow the inter-row in subsequent seasons, without damaging the existing perennial pasture species. The on-farm use of these technologies enables the adoption of double alternate row spacing intercropping on-farm, without the need for new or specialised equipment or technology.

This study also explored new options in intercropping that have the potential to further increase the value of this system to the livestock enterprise, by filling a winter feed gap through in-season grazing. Dual-purpose cropping studies have shown that grazing has the potential to increase returns, whilst having a minimal impact on production (Kirkegaard *et al.* 2008; McMullen & Virgona 2009). In contrast to these studies, grazing of monoculture wheat and wheat intercrops resulted in grain yield reductions. While LER values showed that there was generally an increase in the productivity of the grazing system as a result of intercropping, the gross margins for the grazed intercrops were lower than the un-grazed treatments. The reduction in wheat grain yields were likely due to the poor recovery of wheat during the post-grazing period, resulting in less assimilates being available at grain fill. This presents the opportunity for further research focusing on grazing the crop component of the intercrop to different heights, using different grazing intensities and durations. There may also be opportunities for agronomic manipulation, through the use of fertilisers, to improve the re-growth of crops during the post-grazing period.

Dual-purpose cropping studies have shown that seasonal conditions can have an effect on yield results of grazed crops early in the growing season (Kelman & Dove 2009; Worrell *et al.* 1992). As this experiment was only conducted in a single season, more research is required into the grazing of intercrops, as it offers the potential to further increase flexibility of the intercropping system on a mixed farm, by providing an additional feed source for livestock.

This study has shown that a crop-pasture intercropping system is well-suited to the higher rainfall zones of southern Australia, as it provides production and environmental benefits without compromising profitability. There are opportunities for further research that may improve the productivity and profitability outcomes of this system, and increase the adaptability of intercropping within the study region. In addition to exploring how intercropping fits into a whole farm production system, the development of an intercropping system guideline, based on plant growth characteristics for species selection, seeding rates, row spacing design and agronomic requirements, would enable this system to be promoted as a perennial-annual system for on-farm adoption. By developing a system that reduces reliance on lucerne and cereals, this study has shown that intercropping can be adapted to longer-term rotations in a greater range of environments within the study region.

Chapter 10. References

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Chapter 11. <u>Appendix</u>

Appendix 1. Chapter 3

Herbicides and pesticides use at site 1 and 2 in 2006-08

Date	Chemical Name	Active	Rate	Site
April,2006	Round up	Glyphosate	1L/ha	1
July,2006	Treflan	Trifluralin	1.5L/ha	1
November,2006	Reglone	Diquat	1L/ha	1
June,2007	Dimethoate	Dimethoate		
June,2007	Fastac	Liquid hydrocarbonls and Alpha-cypermethrin	200ml/ha	1 & 2
August,2007	Decision	Diclofop-methyl and Sethoxydim	2L/ha	2
December,2007	Reglone	Diquat	1L/ha	1 & 2
June,2008	Dimethoate	Dimethoate		
June,2008	Fastac	Liquid hydrocarbonls and Alpha-cypermethrin	200ml/ha	1 & 2
December,2008	Reglone	Diquat	1L/ha	1 & 2

Appendix 2. Chapter 4

Wheat, lupin and canola plant numbers (plants/m²) from site 1 and 2 in 2006-08

	Site 1			Site 2	
Treatment	2006	2007	2008	2007	2008
Monoculture wheat	134	159	208	166	191
Wheat-lucerne	47	29	111	70	114
Wheat-chicory	63	28	120	82	99
Half monoculture wheat	61	31	107		
Monoculture lupin	80	43	34		
Lupin-lucerne	33	25	21		
Lupin-chicory	44	20	13		
Half monoculture lupin	33	24	13		
Monoculture canola		124	67		
Canola-lucerne		73	23		
Canola-chicory		70	16		

Appendix 3. Chapter 6

Raw soil moisture data from Site 1, 0-15cm in 2007

Date	Treatment	lower	estimate	upper	mm
24/6/2007	Canola-chicory	18.08	19.04	19.99	28.56
24/6/2007	Canola-lucerne	17.76	18.72	19.68	28.08
24/6/2007	Lupin-chicory	15.92	16.88	17.84	25.32
24/6/2007	Lupin-lucerne	17.90	18.86	19.82	28.29
24/6/2007	Canola	16.32	17.83	19.35	26.75
24/6/2007	Chicory	17.15	18.66	20.17	27.99
24/6/2007	Lucerne	17.51	19.03	20.54	28.54
24/6/2007	Lupin	16.49	18.00	19.51	27.00
24/6/2007	Wheat	18.26	19.77	21.29	29.66
24/6/2007	Wheat-chicory	17.52	18.48	19.43	27.72
24/6/2007	Wheat-lucerne	17.49	18.45	19.40	27.67
10/7/2007	Canola-chicory	26.35	27.30	28.26	40.96
10/7/2007	Canola-lucerne	25.71	26.67	27.62	40.00
10/7/2007	Lupin-chicory	23.96	24.92	25.87	37.38
10/7/2007	Lupin-lucerne	26.98	27.94	28.90	41.91
10/7/2007	Canola	23.77	25.28	26.80	37.93
10/7/2007	Chicory	25.15	26.67	28.18	40.00
10/7/2007	Lucerne	26.74	28.25	29.76	42.38
10/7/2007	Lupin	25.13	26.64	28.15	39.96
10/7/2007	Wheat	25.28	26.79	28.30	40.19
10/7/2007	Wheat-chicory	25.26	26.22	27.17	39.33
10/7/2007	Wheat-lucerne	24.76	25.72	26.67	38.58
28/7/2007	Canola-chicory	24.85	25.81	26.76	38.71
28/7/2007	Canola-lucerne	23.99	24.95	25.90	37.42
28/7/2007	Lupin-chicory	22.95	23.91	24.87	35.87
28/7/2007	Lupin-lucerne	24.37	25.33	26.29	38.00
28/7/2007	Canola	22.69	24.20	25.71	36.30
28/7/2007	Chicory	23.72	25.23	26.75	37.85
28/7/2007	Lucerne	23.72	25.23	26.75	37.85
28/7/2007	Lupin	23.21	24.73	26.24	37.09
28/7/2007	Wheat	24.10	25.61	27.12	38.41
28/7/2007	Wheat-chicory	23.13	24.09	25.04	36.13

28/7/2007	Wheat-lucerne	23.30	24.26	25.22	36.39
23/8/2007	Canola-chicory	25.03	25.98	26.94	38.98
23/8/2007	Canola-lucerne	23.88	24.84	25.80	37.26
23/8/2007	Lupin-chicory	21.49	22.45	23.40	33.67
23/8/2007	Lupin-lucerne	23.80	24.76	25.72	37.14
23/8/2007	Canola	23.22	24.73	26.25	37.10
23/8/2007	Chicory	22.99	24.50	26.01	36.75
23/8/2007	Lucerne	23.94	25.45	26.96	38.17
23/8/2007	Lupin	21.33	22.84	24.35	34.26
23/8/2007	Wheat	26.44	27.95	29.46	41.92
23/8/2007	Wheat-chicory	24.00	24.95	25.91	37.43
23/8/2007	Wheat-lucerne	24.95	25.91	26.87	38.87
27/9/2007	Canola-chicory	12.29	13.48	14.67	20.22
27/9/2007	Canola-lucerne	10.45	12.03	13.61	18.04
27/9/2007	Lupin-chicory	8.57	10.15	11.73	15.22
27/9/2007	Lupin-lucerne	14.87	16.45	18.03	24.68
27/9/2007	Canola	7.77	10.36	12.96	15.54
27/9/2007	Chicory	20.63	23.22	25.82	34.84
27/9/2007	Lucerne	22.44	25.04	27.63	37.56
27/9/2007	Lupin	12.41	15.01	17.60	22.51
27/9/2007	Wheat	7.40	10.00	12.59	15.00
27/9/2007	Wheat-chicory	13.71	15.28	16.86	22.93
27/9/2007	Wheat-lucerne	15.52	17.10	18.68	25.65

Raw soil moisture data from Site 1, 0-35cm in 2007

Date	Treatment	lower	estimate	upper	mm
28/7/2007	Canola-chicory	17.97	19.41	20.86	67.95
28/7/2007	Canola-lucerne	15.12	16.56	18.00	57.96
28/7/2007	Lupin-chicory	13.02	14.46	15.90	50.61
28/7/2007	Lupin-lucerne	19.85	21.29	22.74	74.53
28/7/2007	Canola	13.33	15.62	17.90	54.66
28/7/2007	Chicory	14.10	16.38	18.67	57.34
28/7/2007	Lucerne	15.82	18.10	20.38	63.35
28/7/2007	Lupin	15.65	17.93	20.22	62.77
28/7/2007	Wheat	18.20	20.48	22.77	71.69
28/7/2007	Wheat-chicory	14.71	16.15	17.60	56.54
28/7/2007	Wheat-lucerne	15.35	16.79	18.24	58.78
23/8/2007	Canola-chicory	18.43	19.88	21.33	69.58
23/8/2007	Canola-lucerne	15.70	17.15	18.60	60.04
23/8/2007	Lupin-chicory	13.67	15.12	16.57	52.92
23/8/2007	Lupin-lucerne	19.02	20.47	21.92	71.66
23/8/2007	Canola	13.18	15.55	17.92	54.44
23/8/2007	Chicory	17.03	19.32	21.60	67.61
23/8/2007	Lucerne	17.55	19.83	22.12	69.42
23/8/2007	Lupin	15.03	17.32	19.60	60.61
23/8/2007	Wheat	18.87	21.15	23.43	74.03
23/8/2007	Wheat-chicory	15.40	16.85	18.30	58.96
23/8/2007	Wheat-lucerne	16.42	17.87	19.32	62.56
14/9/2007	Canola-chicory	10.16	11.60	13.04	40.60
14/9/2007	Canola-lucerne	7.50	8.94	10.38	31.29
14/9/2007	Lupin-chicory	6.72	8.17	9.61	28.58
14/9/2007	Lupin-lucerne	13.28	14.73	16.17	51.54
14/9/2007	Canola	5.20	7.48	9.77	26.19
14/9/2007	Chicory	12.22	14.50	16.78	50.75
14/9/2007	Lucerne	10.23	12.52	14.80	43.81
14/9/2007	Lupin	9.45	11.73	14.02	41.07
14/9/2007	Wheat	11.30	13.58	15.87	47.54
14/9/2007	Wheat-chicory	7.41	8.85	10.30	30.99
14/9/2007	Wheat-lucerne	8.47	9.91	11.36	34.70

27/9/2007	Canola-chicory	13.10	14.61	16.12	51.13
27/9/2007	Canola-lucerne	10.96	12.60	14.24	44.09
27/9/2007	Lupin-chicory	10.36	12.00	13.64	42.00
27/9/2007	Lupin-lucerne	17.27	18.91	20.55	66.18
27/9/2007	Canola	8.08	10.70	13.31	37.44
27/9/2007	Chicory	17.92	20.54	23.16	71.89
27/9/2007	Lucerne	14.88	17.49	20.11	61.23
27/9/2007	Lupin	13.08	15.70	18.31	54.94
27/9/2007	Wheat	14.28	16.90	19.52	59.15
27/9/2007	Wheat-chicory	13.20	14.84	16.48	51.93
27/9/2007	Wheat-lucerne	11.02	12.66	14.30	44.30

Raw soil moisture data from Site 1, 0-15cm in 2008

Date	Treatment	lower	estimate	upper	mm
28/7/2008	Canola-chicory	15.27	16.13	17.03	24.19
28/7/2008	Canola-lucerne	15.44	16.30	17.21	24.45
28/7/2008	Lupin-chicory	16.17	17.08	18.03	25.62
28/7/2008	Lupin-lucerne	14.74	15.57	16.44	23.35
28/7/2008	Canola	14.92	16.26	17.72	24.39
28/7/2008	Chicory	14.75	16.08	17.52	24.11
28/7/2008	Lucerne	15.13	16.49	17.97	24.74
28/7/2008	Lupin	13.30	14.50	15.80	21.75
28/7/2008	Wheat	13.72	14.95	16.29	22.42
28/7/2008	Wheat-chicory	13.33	14.08	14.86	21.11
28/7/2008	Wheat-lucerne	14.20	14.99	15.83	22.49
27/8/2008	Canola-chicory	16.26	17.01	17.80	25.51
27/8/2008	Canola-lucerne	20.53	21.48	22.48	32.22
27/8/2008	Lupin-chicory	20.96	21.93	22.95	32.90
27/8/2008	Lupin-lucerne	18.29	19.14	20.02	28.70
27/8/2008	Canola	18.49	19.86	21.33	29.78
27/8/2008	Chicory	20.12	21.61	23.21	32.42
27/8/2008	Lucerne	20.26	21.77	23.38	32.65
27/8/2008	Lupin	16.45	17.67	18.98	26.50
27/8/2008	Wheat	19.19	20.61	22.14	30.92
27/8/2008	Wheat-chicory	18.14	18.98	19.86	28.48
27/8/2008	Wheat-lucerne	20.37	21.31	22.30	31.97
29/9/2008	Canola-chicory	10.49	11.41	12.41	17.11
29/9/2008	Canola-lucerne	11.65	12.67	13.79	19.01
29/9/2008	Lupin-chicory	11.67	12.69	13.81	19.04
29/9/2008	Lupin-lucerne	10.00	10.88	11.83	16.31
29/9/2008	Canola	9.30	10.62	12.13	15.93
29/9/2008	Chicory	10.57	12.07	13.79	18.11
29/9/2008	Lucerne	14.54	16.61	18.98	24.92
29/9/2008	Lupin	6.24	7.12	8.14	10.69
29/9/2008	Wheat	10.93	12.49	14.26	18.73
29/9/2008	Wheat-chicory	8.35	9.08	9.88	13.63
29/9/2008	Wheat-lucerne	11.96	13.01	14.16	19.52

20/10/2008	Canola-chicory	7.43	7.80	8.18	11.69
20/10/2008	Canola-lucerne	8.03	8.43	8.84	12.64
20/10/2008	Lupin-chicory	8.51	8.92	9.36	13.38
20/10/2008	Lupin-lucerne	8.12	8.52	8.94	12.78
20/10/2008	Canola	7.54	8.14	8.78	12.21
20/10/2008	Chicory	7.68	8.29	8.94	12.43
20/10/2008	Lucerne	9.40	10.14	10.93	15.21
20/10/2008	Lupin	6.93	7.47	8.06	11.21
20/10/2008	Wheat	6.68	7.20	7.77	10.80
20/10/2008	Wheat-chicory	7.10	7.45	7.81	11.17
20/10/2008	Wheat-lucerne	7.86	8.25	8.65	12.37
24/11/2008	Canola-chicory	6.75	7.23	7.74	10.84
24/11/2008	Canola-lucerne	7.06	7.56	8.10	11.34
24/11/2008	Lupin-chicory	7.33	7.85	8.41	11.77
24/11/2008	Lupin-lucerne	6.64	7.11	7.61	10.66
24/11/2008	Canola	6.29	7.01	7.82	10.52
24/11/2008	Chicory	6.96	7.76	8.65	11.64
24/11/2008	Lucerne	6.96	7.76	8.66	11.65
24/11/2008	Lupin	5.99	6.67	7.44	10.01
24/11/2008	Wheat	5.56	6.19	6.91	9.29
24/11/2008	Wheat-chicory	5.72	6.13	6.57	9.19
24/11/2008	Wheat-lucerne	6.80	7.28	7.80	10.92
8/12/2008	Canola-chicory	7.68	8.24	8.83	12.36
8/12/2008	Canola-lucerne	7.82	8.38	8.99	12.57
8/12/2008	Lupin-chicory	8.50	9.12	9.78	13.68
8/12/2008	Lupin-lucerne	7.88	8.45	9.06	12.67
8/12/2008	Canola	7.42	8.28	9.23	12.41
8/12/2008	Chicory	6.45	7.19	8.03	10.79
8/12/2008	Lucerne	8.19	9.13	10.19	13.70
8/12/2008	Lupin	7.23	8.13	9.14	12.19
8/12/2008	Wheat	6.87	7.66	8.55	11.50
8/12/2008	Wheat-chicory	6.42	6.89	7.39	10.33
8/12/2008	Wheat-lucerne	7.50	8.04	8.62	12.06

Raw soil moisture data from Site 1, 0-35cm in 2008

Date	Treatment	lower	estimate	upper	mm
28/7/2008	Canola-chicory	12.58	13.73	14.89	48.07
28/7/2008	Canola-lucerne	10.91	12.06	13.21	42.21
28/7/2008	Lupin-chicory	14.67	15.83	16.98	55.39
28/7/2008	Lupin-lucerne	11.86	13.01	14.17	45.55
28/7/2008	Canola	13.41	15.23	17.06	53.32
28/7/2008	Chicory	15.59	17.42	19.24	60.96
28/7/2008	Lucerne	13.36	15.18	17.01	53.14
28/7/2008	Lupin	10.16	11.98	13.81	41.94
28/7/2008	Wheat	12.04	13.87	15.69	48.53
28/7/2008	Wheat-chicory	10.63	11.79	12.94	41.25
28/7/2008	Wheat-lucerne	14.74	15.89	17.05	55.63
27/8/2008	Canola-chicory	15.89	17.15	18.40	60.01
27/8/2008	Canola-lucerne	15.53	16.78	18.03	58.73
27/8/2008	Lupin-chicory	19.58	20.83	22.09	72.92
27/8/2008	Lupin-lucerne	15.21	16.46	17.71	57.61
27/8/2008	Canola	16.15	18.13	20.11	63.47
27/8/2008	Chicory	18.50	20.48	22.46	71.69
27/8/2008	Lucerne	17.17	19.15	21.13	67.02
27/8/2008	Lupin	13.24	15.22	17.20	53.26
27/8/2008	Wheat	17.05	19.03	21.01	66.62
27/8/2008	Wheat-chicory	14.49	15.74	16.99	55.09
27/8/2008	Wheat-lucerne	19.54	20.79	22.05	72.78
29/9/2008	Canola-chicory	12.41	13.93	15.45	48.77
29/9/2008	Canola-lucerne	10.87	12.39	13.91	43.38
29/9/2008	Lupin-chicory	12.49	14.01	15.53	49.05
29/9/2008	Lupin-lucerne	8.43	9.95	11.47	34.84
29/9/2008	Canola	8.19	10.60	13.01	37.10
29/9/2008	Chicory	13.84	16.25	18.66	56.87
29/9/2008	Lucerne	14.46	16.87	19.27	59.03
29/9/2008	Lupin	4.14	6.55	8.96	22.92
29/9/2008	Wheat	8.68	11.08	13.49	38.79
29/9/2008	Wheat-chicory	6.19	7.71	9.23	27.00
29/9/2008	Wheat-lucerne	14.45	15.97	17.49	55.91

20/10/2008	Canola-chicory	7.52	8.64	9.76	30.24
20/10/2008	Canola-lucerne	6.60	7.73	8.85	27.04
20/10/2008	Lupin-chicory	8.16	9.29	10.41	32.50
20/10/2008	Lupin-lucerne	4.95	6.07	7.20	21.26
20/10/2008	Canola	5.11	6.88	8.66	24.09
20/10/2008	Chicory	9.41	11.18	12.96	39.14
20/10/2008	Lucerne	8.47	10.25	12.03	35.88
20/10/2008	Lupin	2.37	4.15	5.93	14.52
20/10/2008	Wheat	4.14	5.92	7.69	20.71
20/10/2008	Wheat-chicory	3.20	4.32	5.44	15.12
20/10/2008	Wheat-lucerne	7.52	8.65	9.77	30.26
24/11/2008	Canola-chicory	6.31	7.20	8.09	25.20
24/11/2008	Canola-lucerne	5.23	6.12	7.01	21.42
24/11/2008	Lupin-chicory	7.06	7.95	8.84	27.84
24/11/2008	Lupin-lucerne	3.89	4.78	5.67	16.73
24/11/2008	Canola	4.33	5.73	7.14	20.07
24/11/2008	Chicory	8.16	9.57	10.97	33.48
24/11/2008	Lucerne	5.39	6.80	8.21	23.80
24/11/2008	Lupin	3.19	4.60	6.01	16.10
24/11/2008	Wheat	3.28	4.68	6.09	16.39
24/11/2008	Wheat-chicory	2.88	3.77	4.66	13.21
24/11/2008	Wheat-lucerne	5.83	6.72	7.61	23.52
8/12/2008	Canola-chicory	6.90	7.87	8.85	27.56
8/12/2008	Canola-lucerne	5.94	6.91	7.89	24.20
8/12/2008	Lupin-chicory	7.07	8.05	9.02	28.16
8/12/2008	Lupin-lucerne	4.62	5.59	6.57	19.58
8/12/2008	Canola	5.51	7.05	8.59	24.68
8/12/2008	Chicory	8.58	10.12	11.65	35.41
8/12/2008	Lucerne	5.85	7.38	8.92	25.84
8/12/2008	Lupin	4.46	6.00	7.54	21.00
8/12/2008	Wheat	4.28	5.82	7.35	20.36
8/12/2008	Wheat-chicory	3.17	4.14	5.12	14.50
8/12/2008	Wheat-lucerne	6.75	7.73	8.70	27.04

Raw soil moisture data, date by treatment, from Site 2, 0-15cm in 2007

Date	Treatment	lower	estimate	upper	mm
24/6/2007	Chicory	19.41	21.38	23.35	32.08
24/6/2007	Lucerne	17.87	19.84	21.81	29.76
24/6/2007	Wheat	19.03	21.00	22.97	31.50
24/6/2007	Wheat-chicory	19.55	20.80	22.04	31.19
24/6/2007	Wheat-lucerne	19.34	20.59	21.84	30.88
10/7/2007	Chicory	30.24	31.78	33.31	47.66
10/7/2007	Lucerne	26.54	28.07	29.61	42.11
10/7/2007	Wheat	27.47	29.01	30.55	43.51
10/7/2007	Wheat-chicory	27.26	28.23	29.20	42.34
10/7/2007	Wheat-lucerne	28.89	29.86	30.83	44.79
28/7/2007	Chicory	29.36	30.49	31.62	45.74
28/7/2007	Lucerne	26.19	27.32	28.45	40.98
28/7/2007	Wheat	28.45	29.58	30.70	44.36
28/7/2007	Wheat-chicory	27.49	28.21	28.92	42.31
28/7/2007	Wheat-lucerne	27.71	28.42	29.13	42.63
23/8/2007	Chicory	27.71	28.88	30.06	43.32
23/8/2007	Lucerne	25.71	26.88	28.06	40.33
23/8/2007	Wheat	28.36	29.53	30.71	44.30
23/8/2007	Wheat-chicory	27.85	28.59	29.34	42.89
23/8/2007	Wheat-lucerne	27.92	28.67	29.41	43.00
14/9/2007	Chicory	16.01	17.86	19.71	26.79
14/9/2007	Lucerne	7.49	9.34	11.19	14.01
14/9/2007	Wheat	10.76	12.61	14.46	18.92
14/9/2007	Wheat-chicory	11.69	12.86	14.03	19.28
14/9/2007	Wheat-lucerne	6.89	8.06	9.23	12.09
27/9/2007	Chicory	22.36	26.12	29.88	39.17
27/9/2007	Lucerne	18.34	22.10	25.86	33.15
27/9/2007	Wheat	14.51	18.27	22.03	27.40
27/9/2007	Wheat-chicory	19.21	21.59	23.96	32.38
27/9/2007	Wheat-lucerne	15.48	17.85	20.23	26.78

Raw soil moisture data, treatment comparison, from Site 2, 0-35cm in 2007

Treatment	lower	estimate	upper	mm
Chicory	23.98	24.97	25.97	87.41
Lucerne	20.37	21.37	22.36	74.78
Wheat	19.23	20.23	21.22	70.80
Wheat-chicory	20.35	21.03	21.71	73.60
Wheat-lucerne	21.50	22.18	22.86	77.62

Raw soil moisture data, date by treatment, from Site 2, 0-15cm in 2008

Date	Treatment	lower	estimate	upper	mm
23/6/2008	Chicory	18.93	22.26	26.18	33.39
23/6/2008	Lucerne	13.41	15.76	18.54	23.65
23/6/2008	Wheat	13.78	16.20	19.05	24.30
23/6/2008	Wheat-chicory	15.30	16.95	18.78	25.43
23/6/2008	Wheat-lucerne	14.76	16.35	18.12	24.53
4/9/2008	Chicory	22.03	25.56	29.66	38.34
4/9/2008	Lucerne				
4/9/2008	Wheat				
4/9/2008	Wheat-chicory				
4/9/2008	Wheat-lucerne	24.50	27.99	31.98	41.99
30/9/2008	Chicory	16.11	18.68	21.67	28.03
30/9/2008	Lucerne	10.04	11.65	13.51	17.47
30/9/2008	Wheat	9.96	11.55	13.39	17.32
30/9/2008	Wheat-chicory	12.53	13.76	15.11	20.64
30/9/2008	Wheat-lucerne	14.62	16.06	17.64	24.09
21/10/2008	Chicory	8.66	9.67	10.81	14.51
21/10/2008	Lucerne	7.44	8.31	9.28	12.46
21/10/2008	Wheat	6.80	7.82	8.98	11.73
21/10/2008	Wheat-chicory	9.96	10.86	11.83	16.28
21/10/2008	Wheat-lucerne	7.07	7.60	8.16	11.40
26/11/2008	Chicory	8.57	9.37	10.25	14.06
26/11/2008	Lucerne	6.20	6.78	7.41	10.17
26/11/2008	Wheat	6.91	7.56	8.27	11.35
26/11/2008	Wheat-chicory	8.07	8.54	9.04	12.81
26/11/2008	Wheat-lucerne	7.37	7.80	8.26	11.71

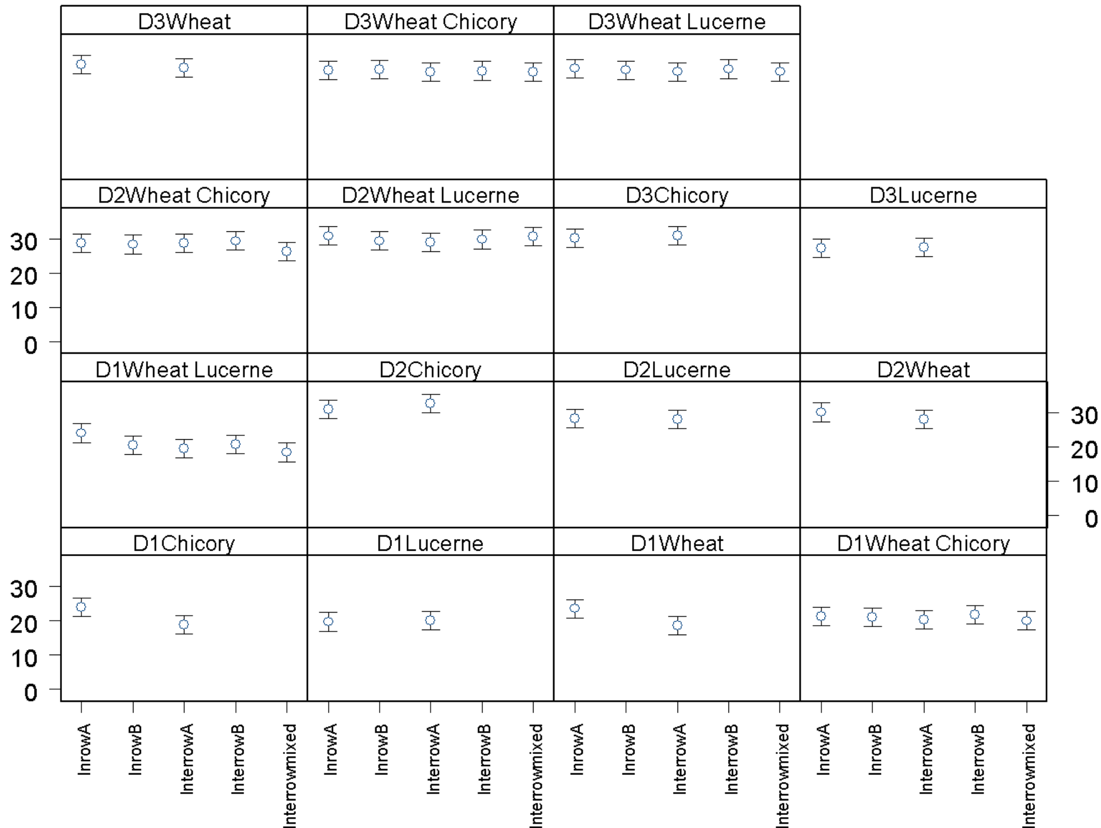
9/12/2008	Chicory	9.04	10.42	12.02	15.63
9/12/2008	Lucerne				0.00
9/12/2008	Wheat	7.66	9.30	11.28	13.95
9/12/2008	Wheat-chicory	9.15	10.04	11.02	15.06
9/12/2008	Wheat-lucerne	6.84	7.71	8.68	11.56
10/12/2008	Chicory	9.14	10.27	11.55	15.41
10/12/2008	Lucerne	8.10	9.11	10.24	13.66
10/12/2008	Wheat	8.66	9.74	10.95	14.61
10/12/2008	Wheat-chicory	10.52	11.33	12.21	17.00
10/12/2008	Wheat-lucerne	8.28	8.94	9.65	13.41

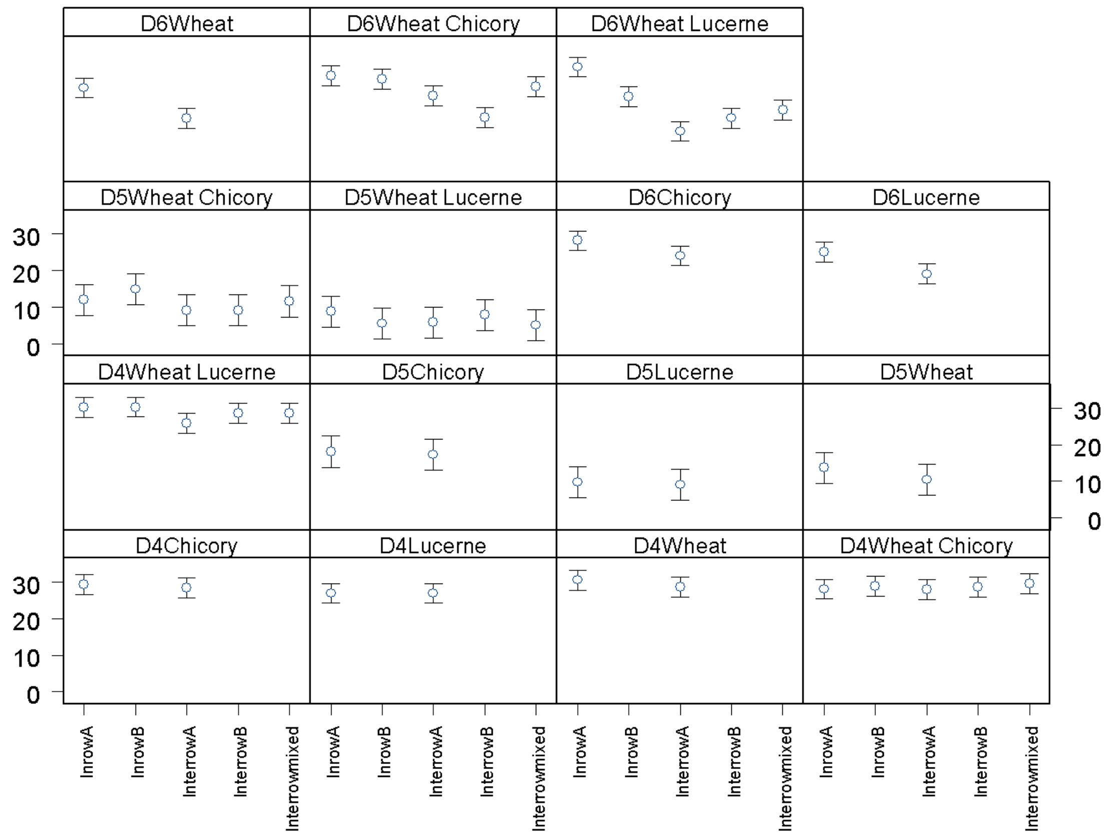
Raw soil moisture data, date by treatment, from Site 2, 0-35cm in 2008

Date	Treatment	lower	estimate	upper	mm
23/6/2008	Chicory	24.39	26.52	28.64	92.81
23/6/2008	Lucerne	19.38	21.50	23.62	75.25
23/6/2008	Wheat	20.09	22.22	24.34	77.76
23/6/2008	Wheat-chicory	19.02	20.36	21.70	71.26
23/6/2008	Wheat-lucerne	21.51	22.85	24.20	79.99
4/9/2008	Chicory	29.99	31.30	32.62	109.56
4/9/2008	Lucerne				
4/9/2008	Wheat				
4/9/2008	Wheat-chicory				
4/9/2008	Wheat-lucerne	26.89	28.00	29.10	97.98
30/9/2008	Chicory	23.29	25.55	27.81	89.43
30/9/2008	Lucerne	14.07	16.33	18.59	57.17
30/9/2008	Wheat	16.94	19.20	21.46	67.20
30/9/2008	Wheat-chicory	15.97	17.40	18.83	60.90
30/9/2008	Wheat-lucerne	20.90	22.33	23.76	78.17
21/10/2008	Chicory	14.66	16.87	19.08	59.03
21/10/2008	Lucerne	7.29	9.50	11.71	33.25
21/10/2008	Wheat	10.43	12.97	15.50	45.39
21/10/2008	Wheat-chicory	10.92	12.50	14.08	43.76
21/10/2008	Wheat-lucerne	11.24	12.65	14.07	44.29
26/11/2008	Chicory	12.88	14.67	16.45	51.33
26/11/2008	Lucerne	7.18	8.97	10.75	31.38
26/11/2008	Wheat	9.35	11.13	12.92	38.97
26/11/2008	Wheat-chicory	7.99	9.12	10.25	31.92
26/11/2008	Wheat-lucerne	9.22	10.35	11.47	36.21
9/12/2008	Chicory	12.45	15.22	17.99	53.27
9/12/2008	Lucerne				0.00
9/12/2008	Wheat	11.39	14.26	17.13	49.91
9/12/2008	Wheat-chicory	9.34	11.10	12.86	38.84
9/12/2008	Wheat-lucerne	10.83	12.64	14.45	44.25
10/12/2008	Chicory	12.61	15.88	19.15	55.59
10/12/2008	Lucerne	7.59	11.03	14.48	38.62
10/12/2008	Wheat	10.38	13.65	16.92	47.77

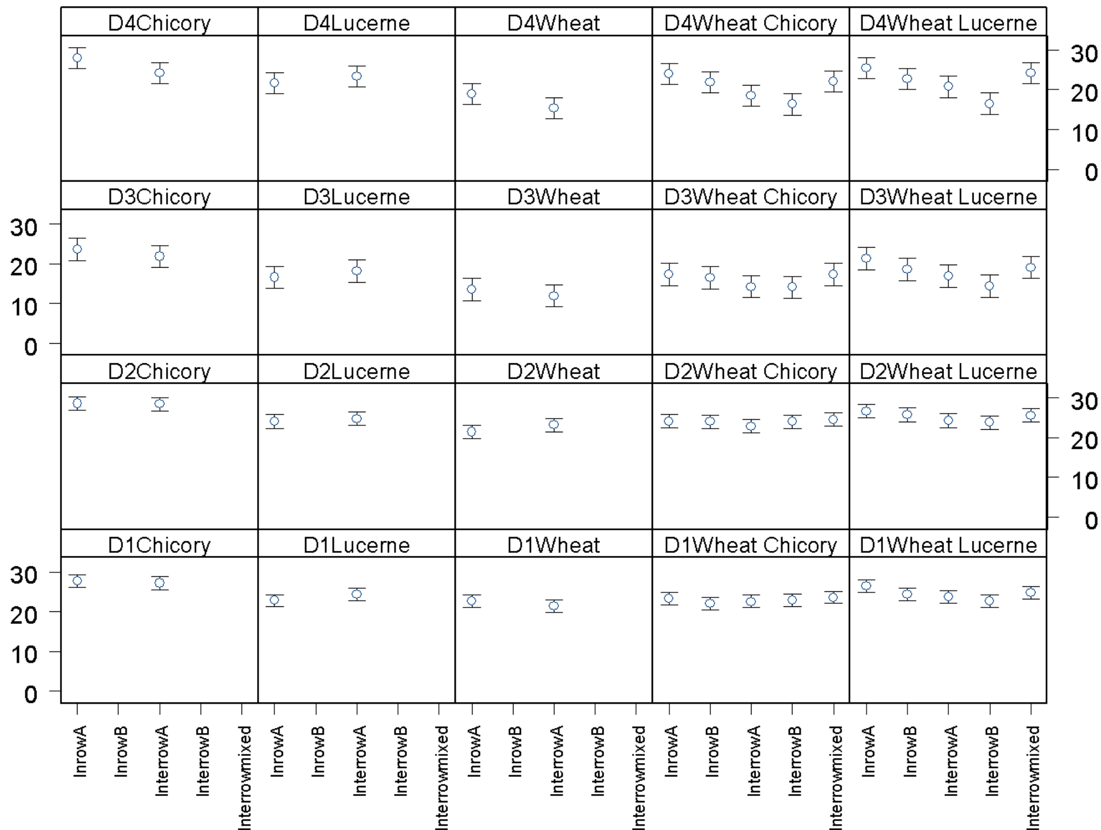
10/12/2008	Wheat-chicory	9.44	11.52	13.60	40.32
10/12/2008	Wheat-lucerne	9.82	11.90	13.98	41.65

Soil moisture, date by treatment by location, from Site 2, 0-15cm in 2007




D6Wheat
D6Wheat Chicory
D6Wheat Lucerne
D5Wheat Chicory
D5Wheat Lucerne
D6Chicory
D6Lucerne
D4Wheat Lucerne
D5Chicory
D5Lucerne
D5Wheat
D4Chicory
D4Lucerne
D4Wheat
D4Wheat Chicory
0
10
20
30
InrowA
InrowB
InterrowA
InterrowB
Interrowmixed

Soil moisture, date by treatment by location, from Site 2, 0-35cm in 2007



Appendix 4. Chapter 7

Raw soil moisture data, treatment by grazing, 0-15cm in 2008

Treatment	Grazing	lower	estimate	upper	mm
Chicory	Grazed	12.22	12.96	13.74	19.43
Chicory	Un-grazed	12.14	12.84	13.58	19.26
Lucerne	Grazed	10.40	11.06	11.76	16.59
Lucerne	Un-grazed	9.38	9.97	10.60	14.95
Wheat	Grazed	10.43	11.11	11.84	16.67
Wheat	Un-grazed	9.74	10.38	11.06	15.57
Wheat Chicory	Grazed	10.71	11.13	11.56	16.69
Wheat Chicory	Un-grazed	11.96	12.44	12.94	18.66
Wheat Lucerne	Grazed	12.90	13.41	13.94	20.12
Wheat Lucerne	Un-grazed	10.38	10.78	11.19	16.17

Raw soil moisture data, date by treatment for grazing trial, 0-15cm in 2008

Date	Treatment	lower	estimate	upper	mm
4/9/2008	Chicory	21.12	23.44	26.00	35.15
4/9/2008	Lucerne				
4/9/2008	Wheat				
4/9/2008	Wheat-chicory				
4/9/2008	Wheat-lucerne	25.25	27.70	30.40	41.55
30/9/2008	Chicory	16.63	18.90	21.48	28.35
30/9/2008	Lucerne	10.48	11.91	13.54	17.86
30/9/2008	Wheat	9.75	11.08	12.60	16.62
30/9/2008	Wheat-chicory	12.34	13.38	14.51	20.07
30/9/2008	Wheat-lucerne	14.49	15.71	17.04	23.57
21/10/2008	Chicory	8.64	9.42	10.29	14.14
21/10/2008	Lucerne	7.87	8.52	9.22	12.78
21/10/2008	Wheat	7.71	8.51	9.39	12.76
21/10/2008	Wheat-chicory	9.12	9.65	10.21	14.48
21/10/2008	Wheat-lucerne	8.44	8.93	9.44	13.39
26/11/2008	Chicory	9.07	9.74	10.47	14.61
26/11/2008	Lucerne	6.70	7.20	7.73	10.79
26/11/2008	Wheat	7.34	7.89	8.48	11.84
26/11/2008	Wheat-chicory	8.01	8.39	8.78	12.58
26/11/2008	Wheat-lucerne	8.17	8.55	8.95	12.83
9/12/2008	Chicory	9.06	10.08	11.22	15.13
9/12/2008	Lucerne				0.00
9/12/2008	Wheat	7.69	8.82	10.11	13.23
9/12/2008	Wheat-chicory	8.59	9.18	9.81	13.77
9/12/2008	Wheat-lucerne	8.85	9.62	10.47	14.44
10/12/2008	Chicory	10.23	11.34	12.57	17.01
10/12/2008	Lucerne	9.07	10.05	11.14	15.07
10/12/2008	Wheat	9.05	10.04	11.12	15.05
10/12/2008	Wheat-chicory	9.98	10.65	11.37	15.97
10/12/2008	Wheat-lucerne	9.65	10.32	11.04	15.48

Raw soil moisture data, date by grazing, 0-35cm in 2008

Date	Treatment	lower	estimate	upper	mm
4/9/2008	Grazed	22.81	23.59	24.37	82.56
4/9/2008	Un-grazed	26.64	27.40	28.15	95.89
30/9/2008	Grazed	19.14	19.96	20.77	69.85
30/9/2008	Un-grazed	19.43	20.25	21.06	70.87
21/10/2008	Grazed	11.67	12.52	13.36	43.80
21/10/2008	Un-grazed	11.93	12.76	13.60	44.68
6/12/2008	Grazed	10.35	11.03	11.71	38.60
6/12/2008	Un-grazed	10.02	10.69	11.37	37.43
9/12/2008	Grazed	11.82	12.55	13.28	43.93
9/12/2008	Un-grazed	11.71	12.44	13.17	43.54
10/12/2008	Grazed	12.01	12.76	13.50	44.65
10/12/2008	Un-grazed	11.98	12.73	13.48	44.56

Raw soil moisture data, date by treatment for grazing trial, 0-35cm in 2008

Date	Treatment	lower	estimate	upper	mm
4/9/2008	Chicory	27.81	28.80	29.78	100.80
4/9/2008	Lucerne				0.00
4/9/2008	Wheat				0.00
4/9/2008	Wheat-chicory				0.00
4/9/2008	Wheat-lucerne	25.70	26.45	27.20	92.58
30/9/2008	Chicory	23.51	25.17	26.82	88.08
30/9/2008	Lucerne	15.40	17.06	18.71	59.70
30/9/2008	Wheat	16.93	18.58	20.24	65.04
30/9/2008	Wheat-chicory	16.48	17.52	18.57	61.33
30/9/2008	Wheat-lucerne	20.81	21.85	22.90	76.49
21/10/2008	Chicory	13.85	15.57	17.29	54.49
21/10/2008	Lucerne	8.78	10.43	12.09	36.52
21/10/2008	Wheat	10.85	12.65	14.44	44.26
21/10/2008	Wheat-chicory	10.31	11.41	12.50	39.92
21/10/2008	Wheat-lucerne	11.89	12.98	14.07	45.42
26/11/2008	Chicory	13.13	14.52	15.91	50.81
26/11/2008	Lucerne	7.76	9.15	10.54	32.03
26/11/2008	Wheat	9.45	10.84	12.23	37.95
26/11/2008	Wheat-chicory	8.67	9.55	10.43	33.43
26/11/2008	Wheat-lucerne	9.67	10.55	11.43	36.94
9/12/2008	Chicory	13.52	15.01	16.49	52.53
9/12/2008	Lucerne				0.00
9/12/2008	Wheat	12.54	14.05	15.57	49.19
9/12/2008	Wheat-chicory	9.96	10.90	11.85	38.16
9/12/2008	Wheat-lucerne	11.15	12.11	13.06	42.38
10/12/2008	Chicory	14.06	15.59	17.12	54.57
10/12/2008	Lucerne	9.97	11.52	13.07	40.33
10/12/2008	Wheat	11.41	12.94	14.47	45.30
10/12/2008	Wheat-chicory	10.48	11.46	12.43	40.09
10/12/2008	Wheat-lucerne	11.67	12.64	13.61	44.24

Significance of fixed factors for site 2, 0-35cm in 2008

Fixed term	Wald statistic	d.f.	chi pr
Date	1575.76	5	<0.001
Grazing	6.66	1	0.010
Treatment	37.97	4	<0.001
Date.Grazing	23.35	5	<0.001
Date.Treatment	64.11	16	<0.001
Grazing.Treatment	1.45	4	0.835
Treatment.Location	10.96	11	0.447
Grazing.Date.Treatment	21.39	16	0.164
Grazing.Treatment.Location	7.34	11	0.771
Date.Treatment.Location	56.87	48	0.178

Plant height (cm) for grazed and un-grazed treatments for Site 2 in 2008

	Plant Height taken 07/09/2008		Plant Height taken 11/12/2008	
Treatment	Grazed	Un-grazed	Grazed	Un-grazed
Monoculture wheat	29	49	68	89
Wheat-lucerne	28	49	66	84
Wheat-chicory	30	45	67	81
l.s.d (P<0.05)	Treatment	3.5	Treatment	3.1
	Grazing	2.8	Grazing	2.5
	Treatment.grazing	4.9	Treatment.grazing	4.3
Monoculture lucerne	10	35	56	63
Wheat-lucerne	9	37	64	70
l.s.d (P<0.05)	Treatment	n.s.	Treatment	n.s.
	Grazing	2.7	Grazing	n.s.
	Treatment.grazing	3.8	Treatment.grazing	n.s.
Monoculture chicory	6	10	43	39
Wheat-chicory	8	15	60	49
l.s.d (P<0.05)	Treatment	2.0	Treatment	n.s.
	Grazing	2.0	Grazing	n.s.
	Treatment.grazing	2.6	Treatment.grazing	n.s.

Appendix 5. Chapter 8

Logic codes used to control the simulated growth of lucerne during the autumn period was as follows:

```
!Reset
!Reduce growth code
if day = 32  then
    lucerne reduce
    reduce_status = 0.5
endif
if (day = 140 and lucerne.crop_class = 'reduced') then
   lucerne spring
   reduce_status = 0
endif
```

Logic codes were also used to achieve lucerne cuts on the same day in the simulations as happen in the field measurements. The coding used was as follows:

```
!Cutting during the growing season in 2006 and 2007 and 2008 and 2009
 if year = 2006 and day = 283 then
        lucerne harvest height = 20 (mm), remove = 0
    endif
 if year = 2006 and day = 341 then
        lucerne harvest height = 20 (mm), remove = 0
   endif
if year = 2007 and day = 67 then
     lucerne harvest height = 20 (mm), remove = 0
    endif
 if year = 2007 and day = 130 then
        lucerne harvest height = 20 (mm), remove = 0
    endif
 if year = 2007 and day = 245 then
        lucerne harvest height = 20 (mm), remove = 0
   endif
if year = 2007 and day = 298 then
     lucerne harvest height = 20 (mm), remove = 0
    endif
```

```
 if year = 2007 and day = 334 then
  lucerne harvest height = 20 (mm), remove = 0
 endif
if year = 2008 and day = 86 then
     lucerne harvest height = 20 (mm), remove = 0
 endif
if year = 2008 and day = 136 then
     lucerne harvest height = 20 (mm), remove = 0
endif
if year = 2008 and day = 253 then
  lucerne harvest height = 20 (mm), remove = 0
 endif
if year = 2008 and day = 310 then
     lucerne harvest height = 20 (mm), remove = 0
 endif
if year = 2008 and day = 350 then
     lucerne harvest height = 20 (mm), remove = 0
endif
if year = 2009 and day = 26 then
  lucerne harvest height = 20 (mm), remove = 0
 endif
if year = 2009 and day = 126 then
  lucerne harvest height = 20 (mm), remove = 0
 endif
```

Economics for grain crops

Grain Price ($/tonne)	2001	2002	2003	2004	2005	2006	2007	2008
Wheat	163	351	146	133	139	187	306	259
Lupin	200	270	176	300	224	450	450	350
Canola			325	317	287	360	541	468

Income Grain Sales	2001	2002	2003	2004	2005	2006	2007	2008
Monoculture wheat	431.62	1126.71	335.07	332.50	397.12	133.52	1082.02	1045.32
Mono wheat + 20%	517.95	1352.05	402.08	399.00	476.55	160.22	1298.42	1254.39
Mono wheat - 20%	345.30	901.37	268.06	266.00	317.70	106.81	865.61	836.26
Monoculture lupin	415.60	588.60	443.52	637.80	500.64	205.20	882.90	749.70
Mono lupin + 20%	498.72	706.32	532.22	765.36	600.77	246.24	1059.48	899.64
Mono lupin - 20%	332.48	470.88	354.82	510.24	400.51	164.16	706.32	599.76
Monoculture canola			747.18	725.93	641.73	389.16	1182.63	1129.75
Mono canola + 20%			896.61	871.12	770.08	466.99	1419.15	1355.70
Mono canola - 20%			597.74	580.74	513.39	311.33	946.10	903.80

Note: Mono = monoculture

Costs ($/ha) for Monoculture Crops								
Chemical	2001	2002	2003	2004	2005	2006	2007	2008
Wheat	45.0	36.6	35.7	69.0	72.0	59.2	78.0	26.0
Lupin	46.1	35.5	22.2	59.2	71.2	48.3	53.7	23.8
Canola			42.3	75.3	120.0	64.7	43.9	57.9
Fertiliser								
Wheat	47.5	43.0	42.8	64.5	47.0	72.8	113.3	78.3
Lupin	38.0	41.5	41.3	34.0	33.7	42.6	45.8	68.4
Canola			79.8	91.8	94.1	123.8	158.8	125.7
Fuel								
Wheat	9.0	9.6	9.4	30.0	42.6	19.7	42.0	25.6
Lupin	9.0	4.6	4.6	30.0	42.6	19.8	29.2	25.6
Canola			6.3	30.0	42.6	39.5	38.8	27.0
Other								
Wheat	20.0	29.8	40.0	30.0	30.0			4.0
Lupin	30.0	40.0	40.0	40.0	61.6		39.9	
Canola			70.0	66.3	70.9	73.8	16.4	39.9
Seed								
Wheat	12.0	15.6	18.0	17.9	18.0	27.7	28.3	25.6
Lupin	25.0	25.0	94.7	35.9	34.0	28.1	27.4	38.0
Canola			21.9	22.4	34.6	18.8	20.9	16.8
Freight&Cartage								
Wheat			8.0	16.8	34.5		37.0	24.3
Lupin				9.2	2.7			
Canola			15.5	13.8	13.0	1.5	16.7	21.8
Less grazing penalty in form of supp feed								
All Crops	44.29	63.88	38.15	34.75	30.90	8.99	49.73	47.14
TOTAL COSTS								
Wheat	177.79	198.48	192.05	262.95	275.00	188.39	348.33	230.89
Lupin	192.39	210.48	240.95	243.05	276.70	147.79	245.73	202.94
Canola	0.00	0.00	273.95	334.35	406.10	331.06	345.23	336.24

Income Grain Sales	2001	2002	2003	2004	2005	2006	2007	2008
Wh-Luc	258.97	811.23	187.64	196.18	246.22	66.76	779.05	752.63
Wh-Luc + 20%	372.92	973.48	241.25	271.32	343.11	80.11	934.86	903.16
Wh-Luc - 20%	193.37	540.82	166.19	146.30	181.09	53.41	536.68	602.11
Wh-Ch	323.72	968.97	207.74	239.40	313.73	80.11	973.81	1003.51
Wh-Ch + 20%	435.08	1257.41	309.60	331.17	424.13	96.13	1272.45	1254.39
Wh-Ch - 20%	207.18	648.98	160.83	159.60	196.97	64.09	683.83	719.18
Lup-Luc	112.21	158.92	119.75	172.21	135.17	55.40	238.38	202.42
Lup-Luc +20%	134.65	190.71	143.70	206.65	162.21	66.48	286.06	242.90
Lup-Luc - 20%	89.77	127.14	95.80	137.76	108.14	44.32	190.71	161.94
Lup-Ch	222.35	314.90	237.28	341.22	267.84	109.78	472.35	401.09
Lup-Ch + 20%	266.82	377.88	284.74	409.47	321.41	131.74	566.82	481.31
Lup-Ch - 20%	177.88	251.92	189.83	272.98	214.27	87.83	377.88	320.87
Can-Luc			605.21	588.00	519.80	315.22	957.93	915.10
Can-Luc + 20%			726.25	705.60	623.76	378.26	1149.51	1098.12
Can-Luc - 20%			484.17	470.40	415.84	252.18	766.34	732.08
Can-Ch			687.40	667.86	590.39	358.03	1088.02	1039.37
Can-Ch + 20%			824.88	801.43	708.47	429.63	1305.62	1247.25
Can-Ch - 20%			549.92	534.28	472.31	286.42	870.41	831.50

Note: Can = canola; Wh = wheat; Lup = lupin; Luc = lucerne; Ch = chicory

Costs ($/ha) for Intercrop Grain Component								
Chemical	2001	2002	2003	2004	2005	2006	2007	2008
Wheat	45.0	36.6	35.7	69.0	72.0	59.2	78.0	26.0
Lupin	46.1	35.5	22.2	59.2	71.2	48.3	53.7	23.8
Canola			42.3	75.3	120.0	64.7	43.9	57.9
Fertiliser								
Wheat	23.8	21.5	21.4	32.3	23.5	36.4	56.7	39.2
Lupin	19.0	20.8	20.7	17.0	16.9	21.3	22.9	34.2
Canola			39.9	45.9	47.1	61.9	79.4	62.9
Fuel								
Wheat	9.0	9.6	9.4	30.0	42.6	19.7	42.0	25.6
Lupin	9.0	4.6	4.6	30.0	42.6	19.8	29.2	25.6
Canola			6.3	30.0	42.6	39.5	38.8	27.0
Other								
Wheat	20.0	29.8	40.0	30.0	30.0			4.0
Lupin	30.0	40.0	40.0	40.0	61.6		39.9	
Canola			70.0	66.3	70.9	73.8	16.4	39.9
Seed								
Wheat	6.0	7.8	9.0	9.0	9.0	13.9	14.2	12.8
Lupin	12.5	12.5	47.4	18.0	17.0	14.0	13.7	19.0
Canola			11.0	11.2	17.3	9.4	10.5	8.4
Freight&Cartage								
Wheat			4.0	8.4	17.3		18.5	12.1
Lupin				4.6	1.4			
Canola			7.8	6.9	6.5	0.7	8.4	10.9
TOTAL COSTS								
Wheat	103.80	105.30	119.50	178.70	194.40	129.20	209.40	119.65
Lupin	116.60	113.40	134.90	168.80	210.70	103.40	159.40	102.60
Canola	0.00	0.00	177.30	235.60	304.40	250.00	197.40	207.00

Gross Margin	2001.00	2002.00	2003.00	2004.00	2005.00	2006.00	2007.00	2008.00
Wh-Luc	155.17	705.93	68.14	17.48	51.82	-62.44	569.65	632.98
Wh-Luc + 20%	269.12	868.18	121.75	92.62	148.71	-49.09	725.46	783.51
Wh-Luc - 20%	89.57	435.52	46.69	-32.40	-13.31	-75.79	327.28	482.46
Wh-Ch	219.92	863.67	88.24	60.70	119.33	-49.09	764.41	883.86
Wh-Ch + 20%	331.28	1152.11	190.10	152.47	229.73	-33.07	1063.05	1134.74
Wh-Ch - 20%	103.38	543.68	41.33	-19.10	2.57	-65.11	474.43	599.53
Lup-Luc	-4.39	45.52	-15.15	3.41	-75.53	-48.00	78.98	99.82
Lup-Luc +20%	18.05	77.31	8.80	37.85	-48.49	-36.92	126.66	140.30
Lup-Luc - 20%	-26.83	13.74	-39.10	-31.04	-102.56	-59.08	31.31	59.34
Lup-Ch	105.75	201.50	102.38	172.42	57.14	6.38	312.95	298.49
Lup-Ch + 20%	150.22	264.48	149.84	240.67	110.71	28.34	407.42	378.71
Lup-Ch - 20%	61.28	138.52	54.93	104.18	3.57	-15.57	218.48	218.27
Can-Luc			427.91	352.40	215.40	65.22	760.53	708.10
Can-Luc + 20%			548.95	470.00	319.36	128.26	952.11	891.12
Can-Luc - 20%			306.87	234.80	111.44	2.18	568.94	525.08
Can-Ch			510.10	432.26	285.99	108.03	890.62	832.37
Can-Ch + 20%			647.58	565.83	404.07	179.63	1108.22	1040.25
Can-Ch - 20%			372.62	298.68	167.91	36.42	673.01	624.50

Note: Can = canola; Wh = wheat; Lup = lupin; Luc = lucerne; Ch = chicory

Livestock and Wool Prices	2001		2002		2003		2004	
Livestock Prices (c/kg)	IGS (Oct)	OGS (Feb)	IGS (Oct)	OGS (Feb)	IGS (Oct)	OGS (Feb)	IGS (Oct)	OGS (Feb)
Price 20-22kg dress	280	315	333	330	340	340	353	333
Price wool $/kg clean	7.1		7.1		4.5		5.4	

Year	2001		2002		2003		2004	
	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS
DSE rating/ha	12	4	13	5	17	9	13	5

Livestock and Wool Prices	2005		2006		2007		2008	
Livestock Prices (c/kg)	IGS (Oct)	OGS (Feb)	IGS (Oct)	OGS (Feb)	IGS (Oct)	OGS (Feb)	IGS (Oct)	OGS (Feb)
Price 20-22kg dress	318	335	270	313	270	330	360	400
Price wool $/kg clean	8		8.6		9.1		8.9	

Year	2005		2006		2007		2008	
	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS
DSE rating/ha	12	4	13	5	14	6	9	4

Note: IGS = In-growing season; OGS = out-of-growing season

Income from Grazing	2001		2002		2003		2004		2005		2006		2007		2008	
($/ha)	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS
Mono lucerne	86.26	19.08	69.56	12.12	101.82	19.39	104.41	18.99	81.94	15.71	16.86	0.00	50.83	9.83	73.68	7.35
Mono lucerne + 20%	105.59	29.72	85.81	19.99	124.00	30.87	127.21	30.23	100.51	25.73	21.22	0.89	52.93	20.96	92.76	14.16
Mono lucerne - 20%	67.29	9.52	53.55	17.66	79.13	18.20	81.54	16.82	63.52	14.52	12.60	0.93	38.57	8.79	57.90	11.92
Wheat-lucerne	24.23	4.42	18.25	1.47	28.21	4.03	29.29	3.95	22.43	3.31	0.00	0.00	10.53	0.49	19.73	1.78
Wheat-lucerne + 20%	31.46	6.45	23.49	2.66	36.59	7.05	36.67	6.12	28.95	4.70	0.50	0.00	16.86	2.04	25.39	3.23
Wheat-lucerne - 20%	18.65	2.49	9.00	0.00	21.23	2.11	21.67	2.06	16.16	1.49	0.00	0.00	6.18	0.00	9.73	0.00
Lupin-lucerne	65.87	8.59	40.30	2.04	78.54	8.56	80.04	8.38	49.65	4.70	2.15	0.00	25.70	1.47	61.09	6.44
Lupin-lucerne + 20%	81.78	11.74	56.51	5.31	95.83	12.80	97.98	11.79	77.59	9.34	5.18	0.00	38.57	3.92	22.48	0.15
Lupin-lucerne - 20%	43.72	3.68	35.83	0.49	48.57	4.03	50.43	3.29	34.22	2.08	0.00	0.00	13.72	0.00	0.00	0.00
Canola-lucerne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mono chicory	57.67	18.26	46.10	11.92	66.78	18.81	68.37	18.42	55.04	15.40	11.62	2.27	34.21	10.29	49.84	14.45
Mono chicory -20%	69.20	22.80	56.36	15.17	82.15	23.93	83.46	23.44	66.38	20.22	14.70	2.88	41.72	13.42	60.93	18.06
Mono chicory + 20%	45.08	13.69	35.63	7.96	52.54	13.82	53.58	13.54	42.29	11.30	8.62	1.02	26.07	7.27	38.52	9.65
Wheat-chicory	5.90	2.21	3.72	0.45	6.28	2.84	6.52	1.66	5.04	1.02	0.45	0.00	2.36	0.46	4.02	0.56
Wheat-chicory +20%	7.43	3.48	5.32	1.01	9.03	3.06	9.37	3.00	6.70	2.35	0.97	0.00	3.60	1.08	5.75	1.31
Wheat-chicory - 20%	3.74	0.96	2.10	0.00	4.54	1.04	3.86	1.02	2.78	0.46	0.00	0.00	1.09	0.00	2.28	0.00
Lupin-chicory	21.79	4.13	17.39	1.65	26.46	3.76	26.35	3.79	21.03	3.01	3.02	0.00	12.46	1.69	18.80	2.05
Lupin-chicory +20%	27.96	5.49	21.14	2.97	33.03	5.93	33.34	5.11	26.45	4.39	4.32	0.00	15.60	2.39	22.86	3.68
Lupin-chicory - 20%	16.93	2.21	12.62	1.01	19.65	2.38	20.06	2.33	15.58	1.67	1.71	0.00	8.68	0.46	13.64	1.31
Canola-chicory	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Income from wool	2001		2002		2003		2004		2005		2006		2007		2008	
($/ha)	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS	IGS	OGS
Mono lucerne	220.54	49.75	153.98	32.04	135.87	29.68	161.04	35.62	207.62	44.08	56.71	0.00	182.02	34.70	205.77	40.50
Mono lucerne + 20%	261.60	74.16	184.27	49.75	160.36	44.98	190.14	53.98	248.78	68.29	95.46	15.57	192.43	63.98	247.88	63.11
Mono lucerne - 20%	187.90	45.71	117.70	43.96	110.87	26.70	126.53	31.88	166.50	41.86	58.61	6.77	142.73	32.16	153.63	33.94
Wheat-lucerne	77.16	28.29	54.44	15.71	47.78	16.62	57.33	19.94	74.52	26.57	0.00	0.00	54.18	13.89	68.25	19.69
Wheat-lucerne + 20%	92.76	37.18	67.10	21.30	57.62	22.76	68.02	25.47	90.72	31.87	4.69	0.00	77.63	23.78	84.11	26.70
Wheat-lucerne - 20%	62.25	22.10	23.82	0.00	38.39	11.76	48.02	13.21	57.77	18.17	0.00	0.00	26.78	0.00	29.86	0.00
Lupin-lucerne	181.82	44.05	99.52	16.41	114.87	25.14	135.31	30.16	148.45	31.49	12.65	0.00	116.25	19.87	174.97	37.95
Lupin-lucerne + 20%	217.53	54.92	139.58	30.27	136.62	33.28	161.45	38.29	214.94	47.94	22.50	0.00	155.09	32.40	82.92	9.83
Lupin-lucerne - 20%	129.86	25.91	105.37	10.23	76.69	16.02	94.03	17.27	110.19	20.10	0.00	0.00	50.09	0.00	0.00	0.00
Canola-lucerne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mono chicory	261.92	70.49	179.72	46.22	159.31	42.96	188.49	51.56	246.00	66.35	79.46	14.00	217.24	52.89	225.28	57.94
Mono chicory -20%	314.30	86.90	214.83	57.06	194.74	53.57	228.67	64.28	299.09	82.94	95.76	17.03	259.13	66.29	271.49	70.27
Mono chicory + 20%	209.34	54.97	145.17	32.95	128.14	32.78	151.05	39.34	199.17	49.48	63.38	7.40	167.87	38.49	181.97	41.30
Wheat-chicory	34.78	12.48	21.56	3.44	18.85	8.41	23.96	7.36	32.76	7.12	4.69	0.00	21.72	4.10	26.61	3.96
Wheat-chicory +20%	40.81	18.06	28.63	6.46	26.29	9.62	31.55	11.54	39.18	14.06	8.99	0.00	31.20	8.46	35.32	8.19
Wheat-chicory - 20%	24.54	6.53	10.83	0.00	15.55	4.14	15.43	4.97	19.39	3.92	0.00	0.00	9.51	0.00	13.58	0.00
Lupin-chicory	104.60	19.71	76.96	8.96	67.34	10.85	78.02	12.98	104.52	16.02	21.76	0.00	88.29	11.21	95.02	10.72
Lupin-chicory +20%	133.59	25.75	88.38	14.22	82.37	16.32	96.08	17.39	125.98	22.20	29.53	0.00	106.10	14.81	110.79	17.82
Lupin-chicory - 20%	86.03	11.56	59.46	6.04	52.47	7.33	61.90	8.79	81.93	10.09	13.12	0.00	68.57	3.82	73.43	7.65
Canola-chicory	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Expenses	2001	2002	2003	2004	2005	2006	2007	2008
Costs/DSE	14.97	18.37	14.02	14.65	29.64	82.02	29.35	14.60
Costs/ha/365days	119.76	165.33	182.26	146.50	237.12	738.18	293.50	73.00
Cost/ha/day	0.33	0.45	0.50	0.40	0.65	2.02	0.80	0.20

Costs/ha	2001	2002	2003	2004	2005.00	2006.00	2007.00	2008.00
Mono lucerne	73.18	103.94	109.25	128.84	208.43	94.12	97.06	65.53
Mono lucerne + 20%	90.18	138.29	143.10	171.72	282.05	218.26	121.80	87.64
Mono lucerne - 20%	58.86	106.17	92.77	108.18	178.65	115.59	77.05	50.94
Wheat-lucerne	25.16	45.54	47.45	59.65	103.13	0.00	26.72	26.75
Wheat-lucerne + 20%	31.38	57.49	61.50	73.57	123.43	7.78	40.14	33.75
Wheat-lucerne - 20%	19.96	10.63	36.36	45.57	75.25	0.00	15.51	6.78
Lupin-lucerne	57.67	67.63	92.85	111.12	150.23	21.00	55.00	57.89
Lupin-lucerne + 20%	70.52	97.11	114.72	135.35	223.04	37.34	78.09	21.94
Lupin-lucerne - 20%	39.42	53.27	60.97	71.04	106.92	0.00	29.01	0.00
Canola-lucerne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mono chicory	88.20	133.97	139.62	167.59	274.20	183.73	117.17	80.00
Mono chicory -20%	105.98	163.17	171.31	204.98	338.63	223.24	142.27	96.67
Mono chicory + 20%	69.33	101.43	109.38	130.75	213.30	126.01	89.69	60.72
Wheat-chicory	12.01	13.00	20.69	22.60	33.29	7.78	11.43	7.61
Wheat-chicory +20%	14.73	20.03	26.44	32.73	51.43	14.78	17.12	12.00

Wheat-chicory - 20%	8.04	4.88	13.48	14.97	18.95	0.00	5.46	3.11
Lupin-chicory	33.72	41.53	48.78	56.25	90.95	35.78	44.47	25.11
Lupin-chicory +20%	42.75	54.01	63.64	71.01	116.67	49.00	54.09	32.69
Lupin-chicory - 20%	26.51	30.84	36.41	41.87	65.24	21.78	32.39	18.89
Canola-chicory	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Mono = monoculture

Gross Margin	2001	2002	2003	2004	2005	2006	2007	2008
Mono lucerne	302.44	163.77	177.50	191.21	140.92	-20.55	180.33	261.78
Mono lucerne + 20%	380.88	201.52	217.11	229.84	161.25	-85.12	208.50	330.27
Mono lucerne - 20%	251.57	126.71	142.14	148.59	107.75	-36.67	145.20	206.44
Wheat-lucerne	108.94	44.33	49.19	50.87	23.69	0.00	52.37	82.69
Wheat-lucerne + 20%	136.46	57.05	62.51	62.71	32.81	-2.59	80.17	105.67
Wheat-lucerne - 20%	85.53	22.19	37.12	39.39	18.34	0.00	17.45	32.81
Lupin-lucerne	242.66	90.64	134.25	142.78	84.06	-6.20	108.28	222.56
Lupin-lucerne + 20%	295.45	134.57	163.81	174.15	126.76	-9.66	151.88	93.43
Lupin-lucerne - 20%	163.74	98.65	84.35	93.97	59.67	0.00	34.81	0.00
Canola-lucerne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-lucerne - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mono chicory	320.13	149.99	148.24	159.25	108.58	-76.38	197.46	267.51
Mono chicory -20%	387.23	180.25	183.08	194.87	130.01	-92.87	238.29	324.08
Mono chicory + 20%	253.74	120.29	117.90	126.75	88.94	-45.59	150.00	210.73
Wheat-chicory	43.34	16.17	15.69	16.90	12.65	-2.64	17.21	27.54
Wheat-chicory +20%	55.06	21.38	21.56	22.73	10.86	-4.82	27.23	38.57
Wheat-chicory - 20%	27.73	8.06	11.79	10.30	7.60	0.00	5.14	12.75
Lupin-chicory	116.50	63.42	59.63	64.88	53.63	-11.01	69.18	101.47
Lupin-chicory +20%	150.05	72.71	74.01	80.90	62.37	-15.16	84.81	122.45
Lupin-chicory - 20%	90.22	48.29	45.41	51.21	44.04	-6.95	49.14	77.14
Canola-chicory	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory +20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canola-chicory - 20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Mono = monoculture

Intercrop gross margins (combined crop and livestock data)

Gross Margin	2001	2002	2003	2004	2005	2006	2007	2008
Wh-Luc	457.62	869.70	245.64	208.69	192.74	-82.99	749.98	894.76
Wh-Luc + 20%	650.00	1069.69	338.86	322.46	309.96	-134.21	933.96	1113.78
Wh-Luc - 20%	341.14	562.23	188.83	116.19	94.44	-112.46	472.48	688.89
Wh-Ch	263.26	879.84	103.93	77.60	131.98	-51.73	781.62	911.40
Wh-Ch + 20%	386.34	1173.49	211.67	175.20	240.58	-37.89	1090.29	1173.31
Wh-Ch - 20%	131.11	551.75	53.12	-8.80	10.17	-65.11	479.58	612.28
Lup-Luc	238.27	136.16	119.10	146.19	8.54	-54.20	187.27	322.38
Lup-Luc +20%	313.51	211.87	172.61	212.00	78.27	-46.57	278.54	233.74
Lup-Luc - 20%	136.91	112.38	45.25	62.94	-42.89	-59.08	66.11	59.34
Lup-Ch	222.25	264.92	162.01	237.30	110.77	-4.62	382.13	399.96
Lup-Ch + 20%	300.27	337.19	223.85	321.57	173.08	13.18	492.23	501.16
Lup-Ch - 20%	151.50	186.81	100.34	155.39	47.61	-22.52	267.62	295.41
Can-Luc	0.00	0.00	427.91	352.40	215.40	65.22	760.53	708.10
Can-Luc + 20%	0.00	0.00	548.95	470.00	319.36	128.26	952.11	891.12
Can-Luc - 20%	0.00	0.00	306.87	234.80	111.44	2.18	568.94	525.08
Can-Ch	0.00	0.00	510.10	432.26	285.99	108.03	890.62	832.37
Can-Ch + 20%	0.00	0.00	647.58	565.83	404.07	179.63	1108.22	1040.25
Can-Ch - 20%	0.00	0.00	372.62	298.68	167.91	36.42	673.01	624.50

Note: Can = canola; Wh = wheat; Lup = lupin; Luc = lucerne; Ch = chicory

Economics of grazing trial

Crop	Yield	Income	Costs	LessMonoCropPenalty	Gross Margin/ha
Mono Wheat	4.59	1188.81	183.75	77.40	927.66
Mono Wheat GRAZED	3.10	802.90	183.75	77.40	541.75
Wh-Luc GRAZED	1.48	383.32	119.65		263.67
Wh-Ch GRAZED	1.76	455.84	119.65		336.19
Wh-Luc UN-GRAZED	2.48	642.32	119.65		522.67
Wh-Ch UN-GRAZED	2.65	686.35	119.65		566.70

Note: Mono = monoculture; Wh = wheat; Luc = lucerne; Ch = chicory

Pasture	Gross Margin/ha
Mono Wheat GRAZED	98.36
Mono Lucerne GRAZED	949.21
Wh-Luc GRAZED	311.68
Mono Chicory GRAZED	592.19
Wh-Ch GRAZED	478.00
Wh-Luc UN-GRAZED	279.30
Wh-Ch UN-GRAZED	374.65

Note: Mono = monoculture; Wh = wheat; Luc = lucerne; Ch = chicory

Combined Gross Margin	Gross margin/ha
Mono wheat Un-grazed	927.66
Wheat-lucerne Un-grazed	801.97
Wheat-chicory Un-grazed	941.35
Mono lucerne	949.21
Mono chicory	592.19
Mono wheat Grazed	640.11
Wheat-lucerne Grazed	575.35
Wheat-chicory Grazed	814.19

Note: Mono = monoculture

Feedtest Results

Date	Treatment	Moisture	Dry Matter	Crude Protein	Neutral Detergent Fiber	Digestibility	Digestibility (calculated)	Metabolisable Energy
8/09/2008	Chicory	88.1	12.0	30.0	24.7	83.2	77.3	12.7
	Lucerne	82.7	17.3	25.1	30.1	74.0	69.5	11.1
	Weed	84.6	15.5	17.8	38.7	83.9	77.9	12.8
	Wheat	87.1	12.9	26.3	43.4	79.4	74.1	12.1
	Wheat-chicory CH	89.7	10.4	27.2	24.3	85.4	79.1	13.1
	Wheat-chicory WH	82.9	17.1	17.6	43.6	77.0	72.0	11.7
	Wheat-lucerne LU	83.9	16.2	25.3	30.0	74.5	69.9	11.2
	Wheat-lucerne WH	86.3	13.8	20.5	45.5	75.3	70.6	11.4
9/01/2009	Chicory		88.5	19.1	37.1	77.7	72.7	11.7
	Lucerne		89.9	20.0	34.7	71.0	66.9	10.6
	Wheat		91.0	3.7	79.7	39.5	40.3	5.2
	Wheat-chicory CH		87.6	18.6	37.6	77.0	72.0	11.6
	Wheat-chicory WH		90.6	3.2	79.7	38.1	39.1	4.9
	Wheat-lucerne LU		89.8	17.0	43.1	61.9	59.2	9.0
	Wheat-lucerne WH		91.2	3.8	81.1	38.4	39.3	5.0
9/03/2009	Chicory		87.3	19.5	34.2	81.7	76.0	12.4
	Lucerne		89.2	16.1	40.2	64.2	61.2	9.4
	Wheat		91.6	4.0	76.1	41.6	42.1	5.5
	Wheat-chicory CH		87.6	17.6	37.9	78.8	73.6	11.9
	Wheat-chicory WH		91.8	3.0	76.1	37.6	38.7	4.9
	Wheat-lucerne LU		90.1	14.4	46.3	58.3	56.2	8.4
	Wheat-lucerne WH		91.9	3.4	79.8	40.1	40.8	5.3