Identifying the cause of cereal yield decline in lucerne companion cropping systems; and the role of agronomy for mitigating cereal productivity losses

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Student Declaration

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ABSTRACT

Integrating perennial plants like lucerne into farming systems has been widely recommended to mimic pre-agricultural native vegetation, to improve year round transpiration and reduce the off-site impacts of agriculture on the surrounding environment. Despite perennial plants providing greater hydrological benefits compared to traditional annual plant based farming systems; integration of lucerne into farming systems remains a challenge. One approach that may enhance the integration is companion cropping, where annual crops are sown directly into an existing lucerne stand. However, past research has shown that this practice can be harmful to the productivity of annual crops, due to competition with lucerne for environmental resources. Yet beyond quantifying the effect on annual crop production, little is understood about what causes the loss of yield. Understanding the underlying mechanisms dictating the performance of annual crops growing with lucerne could help design agronomic strategies that mitigate competition, and improve annual crop productivity; in turn potentially improving industry acceptance and adoption of both lucerne and companion cropping.

In this study, two field experiments showed that competition was apparent early in the growing season prior to cereal stem elongation; when cereal biomass in the presence of lucerne was significantly lower than that of cereal grown in monoculture. Although there were no differences in cereal establishment, companion cereals produced significantly ($P<0.05$) less tillers, spikes, cereal biomass, and consequently grain yield compared with cereals grown in monoculture. Both field experiments showed that fertiliser N could potentially increase companion cereal productivity, and that in-crop lucerne suppression could improve cereal grain quality by reducing lucerne pod contamination. Apart from quantifying the temporal effects of competition between the companion cereal and lucerne and assessing the role of agronomic strategies for mitigating competition, field experiments did not give much insight into what was causing the loss of companion cereal productivity.

Simulation modelling using APSIM (Agricultural Production Systems Simulator) explored competition between the companion cereal and lucerne, and each component's response to resource supply and agronomic intervention over longer periods. APSIM was found to satisfactorily simulate both simultaneous and stand alone wheat and lucerne growth, after comparison with field observed data. Although APSIM tended to deplete soil mineral N more rapidly under lucerne than field observations indicated, necessitating soil mineral N to be constrained within previously measured values in long-term simulations.

Simulations showed that companion cereals were frequently sown into drier soil profiles, due to soil water extraction by lucerne over the preceding summer/autumn period, compared with monoculture cereals sown after the summer/autumn fallow. Competition for soil water appeared the major contributing factor to companion cereal performance, and simulated data predicted that companion cereals had to rely solely on in-crop rainfall. Therefore companion cropping in low rainfall environments where growing season rainfall (April to October) is less than 350 mm, or in environments where crops rely heavily on stored soil water at sowing for subsequent production, would be unsuitable for reliable grain production from companion cropping.

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Chapter 1. Introduction

Since European settlement, widespread replacement of native vegetation with annual crops and pastures has altered the hydrological balance of arable landscapes in temperate Australia, giving rise to greater water movement out of the root zone and into deeper groundwater systems than occurred under the original vegetation (Peck and Williamson 1987). Greater volumes of water leaking from the root zone under current agricultural systems have been the primary cause of dryland salinity. Leaking water mobilises salts stored in the soil profile, and when this salt laden water re-surfaces from groundwater systems, salt accumulates on the surface of the landscape. Dryland salinity threatens the longer-term sustainability of current agricultural practices, as well as damaging the water quality of adjacent aquatic and native ecosystems (George *et al*. 1997). New farming systems designed to mimic the year round water use of the original native vegetation (Dunin *et al*. 1999), whilst maintaining farm income are required to combat this hydrological imbalance. Perennial pastures have been shown to provide such year round water use (Lolicato 2000) whilst maintaining primary production. Unfortunately viable perennial grain crops do not currently exist, but there are opportunities to integrate perennial pastures into temperate cropping systems to prevent water leakage down the soil profile.

Perennial pastures are an option for farming systems in south eastern Australia, which are often characterised by mixed cropping and livestock enterprises. Perennial pastures could provide additional benefits to the livestock enterprise by supplying forage over the summer period between winter crops, potentially improving animal productivity. However, perennial pasture options with summer active growth for temperate cropping regions of southern Australia are limited. Perennial grasses such as Cocksfoot (*Dactylis glomerata*) and Phalaris (*Phalaris aquatica*) grow actively over winter, and while some Tall Fescue grasses (*Festuca arundinacea*) and Chicory (*Cichorium intybus*) have summer active growth habits, current cultivars persist for only short periods in the temperate cropping zone. The perennial forage legume lucerne (*Medicago sativa*) has been suggested for the role of providing greater water use in temperate mixed livestock cropping systems (Crawford and Macfarland 1995; Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ridley *et al*. 2001; Ward *et al.* 2001; Ward *et al.* 2002). Lucerne also provides a source of high quality feed for livestock and is capable of fixing large amounts of nitrogen from the atmosphere, with subsequent mineralisation of its residue releasing nitrogen into the soil (Peoples *et al*. 1998) for future crop use.

Despite the many advantages that lucerne can offer to mixed livestock cropping systems, its adoption remains low, accounting for less than 5% of surveyed paddocks across the cropping landscape of north eastern Victoria, in south eastern Australia (Grey 2004). Development of management strategies for its integration into mixed farming systems is expected to facilitate its broader adoption. Past research has advocated growing lucerne in separate phases with annual crops (Hirth *et al*. 2001), typically three years of lucerne followed by three years of annual cropping, but this approach incurs frequent costly lucerne establishment and removal, as well as increasing the risk of failed establishments and lucerne termination (Davies and Peoples 2003). One approach to minimise the cost and risk of establishment and removal is to maintain lucerne over a longer time frame, and simply sow annual crops into the pasture base; a practice known as companion cropping. This approach might overcome some of the cost and risk associated with growing lucerne in phase with annual crops.

Whilst growing lucerne and annual crops simultaneously may reduce the cost and risk of establishing and killing lucerne, the direct association with the annual crop can result in competition for resources (solar radiation, water and nitrogen) and yield reductions in one or both species (Egan and Ransom 1996; Angus *et al*. 2000; Humphries *et al*. 2004). Yield reductions to the annual crop resulting in loss of income from grain production are likely to deter many farmers from adopting the practice. Therefore research aiming to understand how and when lucerne competes with the annual crop for resources, may help to develop strategies that mitigate competition and improve annual crop performance in the presence of lucerne.

Australian research into companion cropping systems has reported variable grain yield reductions in annual crops growing with lucerne. Egan and Ransom (1996) suggested that competition for soil water during grain filling was the likely reason for grain yield reductions in annual cereals growing with lucerne, compared with cereals sown in monoculture. However, Humphries *et al*. (2004) produced data showing that reductions in cereal growth in the presence of lucerne occur much earlier in growing season, in comparison with cereal grown in monoculture. Such early reductions in cereal growth might be due more to competition for nitrogen than water, which usually becomes limiting later in the season. Angus *et al*. (2000) concluded that grain yield reductions were likely to be lower in higher rainfall environments, and that soil mineral N supply might be the limiting resource determining the yield of the annual crop in the presence of lucerne. Whilst there has been considerable research exploring the use of cover crops for establishing lucerne (Potter 1965; Stephens 1979; Norton and Koetz 1998; Latta and Blacklow 2001); its difficult to draw meaningful comparisons with two species established simultaneously, with a system where a companion crop is sown into an existing population of mature lucerne plants, providing a vastly different growth environment for establishing cereal plants.

Currently there is conflicting evidence and much speculation about the cause of yield reductions in annual crops growing with lucerne. Without identifying the cause of the yield reduction, it’s difficult to formulate strategies aimed at mitigating competition to produce higher annual crop yields growing with lucerne. Therefore the research presented in this thesis, investigates the temporal changes in competition between the cereal crop and lucerne, to identify when competition impacts on the cereal crop. This knowledge then provides a framework for assessing the potential role of different agronomic strategies for mitigating competition, and to ultimately improve cereal production in the presence of lucerne.

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Chapter 2. Review of Literature

Introducing the concept of companion cropping

Companion cropping (also known as polyculture, inter-cropping, over-cropping, mixed cropping or multiple cropping) can be defined as growing two or more crops simultaneously on the same area of ground (Francis 1986, Willey 1979). The individual crops that make up a mixture of crops are known as component crops, and if their growth coincides for a significant period of time, interactions can take place between the two components.

Companion-cropping systems can be classified into two broad categories. ‘Additive’ companion cropping, where the plant densities of the two component crops are the same as the plant density in their respective monocultures; and ‘Replacement’ companion cropping, where the plant densities of the component crops are a certain proportion of the plant density in their respective monocultures, but keeping the sum of the proportions to 1.0 (Snaydon 1991) (Figure 1).

NOTE:
This figure is included on page 16 of the print copy of the thesis held in the University of Adelaide Library.

Fig 1. Planting arrangements for pure stands of component crop A (●) and B (○) and for replacement mixtures and additive mixtures of component crop A with B. (Snaydon 1991)

Historically companion cropping has largely been practiced in developing tropical regions where annual root crops such as sweet potato (*Ipomoea batatas*) and cassava (*Manihot esculenta*) are grown in mixtures with fruit trees, bananas (*Musa acuminata*) and sugarcane (*Saccharum officinarum*) (Francis 1986). In sub-tropical and temperate regions annual legumes are commonly grown simultaneously under winter cereals or summer crops such as maize (*Zea mays*). Generally the practice is found in developing nations where mechanised agriculture is rare and labour is plentiful. In developed countries, mechanised harvesting has largely favoured monoculture farming. More comprehensive reviews on the origin and development of companion cropping or multiple cropping systems can be found in Plucknett and Smith (1986) and Vandemeer (1989).

The potential role of companion cropping in high rainfall temperate cropping systems of south eastern Australia

Cropping systems in the high rainfall (>500 mm annual rainfall) temperate agricultural zones of southern Australia are prone to some soil water leaking beyond the root zone. When rainfall exceeds evaporative demand, generally coinciding with the planting of winter crops, and when crop roots are shallow, excess soil moisture can percolate deeper into the soil profile at a rate faster than crop water use, and beyond the ultimate rooting depth of annual crops and pastures. Many studies in southern Australia have highlighted insufficient use of winter rainfall, leading to water escaping from high rainfall cropping systems (Crawford and Macfarland 1995; Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ward *et al.* 2001; Ward *et al.* 2002) potentially damaging both agricultural and surrounding landscapes.

Traditional high rainfall dryland cropping systems in south eastern Australia have been based around monocultures of annual plants to largely capture rainfall from late winter to mid spring, when soil temperatures are gradually increasing, rainfall is higher and soil evaporative rates are lower than other times of the year (Figure 2). Typically annual plant growth rates and demand for resources such as water, escalate in September and October (Figure 3), before hot temperatures, high evaporation and diminishing rainfall, cause annual plant senescence.

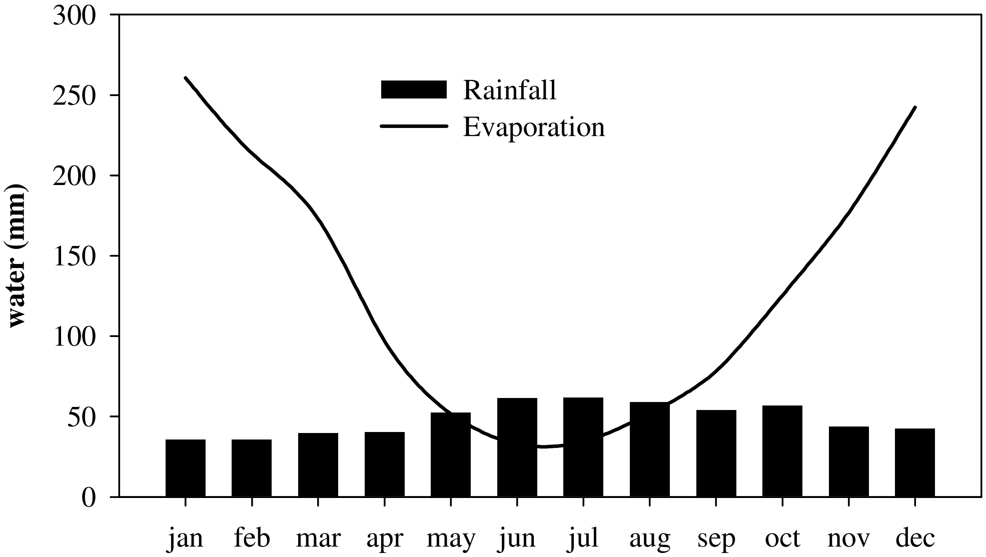

Fig 2. Long-term (1889-2007) mean monthly rainfall (bar) and potential evaporation (line) for Rutherglen in south eastern Australia.

Whilst traditional annual plant based farming systems in south eastern Australia have been effective at producing vast quantities of food, by exploiting favourable growth conditions over the late winter to spring period, they do not always utilise the rainfall received during summer to mid winter. Significant rainfall totals occur during this period; for instance at Rutherglen (146°48'E, 36°06'S) in the high rainfall zone of the south eastern wheat (*Triticum aestivum*) growing region of Australia, the long-term mean summer to mid winter rainfall (1 December to 30 July) contributes 60% of the long-term mean annual rainfall. Low plant water use over the summer to mid winter period provides opportunities for subsoil water to escape during heavy episodic summer and autumn rainfall events, or during winter as soil profiles saturate more rapidly, compared with profiles that have been dried to depth over the summer autumn period (Ridley *et al.* 2001).

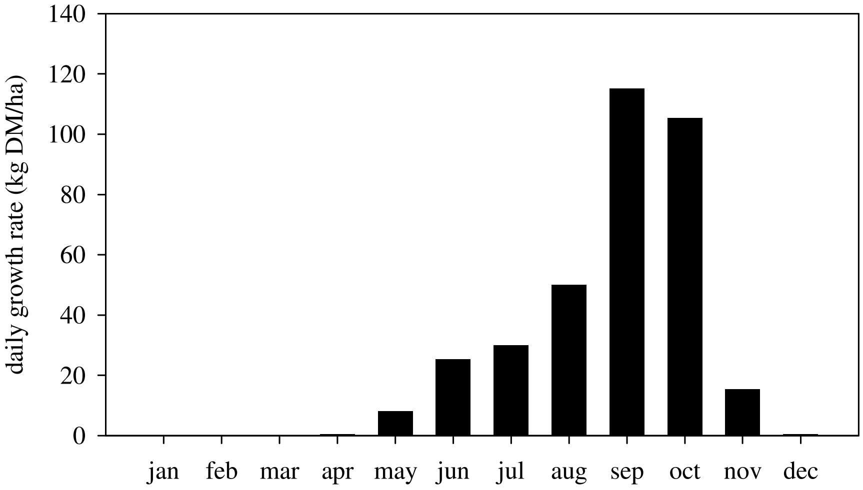

Fig 3. Typical daily growth rate for wheat at Rutherglen in south eastern Australia (data unpublished).

Soil water escaping below the root zone of annual plant based systems can mobilise salts and concentrate them elsewhere in the landscape causing dryland salinity (Lambers 2003), as well as removing valuable anions such as nitrate, leaving behind hydrogen ions in surface soil layers resulting in soil acidification (Bolan *et al.* 1991). Resolving the mismatch in the supply and demand for water by improving the year round water use of cropping systems in south eastern Australia is an important strategy in combating these environmental threats. Prior to European settlement of south eastern Australia, deep-rooted native vegetation dried soil profiles to depth over the summer period, creating a soil profile that could store most water in excess of plant demand over the winter period, resulting in only small losses of water below the root zone (Peck and Williamson 1987). Therefore, farming systems that mimic the water use of native ecosystems whilst maintaining farm income, have the potential to reduce the threat of dryland salinity and soil acidification.

Unfortunately viable perennial grain crops do not currently exist, resulting in the need to explore methods of integrating perennial pastures into temperate high rainfall cropping systems. Perennial pastures have been shown to provide year round water use (Lolicato 2000) whilst maintaining primary production. At first glance, incorporating perennial pastures into cropping systems may appear nonsensical, but in many high rainfall cropping systems in southern Australia with a mix of cropping and livestock enterprises, the inclusion of a perennial pasture could enhance livestock production by extending feed supply over a longer period.

In recent years climate change and the associated need to reduce carbon emissions into the atmosphere have been widely publicised. Increased storage of carbon in the soil is one method under consideration for mitigating atmospheric carbon dioxide build up (Lal 2004). Inclusion of perennial plants into farming systems also has the potential to increase soil carbon stocks (Paustian *et al*. 2000; Chan *et al*. 2001; Newton *et al*. 2006; Su 2007), as well as being better equipped with deeper roots to withstand long periods of dry conditions and more variable rainfall predicted under climate change (McKeon 2006). Perennial plants are thus likely to be a key ingredient in developing adaptive farming systems capable of accommodating changing climatic conditions.

Perennial pasture options could include grasses like phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*) or the perennial legume lucerne (*Medicago sativa*). Most of the perennial grasses except summer active tall fescues, tend to have active winter growth habits, and therefore could compete strongly with neighbouring winter crops. Furthermore, the persistence of current cocksfoot (Ridley and Windsor 1992) and tall fescue (Reed 1996) cultivars in the cropping belt, north of the Great Dividing Range of south eastern Australia is questionable where long-term mean annual rainfall is often less than 650 mm. Chicory (*Cichorium intybus*) could be another option, suited to regions receiving more than 500 mm of annual rainfall, and is more tolerant of acid soils than lucerne (Moore *et al*. 2006). Chicory is dormant over winter, which would compliment a winter active companion crop, but persistence of current cultivars in the cropping belt of southern Australia remain a constraint (Li *et al*. in press).

The perennial forage legume lucerne has shown the most promise for providing greater water use in temperate mixed livestock cropping systems. Ridley *et al.* (2001) reported average vertical water drainage under annual crops and annual pastures of 49 and 35 mm/year respectively, over a four-year period, compared with no drainage under lucerne pasture at Rutherglen in south eastern Australia. They concluded that lucerne created extra soil water storage compared with annual plants by extracting moisture from late spring to midsummer, with additional drying from deeper soil layers until autumn. Other studies within southern Australia have also demonstrated extraction of soil moisture and drying of the soil profile to greater depths under lucerne than annual plant based systems (Crawford and Macfarland 1995; Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ward *et al.* 2001; Ward *et al.* 2002). Lucerne also provides a source of high quality feed for livestock and is capable of fixing large amounts of nitrogen from the atmosphere, with subsequent mineralisation of its organic matter, releasing nitrogen into the soil (Peoples *et al*. 1998; Entz *et al*. 2001) for future crop use.

Despite the many advantages of lucerne in a mixed livestock cropping systems, adoption remains low, accounting for less than 5% of surveyed paddocks across the cropping landscape of north eastern Victoria (Grey 2004). A formula for its successful integration into mixed farming systems has not been developed to facilitate broader adoption. Past research has advocated growing lucerne in separate phases with annual crops (Hirth *et al*. 2001), typically three years of lucerne followed by three years of annual cropping, but this approach incurs frequent costly lucerne establishment and removal, as well as increasing the risk of failed establishments and lucerne termination (Davies and Peoples 2003). One approach to minimise the cost and risk of establishment and removal is to maintain the lucerne over a longer time frame, and simply sow annual crops into the pasture base. In other words a companion cropping approach, along similar concepts to multiple cropping systems found in developing tropical regions. This approach may overcome some of the cost and risk associated with growing lucerne in phase with annual crops, and could facilitate its greater on-farm adoption. In addition, maintaining lucerne in all years prevents any chance of substantial water drainage losses, which may occur after lucerne has made way for crops in phase farming systems, as well as providing additional feed for livestock between annual crops.

Companion cropping with lucerne provides additional advantages over maintaining lucerne monocultures, for example by helping to significantly reduce weed invasion. Lanini *et al*. (1999) found that by companion cropping oats (*Avena sativa*) into lucerne, weed biomass was reduced by 80%, compared with lucerne monoculture, concluding that this strategy was as effective at combating weeds as an application of paraquat, but without the initial loss of lucerne biomass from the herbicide application. The Lanini *et al*. (1999) study concluded that sowing oats between the lucerne crowns could reduce the open space for spring weed invasion, in comparison with untreated lucerne grown as monoculture. Putnam *et al*. (2001) and Cummings *et al*. (2004) also reported reductions in weed populations from companion cropping oats and wheat respectively.

The inclusion of lucerne into both companion and phase farming systems can also increase whole farm income by providing high quality summer feed which annual pastures are unable to supply. Bathgate and Pannell (2002) concluded from whole farm economic modelling that profits in Western Australia would increased from the inclusion of lucerne; mainly due to supply of quality summer feed at costs competitive with other feed sources such as grain supplements, enabling increased stocking rates and additional income from greater wool and meat sales. The same conclusion was made from whole farm economic modelling in south eastern Australia (Hoque and Bathgate 2008).

Lucerne can deliver year round water use whilst maintaining whole farm profits, but when in direct association with the annual crop; its growth can negatively impact on the performance of the annual crop. Companion cropping can expose the annual crop to direct competition with lucerne for essential resources such as sunlight, water and nutrients, often reducing the yield of the annual crop (Egan and Ransom 1996; Humphries *et al*. 2004). For companion cropping to become more than just a novel idea for sustainable farming and to gain greater acceptance and adoption from the farming community, the yield loss often experienced by the annual crop must be reduced. Research to understand how the presence of lucerne reduces the growth of the neighbouring annual crop, could help to design strategies to mitigate competition and produce more favourable outcomes for annual crop production in association with lucerne.

Companion cropping can lead to competition for resources between different plant species

In theory lucerne's summer active growth and winter dormancy, should not interfere with the growth of an annual winter crop. However, there are periods over the spring, where the species will compete directly with one another for resources. Consequently companion cropping can lead to periodic competition for resources between the annual crop and lucerne, negatively impacting on the yield of the annual crop (Egan and Ransom 1996). Underlying principles of plant competition becomes an important starting point for studying the interactions between lucerne and the annual crop. There is limited published information regarding competition between annual crops growing with lucerne, and accordingly subsequent discussions will cover the broader topic of plant competition in multi species herbaceous plant communities.

Zimdahl (1999) defined competition as occurring, "when two or more organisms seek what they want or need and the supply falls below the combined demand". There are two forms of competition occurring in multi species plant communities; 'intra-specific' competition, where plants of the same species compete for the same pool of available resources; and 'inter-specific' competition, where plants of two or more species compete for the same pool of available resources (Keddy 2001).

Competition is evident when plants decrease the growth, survival or fecundity of neighbouring plants. In other words the competition for resources has a negative impact on the growth of at least one plant species in the crop mixture on an individual or per unit size (Casper and Jackson 1997). Plant growth in a multi-species population is not always affected by competition for resources alone. Some plants can release toxic chemicals in a process called allelopathy; these allelochemicals interfere with neighbouring plants of different species, reducing their effectiveness in obtaining resources. Sometimes plant growth can be affected by both competition for resources and allelopathic chemicals, in this situation the term ‘interference’ can be used to describe the collective effect (Zimdahl 1999).

The degree of competition in multi-species plant communities is largely determined by (i) the supply of environmental resources, which is affected by soil and atmospheric conditions (Fukai and Trenbath 1993); (ii) the growth patterns of plant species within the community which dictates the demand for resources, and the degree to which demand for resources overlap (Fukai and Trenbath 1993); and (iii) the spatial arrangement (density and distribution) of the plant species within the community (Yunusa 1989; Bulson *et al.* 1997).

The productivity of companion cropping systems is determined by the ability of the component crops to capture limiting environmental resources (competitive ability), and the efficiency by which those resources are converted into biomass and harvested products. The growth environment significantly affects the competitive ability of component crops (Fukai and Trenbath 1993). However, there are few published studies that have attempted to quantify how the changing growth environment might alter component crop productivity. In one of the few studies, Ofori and Stern (1987) found that cowpea was often suppressed when grown with maize, but under low soil nitrogen conditions the competitive ability of cowpea (*Vigna unguiculata*) increased resulting in greater grain yield. Cowpea continued to satisfy its demand for N by fixing it from the atmosphere, while the neighbouring maize crop exhausted soil N. One might expect a similar interaction could take place between annual cereal crops and leguminous lucerne mixtures in low soil N environments.

Companion crops are most productive when the periods of active growth in the component crops differ greatly, thereby reducing the degree of competition for resources (Smith and Francis 1986). For example, Rao and Willey (1980) found that late maturing pigeon pea grown with early maturing millet was a more productive cropping mix than pigeon pea (*Cajanus cajan*) grown with later maturing pearl millet (*Pennisetum glaucum*) or sorghum (*Sorghum bicolor*). In the case of lucerne-annual crop mixtures, annual crops that mature earlier may be better suited for avoiding peak lucerne biomass production periods common in the late spring.

In contrast, when the periods of active growth in component crops coincide, the degree of competition for resources is more intense. Component crops that exhibit fast early growth often have greater competitive ability, gaining resource-capturing superiority and consequently greater yield over their slower companions. This crop is termed the ‘dominant’ component, while the other component is termed the ‘suppressed’. The greater the amount of resource captured by the dominant component, the greater its competitive ability over the suppressed component (Fukai and Trenbath 1993). Once the dominant component develops a competitive advantage over the suppressed component, there is a tendency for it to become progressively better at using more of the limited resources than the suppressed component (Donald 1958). In the context of annual crops growing with lucerne, management strategies that enhance early annual crop growth (N fertiliser) and simultaneously restrict lucerne growth (lucerne suppression), could improve the competitive ability of the annual crop which might be maintained until maturity.

Some of the best examples of plant density effects on crop productivity have been found in weed-crop competition studies. Cousens (1985) described a simple rectangular hyperbola model to describe crop yield loss as a function of weed density (Figure 4), while other researchers have proposed a sigmoidal relationship (Zimdahl 1980). Cousens *et al.* (1987) suggest that non-linear regression analyses of crop yield versus weed density gives the most accurate representation of the relationship. Returning to the context of annual crop lucerne mixtures, there is enough evidence to suggest that similar relationships could exist between lucerne density and associated annual crop yield.

NOTE:
This figure is included on page 26 of the print copy of
the thesis held in the University of Adelaide Library.

Fig 4. Rectangular hyperbola relationship depicting the effect of increasing weed density on crop yield losses (Cousens 1985)

Current understanding of the impact of lucerne growth on associated temperate agricultural crops

While the broader literature describing competition in multi-plant communities provides a framework to study annual crop-lucerne mixtures, there is not enough information to conclude how and when lucerne growth negatively impacts on the growth of neighbouring annual crops. Without this information, it’s difficult to progress and devise strategies for mitigating competition, and to ultimately improve annual crop yields in the presence of lucerne. Therefore we need to look more specifically at cases involving lucerne growing with other temperate agricultural plants, to provide further insight into the potential interactions taking place when annual crops are sown into existing lucerne.

The productivity of the annual crop growing with lucerne is likely to depend on the genetic composition of the component crops, the growth environment (atmosphere and soil) which will influence resource supply and agronomic manipulation of the microenvironment (Fukai and Trenbath 1993). Agronomic intervention could potentially alter the balance of resource capture between the annual crop and lucerne to favour one over the other.

Research studying cocksfoot growing with lucerne in the United States concluded that the ability of lucerne to compete for soil water was enhanced by extracting water at lower depths compared with cocksfoot, and that competition between lucerne and cocksfoot for soil water occurred on an equal basis in the upper soil layers (Chemblee 1958). One might expect a similar root distribution under lucerne and annual cereal crop mixtures, with cereals also having fibrous root systems with a similar rooting depth to cocksfoot (Evans 1978), but again lucerne's capacity to compete with the cereal crop for soil water, is likely to be enhanced by its deeper rooting system (Evans 1978). This difference in root distribution may also provide some degree of complimentary association, whereby resource utilisation is separated, as lucerne could access below ground resources beyond the reach of the companion crop roots.

Competition for soil water appears likely where annual cereals are sown into existing lucerne. Egan and Ranson (1996) studied cereals sown into young lucerne stands in central Victoria, reporting grain yield reductions of 6 to 60% over different seasons compared with conventionally sown sole crops. They concluded that the differences in companion crop yields between seasons could be attributed to lucerne vigour, seasonal conditions and sowing date. In most seasons Egan and Ransom (1996) found above-ground crop biomass yields at anthesis were similar in the companion cropping and sole crop treatments and that differences in yields appeared during the post-anthesis period, when they speculate competition for soil water was hindering grain filling and reducing grain yields in the companion cereals. Research elsewhere by Eberlein *et al.* (1992) also concluded that available soil water was the most limiting factor determining the success of lucerne and corn (*Zea mays*) cropping mixes, with and without irrigation in the United States. They measured less available soil water under non-suppressed lucerne in all seasons and under suppressed lucerne in a dry season, compared with moisture available to corn in the absence of lucerne. Suppression of lucerne coinciding with planting of the companion corn involved the use of herbicide to temporarily retard lucerne growth, while the corn seedling grows and gains height advantage over the lucerne. Eberlein *et al.* (1992) found that the lower available soil water under companion cropped corn compromised corn leaf area development and thus light interception, resulting in reduced corn herbage and grain yield. They concluded that if lucerne suppression or rainfall were inadequate, corn production could suffer from competition for water and sometimes light.

In south eastern Australia, the Egan and Ransom (1996) study was conducted in an environment receiving a long-term mean annual rainfall of 450 mm. In a higher annual rainfall environment of 525 mm, Angus *et al.* (2000) found wheat yields were unaffected by the presence of lucerne compared to wheat grown after lucerne removal over one season. However, in the same season they found a 0.3 % fall in grain protein, where wheat was grown with lucerne, concluding that competition for soil mineral nitrogen at grain filling was the likely cause. In the following season they measured only a 10% reduction in canola (*Brassica napus*) yields growing with lucerne compared with canola after lucerne removal. They concluded that the success of companion cropping with lucerne was most likely in high rainfall environments (ie > 525 mm of annual rainfall), and they speculated that in such environments nitrogen supply might be a greater limitation than water supply.

Similar grain yield reductions to the Egan and Ransom (1996) study were reported by Humphries *et al*. (2004), where yield of wheat sown into lucerne was reduced by 13 to 63% in Western Australia and South Australia, compared with wheat grown alone. However, the differences in companion wheat and sole wheat productivity appeared much earlier in the growing season than the Egan and Ranson (1996) study, with winter biomass production reduced by up to 50% in the companion wheat compared with sole wheat. Humphries *et al*. (2004) speculated that the yield reduction in the companion cropped wheat may have resulted from competition for N and or light.

In theory, annual crops growing with legumes such as lucerne have the potential to obtain N from the association. Lucerne has been found to fix large amounts of N in the south eastern wheat belt of Australia (Peoples *et al*. 1998). While there are no measurements of N transfer from actively growing lucerne to neighbouring annual crops in this environment, research elsewhere would suggest there is potential for some transfer through lucerne residue decomposition or root exudates releasing N. For example, Jordan *et al.* (1993) studied nitrogen transfer from N^{15} labelled lucerne to companion-cropped corn in the United States, concluding that the severity of lucerne suppression would determine the availability of nitrogen to associated corn. They reported that when lucerne had been suppressed by glyphosate injury followed by cutting, associated corn recovered 12% of labelled N^{15} compared with only 4% where lucerne was only cut. Jordan *et al.* (1993) concluded that the glyphosate followed by cutting treatment appeared to have a greater suppressive affect on the lucerne, improving the companion corn growth and competitive capacity, in comparison to corn sown into lucerne that had only been cut. Varco *et al.* (1991) monitored soil mineral nitrogen (ammonium and nitrate) under lucerne subject to different suppression strategies, such as cut and remove, cut and return, above ground kill with paraquat and complete kill with glyphosate. They reported that initial (14 days) release of N was similar under all treatments where lucerne residues were retained, but that subsequent lucerne growth immobilised much of the mineralised N in all treatments, except where the lucerne was killed. Consequently Varco *et al*. (1991) concluded that lucerne grown in association with corn would compete strongly for soil nitrogen.

Other studies in the United States investigating lucerne corn cropping mixes under high rainfall (> 600 mm growing season rainfall) or irrigation have reached similar conclusions.

Kurtz *et al.* (1952) found that over a three year period corn yields in the presence of lucerne were boosted by an average of 78%, from top-dressing nitrogen. Corresponding yield responses from N application to corn sown in monoculture were lower, with a 41% increase in corn yield from top-dressed N. N input for mitigating competition was also reported by Jellum and Kuo (1997) who estimated that to achieve the same yield as corn grown alone, corn grown with lucerne required an additional 83kg/ha of fertiliser N to overcome competition with lucerne. Kaspar and Bland (1992) also concluded that competition for nitrogen between lucerne and corn roots could restrict nitrogen availability and consequently restrict corn productivity. Research elsewhere has concluded that lucerne can be a very effective scavenger of inorganic soil N (Ruselle *et al*. 2001; Ruselle *et al*. 2007)

The theory that competition for N between lucerne and an annual crop is likely due to lucerne's capacity to effectively scavenge soil N, is further supported by research at Rutherglen in the high rainfall cropping zone of south eastern Australia. Hirth *et al.* (2001) measured significantly lower soil mineral N at the seasonal break under lucerne compared with subterranean clover (*Trifolium subterranean*) pasture in four out of five seasons. Although the authors do not explain why this result was observed, it was probably due to lucernes' continuous active growth immobilising available mineral nitrogen, in much the same way as that described by Varco *et al*. (1991).

Examples can be found in the literature illustrating how resource (soil water, N and light) supply can impact on the productivity of the annual crop growing with lucerne. However, the supply of resources to the neighbouring cereal crop will also be affected by the population of the existing lucerne stand. For example Egan and Ransom (1996) found no significant grain yield differences where wheat was sown into lucerne densities of 5 and 10 plants/m^2, but at 15 plants/m^2, grain yields were significantly lower than wheat growing in monoculture. This is further supported by Latta and Lyons (2006), who found grain yields were significantly lower where wheat was planted into lucerne stands of 19 plants/m^2 in all seasons, compared with wheat sown into monoculture and into lucerne stands of 4 plants/m^2 in Western Australia. The same study only found significant grain yield differences between the wheat monoculture and wheat sown into lucerne stands of 4 plants/m^2, in low rainfall years.

Population density in combination with the winter activity class of lucerne appears to also impact on the productivity of the neighbouring annual crop. For instance Humphries *et al.* (2004) reported lower yield losses in wheat sown into winter dormant lucerne (winter activity class 0.5 – 2) compared with wheat sown into winter active lucerne (winter activity class 6 – 10), observing that wheat growing with winter dormant lucerne was more responsive to applied N. This would suggest that the growth of winter dormant lucerne varieties, are less competitive with neighbouring winter cereals, utilising less resources over the winter period.

The tillage method employed when sowing the annual crop into lucerne may also impact on companion crop productivity. Skelton and Barrett (2005) measured a 57% reduction in wheat yield where no-till sowing was used, compared with coarsely disking the surface soil between the lucerne plants, before establishing the wheat companion crop. However, the Skelton and Barrett (2005) study did not perform any chemical suppression prior to establishing the companion crop, and the disk cultivation could have had a suppressive effect on the lucerne, giving the wheat companion crop a head start over lucerne.

Another possibility for the observed decline in cereal yield in the presence of lucerne not considered in many field studies is the potential release of allelopathic compounds from the lucerne, interfering with the growth and development of the neighbouring cereal seedlings. There is evidence that lucerne produces water-soluble substances that are toxic to itself (autotoxicity) and to other species (allelopathy) (Chung and Miller 1995a; Miller 1983). Chung and Miller (1995a) reported allelochemicals were present in lucerne plant parts at different concentrations, and that increasing the concentration of aqueous extracts corresponded with increased growth inhibition. Although in another study by Chung and

Miller (1995b) they concluded that aqueous extracts from lucerne inhibited weed seed germination and seedling growth more in dicotyledonous species than monocotyledons.

All evidence for the potential of allelochemicals in lucerne has been derived from glasshouse bioassay studies, where crop seeds and seedling have been exposed to different concentrations of aqueous extracts from lucerne plants. Whether these allelochemical concentrations actually occur in the field is not known, and the effect of lucerne allelochemicals on neighbouring plants in the field remains unexplored (Waller *et al*. 1993). Future field research investigating cereal growth in the presence of lucerne should at least compare crop emergence in the presence and absence of lucerne which might indicate allelopathic activity.

The current information regarding interactions between the lucerne and annual crop components is inadequate, and does not allow formulation of agronomic strategies for mitigating competition in such associations. Future research should determine which resources are implicated in competition between lucerne and cereals and when competition for the resource or resources occurs. Acknowledging that the environment, particularly rainfall and lucerne density will be important factors influencing resource supply. Such information will enable development of strategies to mitigate competition and produce greater yielding cereal crops sown into lucerne.

Could simulation modelling using APSIM improve knowledge of lucerne and annual crop interactions and help design agronomic strategies to mitigate competition?

In the past many multi-plant species studies have tended to quantify the consequences of competition, without understanding the factors contributing to the measured outcomes. Often the findings from such studies have been site and season specific, with little scope to apply the findings to a greater range of seasonal conditions. Furthermore, assessment of how agronomic intervention might alter plant competition in annual winter crops/lucerne mixes remains largely unexplored. Providing answers to these questions represents many years of field experimentation; and therefore computer simulated modelling of lucerne-companion cropping systems offers the potential to obtain insight into these important questions over a much shorter time frame, and at a lower expense.

The Agricultural Production Systems Research Unit (APSRU) involving researchers from CSIRO and Queensland state agencies have developed the Agricultural Production Systems Simulator (APSIM) model, which simulates biophysical processes in farming systems. The computer model consists of a series of crop and soil modules, module interfaces and a simulation engine, with model users “plugging in” the appropriate modules required for simulating specific farming systems (Keating *et al.* 2003). APSIM has a number of crop modules, including most annual winter cereals and lucerne, and possesses the capability of modelling competition for environmental resources between components (Carberry *et al.* 1996). Furthermore APSIM offers the user, the unique flexibility of stipulating specific management inputs, which is important in modelling the impact of cultural conditions on competition. Whilst there are other models available such as the Decision Support System for Agrotechnology Transfer (DSSAT), which offer the ability to stipulate specific management intervention (Jones *et al*. 2003), they do not have the capacity to model competition. Other crop models have been built to simulate competition in crop weed mixtures (Deen *et al*. 2002), but none currently have the capacity to model both above and below ground competition involving mixed communities of cereal and lucerne. This feature sets APSIM apart from other crop models commercially available in Australia, which allows the user to explore the potential role of agronomic inputs for altering resource capture in annual crops sown into existing lucerne. More detailed description of the APSIM modelling framework can be found in Keating *et al.* (2003).

Competition is simulated by the respective influences of component crops on resource stocks/fluxes supplied through the radiation, water and soil nitrogen modules. APSIM allows any number of biological modules to compete for resources on a daily basis via allocated rules specified in the "Arbitrator" module, which is linked to the APSIM engine (Keating *et al.* 2003). The number of competing species within the mixed plant community determines the number of canopy layers in the model, with the leaf area of each species distributed between the canopy layers on the assumption that leaf area index increases exponentially with plant height (Carberry *et al.* 1996). Total absorbed radiation within the mixed plant community is distributed on the basis of differences in leaf area profile, plant height and light extinction coefficients of each respective species (Deen *et al*. 2002). One dimensional root growth is simulated in all species (Deen *et al*. 2002) and soil water and N are allocated to the roots of each species on an alternating day by day basis (Robertson *et al*. 2004). Carberry *et al.* (1996) provides a detailed description of the scientific basis for simulation of competition in APSIM.

APSIM has already been used to model the performance of lucerne companion-cropping systems in terms of reducing excess water loss from farming systems (Keating *et al.* 2003) and validation of simulated versus observed responses of wheat and canola grown in mixture with lucerne from field research (Robertson *et al.* 2004) in southern Australia.

Robertson *et al.* (2004) tested the ability of APSIM to simulate competition between lucerne and an annual crop, concluding that APSIM could satisfactorily simulate wheat, canola and lucerne productivity as well as soil dynamics in companion cropping systems. At two field sites over two seasons, Robertson *et al*. (2004) reported differences between observed and simulated companion wheat grain yields of no more that 140 kg/ha, with observed companion wheat grain yields varying from 200 to 2200 kg/ha. However, the study provides no detail regarding the model's performance in relation to predicting lucerne biomass production in presence of the companion wheat. They point out that sound performance of APSIM against such detailed data sets is a prerequisite to identifying environments and circumstances in which grain yield losses might be mitigated in lucerne companion cropping systems.

Conclusion

Evidence presented in this review, suggests that proposed research studying the interactions between annual crops and lucerne should focus on competition for water and nitrogen. Competition for light may be a contributing factor in reducing annual crop performance under certain circumstances (ie where lucerne shades the annual crop component). Release of allelopathic compounds from lucerne residue are likely to play a minor role in reducing the growth of associated annual crops, Therefore research seeking to investigate interactions between annual crops and lucerne should focus on competition for below ground resources, namely water and nitrogen, which are likely to be the most significant constraints on annual crop growth in the presence of lucerne.

In the past many multi-plant species studies have tended to quantify component plant yields, without a firm understanding of the factors contributing to the measured outcome. Exploring crop growth in the presence of lucerne through field research complimented by simulation modelling has the potential to quantify crop responses under a large range of climatic and agronomic scenarios, potentially providing answers to the following fundamental questions:

1. What causes the yield decline in cereals growing in association with lucerne in the high rainfall temperate environment of south-eastern Australia?
2. How might agronomic intervention alter resource capture and competition between the cereal crop and lucerne to produce better cereal crop yield in the presence of lucerne?
3. Does companion cropping negate lucernes' capacity to dry the soil profile and provide hydrological benefits in a higher rainfall cropping environment of south-eastern Australia?

Currently there is no documented evidence in the literature addressing these important questions; clearer understanding of these underlying issues would better define the potential role of lucerne companion-cropping in the south eastern cropping zone of Australia.

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Chapter 3. Companion crop performance in relation to annual biomass production, resource supply and subsoil drying

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Running title: The effect of cereal and lucerne mixture on biomass production, species responses to additional N and water, and lucerne's capacity to dry subsoil.

Co-author declarations

MC Crawford

I give written permission for the paper “Companion crop performance in relation to annual biomass production, resource supply and subsoil drying” to be included in Rob’s PhD Thesis.

I made a minor contribution to the work in the area of hypothesis formulation, protocol developments and editing of the paper.

Yours Sincerely

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To whom it may concern,

Contribution to publications by Mr Rob Harris included in his thesis to be submitted for the award of Doctor of Philosophy

This note is to confirm that my contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Crawford MC, Bellotti WD, Peoples MB, Norng S (2008) Companion crop performance in relation to annual biomass production, resource supply and subsoil drying. *Australian Journal of Agricultural Research*. 59, 1-12.

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

Yours sincerely,

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Vincent Fairfax Chair in Sustainable Agriculture and Rural Development

MB Peoples

28 November 2008

To whom it may concern

This note is to confirm that my contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Hirth JR, Crawford MC, Bellotti WD, Peoples MB and Norng S (2008). Companion crop performance in relation to annual biomass production, resource supply and subsoil drying. *Australian Journal of Agricultural Research* 59: 1-12.

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Yours sincerely

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I give Rob Harris permission for the paper “Companion crop performance in relation to annual biomass production, resource supply and subsoil drying” to be included in his PhD Thesis.

I carried out the REML statistical analysis for the soil water data presented in the paper, and provided guidance regarding soil water data interpretation.

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Abstract

A field experiment located in North East Victoria compared the productivity of cereals sown into mature lucerne (companion crop) with cereals and lucerne grown as monocultures. Additional nitrogen (N) and water was applied to investigate if increased resource supply could alleviate competition and improve cereal performance in the presence of lucerne. Cereal plant populations, lucerne and cereal biomass, and cereal grain yields and protein were measured throughout the experiment. Soil water content was also monitored over time to determine whether companion cropping compromised the ability of lucerne to extract deep soil water. Whilst companion cropping depressed both lucerne and cereal production, the combined annual biomass production was greater than cereal and lucerne when grown alone. Averaged over the three seasons, companion cropping resulted in a 31% increase ($P<0.05$) in total annual biomass compared with the lucerne monoculture, and an 18% increase compared with the cereal monoculture in the 2004/05 and 2005/06 seasons. Cereals growing with lucerne produced fewer tillers, spikes and consequently cereal biomass compared with cereals growing as a monoculture. Therefore, companion crops yielded 25% less ($P<0.05$) grain compared with the cereal monoculture over the three-year study. Competition for N and light prior to cereal stem elongation, were likely causes. Increasing the supply of N and water did not result in a main treatment (monoculture versus companion crop) by additional resource interaction, indicating that cereal responses were the same irrespective of lucerne's presence. The application of N, water and these combined inputs, resulted in a 13 - 40%, 35% and 49% respectively, increase ($P<0.05$) in cereal grain yields. While companion cropping compromised lucerne's capacity to extract water from deep soil layers to a degree, this practice was still able to maintain drier subsoil in comparison to the cereal monoculture.

Additional keywords: nitrogen application; companion crops; *Medicago sativa*; lucerne; triticale; wheat; inter-cropping; over-cropping; pasture cropping.

Introduction

In recent years, there has been increasing emphasis on designing farming systems that better integrate perennial plants like lucerne (*Medicago sativa*) into dryland cropping systems, to utilise a greater proportion of the yearly rainfall than annual pastures and crops to reduce the potential risk of off-site impacts of agriculture on the surrounding environment. Numerous studies throughout Australia have demonstrated that lucerne can dry the soil profile to a greater depth compared with traditional annual plant based farming systems (Crawford and Macfarlane 1995; Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ward *et al.* 2002) and therefore reduce water leakage to groundwater (Ridley *et al*. 2001) and potentially the associated harmful effects of dryland salinity. However, the challenge remains regarding how to integrate lucerne into dryland cropping systems to provide leakage control without substantially reducing crop production and economic returns.

One potential approach for achieving this integration is lucerne companion cropping, where annual crops are sown directly into established lucerne stands (Harris *et al*. 2003; Robertson *et al*. 2004). This practice provides the advantages of avoiding the costly and often difficult need to terminate lucerne prior to cropping (Angus *et al*. 2000; Davies *et al*. 2005) and reduces the frequency and therefore cost of re-establishing lucerne commonly associated with phase farming systems (Hirth *et al*. 2001).

In theory, companion cropping seems a convenient means of integrating lucerne into dryland cropping systems. However, in practice this approach can often penalise the production of both the companion crop and lucerne, a result of direct competition for resources. Several Australian studies have quantified grain yield reductions of 6- 63% (Egan and Ransom 1996; Humphries *et al*. 2004; Harris *et al*. 2006), and lucerne biomass reductions of 49- 79% (Harris *et al*. in press) from companion cropping. In addition, these studies have also investigated agronomic strategies for improving companion crop production (Egan and Ransom 1996;

Humphries *et al*. 2004; Harris *et al*. 2006), with improvements observed only under favourable growing season conditions (Harris *et al*. 2006). Despite these studies, only limited attempts have been made to understand the effects of resource supply on companion crop performance, and little attempt has been made to identify the main factors contributing to grain yield reductions commonly observed in companion crops. In addition, only Humphries *et al*. (2004) has assessed the overall productivity (cereal and lucerne) of companion cropping in comparison with traditional cereal and lucerne monocultures, and then only in Western Australian and South Australian cropping environments. Furthermore, no conclusive evidence exists to indicate whether companion cropping restricts the ability of lucerne to dry subsoils and maintain minimal leakage losses.

This study attempted to answer three fundamental questions regarding simultaneous growth of companion crop and lucerne. Firstly, what role might companion cropping play in terms of improving rainfall utilisation and annual biomass production? Secondly, when does the association with lucerne negatively impact on cereal performance, and what is the likely resource or resources (water, N and/or solar radiation) contributing to this negative expression in companion crop grain yield? Thirdly, does the association with a companion crop compromise lucerne's capacity to dry subsoils and maintain minimal leakage levels?

Materials and Methods

Experimental site

The experiment was conducted from 2003 to 2006 at North Boorhaman (146°23'E, 36°10'S) in North East Victoria, on a slightly acidic (pH 6.4 in $CaCl_2$, 0-12 cm) Calcic, Mottled-Subnatric, Red Sodosol soil (Isbell 1996). The subsoil was characterised by an alkaline reaction trend (pH 8.1 in $CaCl_2$, 90-140 cm) with medium to heavy clay texture.

Paddock history

The paddock on which the experiment was to be established consisted of annual pasture in 2000, followed by wheat (*Triticum aestivum*) cv. Diamondbird in 2001. In 2002, prior to lucerne establishment, the wheat stubble was burnt, and on 14 July Lillydale AgLime was applied at 3 t/ha followed by an application of glyphosate (540 g of a.i./ha) and dimethoate (32 g of a.i./ha) to kill weeds and insects before sowing. On 10 August 2002, trifluralin (960 g of a.i./ha) was applied and incorporated, before sowing lime coated cv. Pioneer 54Q53 lucerne at 4 kg/ha. Phosmet (45 g of a.i./ha) was later sprayed on 18 October 2002 to kill Red-Legged Earthmite (*Haleotydeus destructor*) and Lucerne Flea (*Sminthurus virdis*) infestations of lucerne seedlings. The site was periodically grazed over the 2002/03 summer, at stocking rates varying from 7-10 DSE/ha.

Experimental design

Six main treatments were established in 2003, initially replicated three times in the first year, but in later years replicated four times in a randomised complete block design. Treatments included two lucerne monocultures, two cereal monocultures and two cereal companion crops. In 2004, one of the cereal monoculture, lucerne monoculture and companion crop treatments received additional water to maintain soil moisture close to field capacity over the spring period. A sequence of wheat - triticale (*Triticosecale*) - wheat was sown in the cereal monoculture and companion crop treatments. In all years each main plot was divided into two sub-plots, with one sub-plot randomly allocated top-dressed N. Individual plots were 6 m by 8 m in dimension.

Lucerne removal

On 10 April 2003 plots allocated to cereal monocultures in the first three blocks had lucerne eradicated by applying a mix of glyphosate (500 g of a.i./ha) and clopyralid (150 g of a.i./ha).

In the following year, plots allocated to cereal monocultures in the fourth block had lucerne initially eradicated by mechanical cultivation because of dry seasonal conditions, and later an application of clopyralid (150 g of a.i./ha) in the crop on 19 August 2004 to remove surviving lucerne plants.

Crop establishment, in-crop weed control and stubble management

Shortly after the seasonal break in 2003, 2004 and 2005, all treatments were sprayed with paraquat/diquat (338 g / 288 g of a.i./ha) to suppress lucerne and eradicate weeds prior to sowing. Wheat (cv. Galaxy H45), triticale (cv. Kosciusko) and wheat (cv. Diamondbird) were sown in 2003, 2004 and 2005 respectively. Nitrogen (N) and phosphorus (P) were applied as DAP (18 and 20 kg/ha respectively) with the seed in all years. Cereals were sown into lucerne stands (both lucerne monoculture and companion crop treatments) with a density of 12, 10 and 8 plants/m^2 in 2003, 2004 and 2005 respectively. In 2005 Flutriafol (125 g of a.i./ha) was applied to the DAP to combat the threat of stripe rust (*Puccinia striiformis*) later in the growing season. The site was sown on 27 April 2003, 3 June 2004, and on 2 June 2005. In-crop germination of capeweed (*Arctotheca calendula*) was eradicated by applying Bromoxynil (250 g of a.i./ha) + Diflufenican (25 g of a.i./ha) on 6 July 2003 and 11 July 2005, and annual grass germinations eradicated by applying Diclopfop-methyl (750 g of a.i./ha) on 16 July 2005. All cereal treatments received Propiconazole (125 g of a.i./ha) on 14 October 2003, 30 September 2004 and 22 September 2005 to control outbreaks of stripe rust. In 2003 cereal stubbles were left standing, while in 2004 and 2005 stubbles were slashed shortly after grain harvest.

N management

Urea was top-dressed at 60 kg N/ha to all sub-plots allocated to receive additional N, on 23 July 2003 and 30 August 2004 when cereal crops had reached the first node stage (GS 31) of growth. However in 2005, Urea was top-dressed at 100 kg N/ha at the second leaf stage (GS 12) of cereal growth on 12 August. Urea was also top-dressed to all plots at 40 kg N/ha on 29 June 2004, as there was concern about potential poor seedling emergence through the heavy stubbles from the previous year's crop.

Water application to individual plots

Water was applied to individual plots through 20, 16 mm wide Aqua-Traxx dripper tapes, placed along the length of the plot at 0.3 m apart, between crop drill rows and over lucerne plants. At one end of the plot, the dripper tapes were sealed, while at the other end they were attached to an 8 m 25 mm poly pipe running perpendicular to the dripper tapes. Each end of the 25 mm poly pipe was sealed, and an inlet placed half way along the pipe allowing for the delivery of water.

Irrigation scheduling

Lucerne and triticale water requirements were calculated by multiplying Class A pan evaporation by a crop factor and subtracting actual rainfall events over the irrigation period. The crop factor used was 1.15 for both lucerne and cereal crops. Irrigation start up was determined by the use of the double puncture tensiometer method described by Greenwood and Daniel (1996), and thereafter to monitor soil tension and ensure that the irrigation schedule maintained tension close to field capacity.

Biomass measurements

Lucerne and cereal biomass was measured when cereal crops reached first node (GS 31), anthesis (GS 65) and maturity (GS 95) growth stages. Lucerne biomass was also collected on three occasions for each of the three summers that the experiment was conducted. In our study cumulative biomass results are presented for different periods (Table 1). In all years two 0.5

m^2 quadrats were randomly placed within each sub-plot at each sampling date. Quadrats were cut to within 2 cm of the ground and bulked. Samples taken from the companion crop treatments were sorted into cereal and lucerne biomass, and all samples oven dried at 65^{o}C until constant weight was reached.

Table 1. Dates defining the periods of biomass accumulation and biomass sampling dates

Period	Dates defining periods	Biomass sampling dates
	2003/04	
Winter	27 April 2003 - 11 July 2003	11 July 2003
Summer	27 November 2003 - 3 May 2004	11 September 2003
Annual[A]	27 April 2003 - 3 May 2004	26 November 2003
		12 January 2004
		1 March 2004
		3 May 2004
	2004/05	
Winter	3 June 2004 - 14 September 2004	14 September 2004
Cereal anthesis	3 June 2004 - 20 October 2004	20 October 2004
Cereal maturity	3 June 2004 - 2 December 2004	2 December 2004
Summer	3 December 2004 - 5 May 2005	12 January 2005
Annual[A]	3 June 2004 - 5 May 2005	3 March 2005
		5 May 2005
	2005/06	
Winter	2 June 2005 - 6 September 2005	6 September 2005
Summer	6 December 2005 - 3 May 2006	24 October 2005
Annual[A]	2 June 2005 - 3 May 2006	5 December 2005
		13 January 2006
		7 March 2006
		3 May 2006

[A] Annual defined as the period from sowing the cereal crop to the break of season in the following year.

Winter herbage N uptake

Winter herbage N (kg N/ha) uptake was calculated by multiplying herbage N concentrations of lucerne and cereal by their respective winter biomass production.

Crop population measurements

In each season, seedling density was measured at the second leaf stage of crop growth, by counting cereal plants on both sides of a 0.5 m stick, randomly placed four times within each sub-plot. Spike density was measured by counting fully emerged cereal ears collected from the quadrats cut for anthesis biomass. In 2005, tillers were counted before and after the application of top-dressed N, by counting all tillers other than the primary stem on both sides of a 0.5 m stick, randomly placed four times within each sub-plot.

Grain harvest measurements

In all years grain yield was measured by mechanically harvesting each sub-plot. A sub-sample of grain was retained to assess grain quality. Grain protein was calculated by multiplying grain N concentration by 5.7.

Soil water measurements

Soil water content was measured with a calibrated neutron moisture meter (CPN Corporation Martinez, CA) (Greacen 1981) from 29 April 2002 to 4 May 2006. One 3.0 m length of PVC access tube with the lower end sealed was placed close to the centre of the sub-plot receiving additional N in each main plot of the first three blocks. The first measurement was taken at 0.2 m then at 0.2 m increments thereafter to 2.8 m depth, at the sowing of cereal crops (GS 00), mid-winter (GS 12 – 15), early spring (GS 25-32), cereal anthesis (GS 65), cereal maturity (GS 95) and three times over each summer period.

Calibration of the neutron moisture meter

The neutron moisture meter was calibrated twice to cover both wet and dry soil conditions at each depth increment. Sacrifice access tubes located close to the field experiment were neutron probed and converted into count ratios by dividing the count number by a shield count taken on the day of measurement. Three soil cores (diameter 42 mm) extracted to a depth of 2.9 m, within 0.5 m of the access tube, were taken and divided into the corresponding probing depths from 0.1 m depth and divided into 0.2 m increments thereafter to 2.9 m, and bagged separately. Soil samples were then weighed and oven dried at 105°C for 48 hours and weighed again to determine bulk density and volumetric water. A regression analysis determined a single equation, which was used to convert experimental neutron probe count ratios to volumetric soil water. The calibration equation used was:

Volumetric soil water = (0.245 x count ratio) - 0.0435 ($R^2 = 0.73$)

Soil collection and preparation for in-crop mineral N analysis

Surface soil mineral N ($NH_4^+ + NO_3^-$) was measured before and after N was top-dressed during the 2005 growing season on 2 August and 18 August respectively. On both occasions five soil cores (internal diameter 20 mm) were collected from randomly selected positions within each sub-plot. Cores were collected to 0.2 m and divided into two 0.1 m increments and bulked for each depth in each sub-plot. Samples were oven dried at 40°C for 48 hours, and passed through a 2 mm sieve prior to measuring soil mineral N.

Chemical analysis

Soil mineral N concentrations were determined using the method of Rayment and Higginson (1992) via an automated colorimetric procedure and dual-channel auto analyser. The mean bulk density of soils collected when calibrating the neutron probe was used to calculate mineral N per unit volume. Grain and herbage N concentrations were measured using a LECO CNS2000 analyser apparatus.

Statistical analysis

Statistical analyses were performed to determine the impact of companion cropping on the productivity of both the cereal and lucerne components, as well as on lucerne's ability to maintain dry subsoils, and determine the effect of additional N and water for increasing cereal productivity. The plant populations, biomass, grain yield and grain quality data were analysed using analysis of variance (ANOVA) appropriate for a completely randomised block design to assess the significant difference amongst treatments. Soil water data was analysed by fitting a linear mixed model for each individual depth using Residual Maximum Likelihood (REML) to determine treatment differences over time. The analysis also included fitting a cubic spline of time to investigate non-linear trends (Verbyla *et al.* 1999). All statistical analyses were performed using GENSTAT 8 Release 8.2 (Genstat 2004).

Results

Rainfall

In 2003 and 2005, annual rainfall was 53 mm (decile 8) and 160 mm (decile 10) greater, respectively, than the long-term mean of 541 mm (62 year average). In 2004 annual rainfall was 119 mm (decile 4) below the long-term mean. Growing season rainfall (April to October) was 57 mm (decile 8) and 25 mm (decile 7) above the long-term mean of 358 mm in 2003 and 2005, respectively; but in 2004 it was 39 mm (decile 5) below the long-term mean (Figure 1).

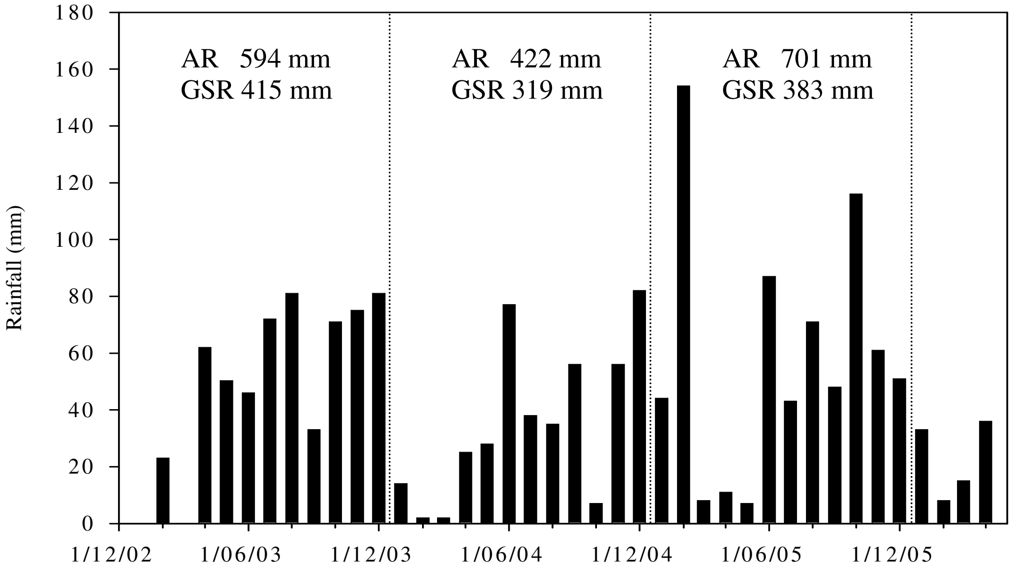

Fig 1. Monthly rainfall (mm) for North Boorhaman, from January 2003 to April 2006. AR denotes annual rainfall, GSR denotes growing season rainfall (April – October).

Lucerne and cereal biomass

In all years the lucerne monoculture produced greater (*P*<0.05) winter and annual lucerne biomass than the companion crop treatment (Table 2). Averaged over the three-year experiment the lucerne monoculture produced 47% and 60% more lucerne biomass over the winter and yearly basis respectively, than the companion crop treatment.

Table 2. Lucerne, cereal and total biomass (kg DM/ha) production over different periods of companion crop, cereal and lucerne monoculture treatments.

Mean of the two rates of N.

Mean of the two rates of water in 2004/05.

Treatment	Winter^A			Summer^A	Annual^A		
	Lucerne	Cereal	Total	Lucerne	Lucerne	Cereal	Total
				2003/04			
Cereal monoculture		1310	1310			13226	13226
Companion crop	696	988	1684	1653	3552	10275	13827
Lucerne monoculture	1334		1334	2219	11037		11037
l.s.d (*P*<0.05)	370	n.s	319	264	1761	1910	1702
				2004/05			
Cereal monoculture		2068	2068			11292	11292
Companion crop	559	1945	2503	3912	5026	9282	14308
Lucerne monoculture	1283		1283	3485	9852		9852
l.s.d (*P*<0.05)	320	n.s	383	405	1211	n.s	2614
				2005/06			
Cereal monoculture		1399	1399			10782	10782
Companion crop	530	1242	1772	1233	2607	9901	12508
Lucerne monoculture	844		844	800	7303		7303
l.s.d (*P*<0.05)	175	n.s	217	360	1298	803	1237

n.s indicates no significant difference, ^{A}Table 1 specifies dates for this period of biomass accumulation

There were no differences in cereal biomass production over the winter period in all three years between the cereal monoculture and companion crop treatments. However, the cereal monoculture did produced 22% and 8% more annual cereal biomass ($P<0.05$) in 2003/04 and 2005/06, respectively, than the companion crop treatment (Table 2).

Although the companion crop treatment did not produce as much lucerne and cereal biomass as the lucerne and cereal monocultures, total (lucerne and cereal) biomass production the companion crop treatment was greater ($P<0.05$) over the winter and yearly basis. Averaged over the three winter periods, the companion crop treatment produced 20% and 41% more total biomass than the cereal monoculture and the lucerne monoculture treatments, respectively (Table 2).

In all years the companion crop treatment produced more ($P<0.05$) than the lucerne monoculture; and more ($P<0.05$) total annual biomass than the cereal monoculture in 2004/05 and 2005/06 seasons. Over the three years, companion cropping improved average total annual biomass by 31% compared with the lucerne monoculture, and by 18% compared with the cereal monoculture over 2004/05 and 2005/06.

In 2003/04 the lucerne monoculture produced greater ($P<0.05$) lucerne biomass over the summer period compared with the companion crop treatment (Table 2). However, in 2004/05 and 2005/06 the companion crop treatment produced 11% and 35% more lucerne biomass ($P<0.05$) respectively, over the summer period compared with the lucerne monoculture.

Productivity of the cereal's grown with and without lucerne

In all three years there were no differences in cereal seedling emergence (Table 3). Winter herbage N uptake was higher ($P<0.05$) in the companion crop treatment (includes both cereal and lucerne N uptake) compared with the cereal monoculture. Companion cropping removed on average an additional 14 kg of N/ha over the winter period compared with the cereal monoculture.

Table 3. Cereal plant populations, herbage N uptake, cereal biomass at maturity, grain yield, harvest index (grain yield/cereal biomass) and cereal grain protein for all years; and in-crop soil mineral N (0-0.2 m depth) and cereal tiller populations for 2005 of companion crop compared with cereal monoculture

Mean of the two rates of N.

Mean of the two rates of water in 2004.

Measurement	Cereal monoculture	Companion crop	l.s.d ($P<0.05$)
		2003	
Seedling density (seedlings/m^2)	126	127	n.s
Winter herbage N uptake (kg N/ha)^A	17	33^B	6
Spike density (spikes/m^2)	293	159	52
Cereal biomass at maturity (kg DM/ha)	13226	10275	1910
Grain yield (t/ha)	3.8	2.8	0.8
Harvest index	0.29	0.28	n.s
Grain protein (%)	12.4	10.7	0.95
		2004	
Seedling density (seedlings/m^2)	101	96	n.s
Winter herbage N uptake (kg N/ha)^A	27	41^B	7
Spike density (spikes/m^2)	196	162	25
Cereal biomass at maturity (kg DM/ha)	11292	9282	1392
Grain yield (t/ha)	4.1	3.0	0.6
Harvest index	0.37	0.34	n.s
Grain protein (%)	9.0	9.2	n.s
		2005	
Seedling density (seedlings/m^2)	164	169	n.s
Tillers 11 August (tillers/m^2)	199	145	28
Tillers 29 August (tillers/m^2)	290	251	38
Winter herbage N uptake (kg N/ha)^A	18	31^B	4
Spike density (spikes/m^2)	382	342	28
Cereal biomass at maturity (kg DM/ha)	10782	9901	803
Grain yield (t/ha)	4.3	3.3	0.3
Harvest index	0.41	0.33	0.04
Grain protein (%)	9.5	9.5	n.s

^{A}Corresponds to biomass collection dates specified for winter periods in Table 1.

^{B}Includes N uptake by both the cereal and lucerne components in the companion crop.

n.s indicates no significant difference

Although there was no effect of lucerne on cereal crop establishment, by cereal anthesis the companion crop treatment had on average 24% decline ($P<0.05$) in cereal spike densities than the cereal monoculture (Table 3).

In 2005, the companion crop treatment recorded less ($P<0.05$) tillers than the cereal monoculture on both occasions, with an additional 54 and 49 tillers in cereals grown without lucerne (Table 3).

The cereal monoculture yielded on average 16% and 25% more ($P<0.05$) cereal biomass and grain respectively, than the companion crop (Table 3). Cereal grain protein levels appeared to be unaffected by the presence of lucerne, except in 2003 when the grain protein levels in the companion crop treatment was 1.7 units less ($P<0.05$) than the cereal monoculture. Initially harvest index was unaffected by the presence of lucerne, but in 2004 and 2005 companion cropping resulted in lower ($P<0.05$) harvest indexes.

The impact of additional N

With the exception of annual lucerne biomass and total annual biomass, there was no significant ($P>0.05$) interaction between main treatment (monoculture versus companion crop) and N application (Table 4). However, the addition of N did result in significant responses ($P<0.05$) across the experiment (mean of all treatments), expressed in a number of measurements (Table 5).

Table 4. F probabilities from analyses of variance for annual biomass (lucerne, cereal and total), cereal spike density, grain yield and grain protein in all years to explore main treatment (monoculture v companion crop) by N application interactions

	2003/04	2004/05	2005/06	2003/04	2004/05	2005/06	2003/04	2004/05	2005/06
Source of variation	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.
	Annual lucerne biomass			*Annual cereal biomass*			*Annual total biomass*		
Block.plot stratum									
Monoculture v companion	<.001	<.001	<.001	0.007	0.189	0.034	0.009	0.007	<.001
Block.plot.sub_plot stratum									
N application	0.054	0.012	0.011	0.035	<.001	<.001	0.005	<.001	<.001
Monoculture v companion x N application	0.189	0.023	<.001	0.254	0.053	0.06	0.57	0.039	0.003
	Cereal spike density			*Cereal grain yield*			*Cereal grain protein*		
Block.plot stratum									
Monoculture v companion	<.001	0.01	<.001	<.001	0.049	<.001	0.004	0.766	0.705
Block.plot.sub_plot stratum									
N application	0.132	<.001	<.001	<.001	<.001	<.001	0.011	<.001	0.004
Monoculture v companion x N application	0.338	0.054	0.97	0.435	0.736	0.241	0.43	0.453	0.506

Table 5. The effect of N application on annual biomass (lucerne, cereal and total), cereal spike density, cereal grain yield and cereal grain protein in all years; and in-crop soil mineral N (0-0.2 m depth) and cereal tiller formation in 2005

Mean of the cereal monoculture; companion crop and lucerne monoculture treatments.

Mean of the two rates of water in 2004/05.

Measurement	Additional N	No Additional N	l.s.d ($P<0.05$)
		2003/04	
Annual lucerne biomass (kg DM/ha)^A	7825	6763	n.s
Annual cereal biomass (kg DM/ha)^A	12728	10773	1786
Total annual biomass (kg DM/ha)^A	13702	11691	1313
Cereal spike density (spikes/m^2)	222	231	n.s
Cereal grain yield (t/ha)	3.5	3.0	0.3
Cereal grain protein (%)	12.0	11.1	0.64
		2004/05	
Annual lucerne biomass (kg DM/ha)^A	7832	7045	589
Annual cereal biomass (kg DM/ha)^A	11592	8982	1178
Total annual biomass (kg DM/ha)^A	12950	10685	850
Cereal spike density (spikes/m^2)	202	155	17
Cereal grain yield (t/ha)	4.1	3.0	0.3
Cereal grain protein (%)	10.3	7.9	0.48
		2005/06	
Annual lucerne biomass (kg DM/ha)^A	5815	4609	880
Annual cereal biomass (kg DM/ha)^A	13326	7357	760
Total annual biomass (kg DM/ha)^A	12761	7977	797
Soil mineral N on 2 August (kg N/ha)	31	33	n.s
Cereal tiller density 11 August (tillers/m^2)	173	172	n.s
Soil mineral N on 18 August (kg N/ha)	69	21	13
Cereal tiller density 29 August (tillers/m^2)	313	229	20
Cereal spike density (spikes/m^2)	459	265	23
Cereal grain yield (t/ha)	4.7	2.8	0.3
Cereal grain protein (%)	9.9	9.2	0.45

n.s indicates no significant difference

^{A}Table 1 specifies dates for this period of biomass accumulation.

While additional N increased ($P<0.05$) lucerne biomass by 10 – 21% over the three years of the experiment (Table 5), supplementary N had a greater ($P<0.05$) effect on cereal biomass production, with improvements ranging from 15% in 2003/04, 23% in 2004/05, to 45% in

2005/06. Cereal spike density was unaffected by N application in 2003/04, but was higher ($P<0.05$) in 2004/05 and 2005/06 where additional N was applied (Table 5). Increases ($P<0.05$) in cereal grain from additional N were observed in all years, with increases of 0.5 t/ha in 2003/04, 1.1 t/ha in 2004/05 and 1.9 t/ha in 2005/06. Improvements in cereal grain protein levels ranged from 0.7 – 2.4 units greater ($P<0.05$) where additional N was applied, with the greatest increase in the 2004/05 season.

In 2005, when additional measurements were taken, there was no difference in soil mineral N or tiller density on 2 August and 11 August respectively. After the application of additional N, soil mineral N levels in the top 0.2 m and tiller density were higher ($P<0.05$) on 18 August and 29 August respectively (Table 5), with a 71 and 27% increase in soil mineral N and tiller density respectively.

Significant ($P>0.05$) interactions between main treatment (monoculture versus companion crop) and N application were observed in either annual lucerne production, or total biomass, in 2004/05 and 2005/06 (Table 4). In both these years the application of N resulted in an increase in annual lucerne biomass in the lucerne monoculture, but not in the companion crop treatment, and regardless of the application of N, annual lucerne biomass was greatest in the lucerne monoculture compared with the companion crop treatment (Table 6).

In terms of total biomass production, the application of additional N resulted in a significant response ($P<0.05$) in the companion crop treatment only in 2004/05 (Table 6), whilst regardless of additional N application, the companion crop treatment outperformed the cereal and lucerne monocultures. In 2005/06, additional N resulted in higher ($P<0.05$) total annual biomass accumulation across all treatments, and like the other seasons the companion crop treatment again outperformed both the lucerne and cereal monocultures (Table 6).

Table 6. The interaction between main treatment (monocultures v companion crop) and N application on annual lucerne biomass (kg/ha) and total (cereal + lucerne) biomass (kg/ha)

Mean of the two rates of water in 2004/05.

	Annual lucerne biomass[A]			Total biomass[A]		
	Additional N	No Additional N	l.s.d (P<0.05)	Additional N	No Additional N	l.s.d (P<0.05)
			2003/04			
Cereal monoculture				14689	11764	n.s
Companion crop	3740	3364	n.s	14507	13146	n.s
Lucerne monoculture	11910	10163	n.s	11910	10163	
l.s.d (P<0.05)	n.s	n.s		n.s	n.s	
			2004/05			
Cereal monoculture				12016	10568	n.s
Companion crop	5070	4982	n.s	16238	12379	2769
Lucerne monoculture	10596	9108	1301	10596	9108	n.s
l.s.d (P<0.05)	833	833		1471	1471	
			2005/06			
Cereal monoculture				14129	7435	1536
Companion crop	2552	3212	n.s	15075	10490	1536
Lucerne monoculture	9079	6006	1500	9079	6006	1536
l.s.d (P<0.05)	1244	1244		1380	1380	

n.s indicates no significant difference,

[A] Table 1 specifies dates for these periods of biomass accumulation.

The impact of additional water

The application of additional water over the late growing season of 2004 did not result in a significant interaction (P>0.05) between main treatment (monoculture versus companion crop) and the application of water (Table 7). However, the addition of water did result in significant responses (P<0.05) across the experiment (mean of all treatments), expressed in a number of measurements, but only at cereal maturity.

Table 7. F probabilities from analyses of variance for cereal anthesis and maturity biomass (lucerne, cereal and total), cereal spike density, grain yield and grain protein in 2004 to explore main treatment (monoculture v companion crop) by water application by N application interactions

Source of variation	F pr.	F pr.	F pr.	F pr.	F pr.
			Cereal anthesis		
	Lucerne biomass	Cereal biomass	Total biomass	Cereal spike density	
Block.plot stratum					
Monoculture v companion	<.001	0.01	<.001	0.014	
Water application	0.265	0.15	0.056	0.237	
Monoculture v companion x water application	0.594	0.836	0.838	0.747	
Block.plot.sub_plot stratum					
N application	0.077	<.001	<.001	<.001	
Monoculture v companion x topdressed N	<.001	0.052	0.162	0.071	
Water application x N application	0.804	0.522	0.487	0.561	
Monoculture v companion x water application x N application	0.509	0.41	0.708	0.782	
			Cereal maturity		
	Lucerne biomass	Cereal biomass	Total biomass	Cereal grain yield	Cereal grain protein
Block.plot stratum					
Monoculture v companion	<.001	0.01	<.001	0.002	0.627
Water application	0.014	<.001	<.001	<.001	0.001
Monoculture v companion x water application	0.113	0.575	0.063	0.955	0.519
Block.plot.sub_plot stratum					
N application	0.004	<.001	<.001	<.001	<.001
Monoculture v companion x topdressed N	0.016	0.06	0.012	0.658	0.35
Water application x N application	0.444	0.036	0.024	0.004	0.013
Monoculture v companion x water application x N application	0.198	0.226	0.251	0.94	0.219

The application of water resulted in a 23, 35 and 32% increase ($P<0.05$) in lucerne, cereal and total biomass respectively, while cereal grain yield was boosted ($P<0.05$) by an additional 35% (Table 8). Conversely, additional water over the late growing season resulted in a 1.9 unit decline ($P<0.05$) in cereal grain protein.

Table 8. The effect of water on biomass (lucerne, cereal and total) cereal spike density, cereal grain yield and cereal grain protein in 2004

Mean of the cereal monoculture; companion crop and lucerne monoculture treatments.

Mean of the two rates of N.

Measurement	No additional water	Additional water	l.s.d ($P<0.05$)
		Cereal anthesis[A]	
Lucerne biomass (kg DM/ha)	2446	2837	n.s
Cereal biomass (kg DM/ha)	6950	7727	n.s
Total biomass (kg DM/ha)	6264	7043	n.s
Cereal spike density (spikes/m^2)	172	186	n.s
		Cereal maturity[A]	
Lucerne biomass (kg DM/ha)	3249	4231	322
Cereal biomass (kg DM/ha)	8100	12474	1392
Total biomass (kg DM/ha)	7566	11137	934
Cereal grain yield (t/ha)	2.8	4.3	0.6
Cereal grain protein (%)	10.1	8.2	0.96

n.s indicates no significant difference

[A] Table 1 specifies dates for biomass accumulation.

The combination of additional water and N resulted in greater ($P<0.05$) cereal biomass, total biomass and cereal grain yield at cereal maturity (Table 9). The combined applications of water and N resulted in a 49, 46 and 49% increase in cereal biomass, total biomass and cereal grain yield, respectively, compared to no additional water or N. Cereal grain protein levels were more influenced by the addition of N rather than the addition of water.

Table 9. The interaction between additional N and additional water on biomass (lucerne, cereal and total) at cereal maturity, cereal grain yield and cereal grain protein in 2004

Mean of the cereal monoculture; companion crop and lucerne monoculture treatments.

	Additional N	No Additional N	l.s.d ($P<0.05$)
	Lucerne biomass (kg DM/ha)^{A}		
No additional water	3564	2934	n.s
Additional water	4724	3738	n.s
l.s.d ($P<0.05$)	n.s	n.s	
	Cereal biomass (kg DM/ha)^{A}		
No additional water	8850	7349	n.s
Additional water	14333	10615	1624
l.s.d ($P<0.05$)	1445	1445	
	Total biomass (kg DM/ha)^{A}		
No additional water	8276	6855	1143
Additional water	12705	9568	1143
l.s.d ($P<0.05$)	1034	1034	
	Cereal grain yield (t/ha)		
No additional water	3.0	2.6	n.s
Additional water	5.1	3.5	0.6
l.s.d ($P<0.05$)	0.5	0.5	
	Cereal grain protein (%)		
No additional water	11.6	8.6	1.03
Additional water	9.1	7.3	1.03
l.s.d ($P<0.05$)	0.68	0.68	

n.s indicates no significant difference

^{A}Table 1 specifies dates for biomass accumulation.

Soil water distribution

Over the duration of the experiment applying irrigation in October 2004 did not significantly effect soil water levels at all depths, except at 0.2 m depth ($P=0.029$), where an additional 4 mm of soil water was found across all treatments receiving additional water. Therefore our analysis concentrated on the quantifying the effect that monocultures and companion crop treatments had on soil water content over time. Analysis of soil water content at individual depths found differences ($P<0.05$) at and below 1.2 m (Table 10). On the basis of this analysis we grouped individual depths into two layers, 0.2 to 1.0 m and 1.2 to 2.8 m. This analysis found that there were generally no differences in soil water content between treatments in the 0.2 to 1.0 m layer, except during the fallow period where the cereal monoculture was wetter ($P<0.05$) compared with the other treatments. In the deeper layer there was a consistent significant ($P<0.001$) treatment effect over time (Table 10).

In the top layer (0.2 – 1.0 m) soil water largely responded to fluctuations in rainfall and plant water use under all treatments (Figure 2a), especially during the growing season (April-October). However, higher soil water contents from summer rainfall in the absence of plant water use was found under the cereal monoculture over the summer months, reflected by wetter profiles on 13 January 2004, 14 January to 14 June 2005 and 9 December 2005 to 16 January 2006 (Figure 2a). In the deeper layer (1.0 – 2.8 m) there was a downward trend in soil water content from 13 January 2004 to the completion of the experiment under both the companion crop and lucerne treatments (Figure 2b). In contrast the soil water content remained largely unchanged under the cereal monoculture in the deeper layer over the experiment. At the completion of the experiment on 4 May 2006 the companion crop and lucerne treatments were 39.2 and 56.5 mm respectively, drier than the cereal monoculture in the deeper layer. Differences in soil water content in the lower layer were also measured between the companion crop and lucerne monoculture treatments, except on 3 September 2003, 10 October 2003 and 26 August 2005 – 9 December 2005.

Table 10. Fixed terms included in the chosen fitted spline model for volumetric soil water content data collected under the lucerne, companion crop and cereal treatments at two depth intervals.

	Treatment			Time			Treatment x Time		
Depth (m)	Wald Statistic	d.f.	P-value	Wald Statistic	d.f.	P-value	Wald Statistic	d.f.	P-value
				Individual depths					
0.2	0.83	2	0.66	2372.22	24	<0.001	79.93	48	0.003
0.4	2.86	2	0.239	981.23	24	<0.001	85.61	48	<0.001
0.6	8.17	2	0.017	1331.75	24	<0.001	167.27	48	<0.001
0.8	3.48	2	0.175	1023.25	24	<0.001	123.18	48	<0.001
1.0	4.25	2	0.12	727.59	24	<0.001	103.86	48	<0.001
1.2	10.54	2	0.005	305.92	24	<0.001	129.71	48	<0.001
1.4	78.5	2	<0.001	102.17	24	<0.001	111.75	48	<0.001
1.6	62.98	2	<0.001	53	24	<0.001	82.93	48	<0.001
1.8	40.25	2	<0.001	81.37	24	<0.001	85.63	48	<0.001
2.0	7.43	2	0.024	48.96	24	0.002	66.16	48	0.042
2.2	11.03	2	0.004	59.48	24	<0.001	63.52	48	0.066
2.4	40.14	2	<0.001	97.18	24	<0.001	95.67	48	<0.001
2.6	53.1	2	<0.001	141.02	24	<0.001	121.82	48	<0.001
2.8	46.1	2	<0.001	84.54	24	<0.001	87.31	48	<0.001
				Layers					
0.2-1.0	8.41	2	0.015	2241.31	24	<0.001	109.63	48	<0.001
1.2-2.8	82.56	2	<0.001	298.91	24	<0.001	248.78	48	<0.001

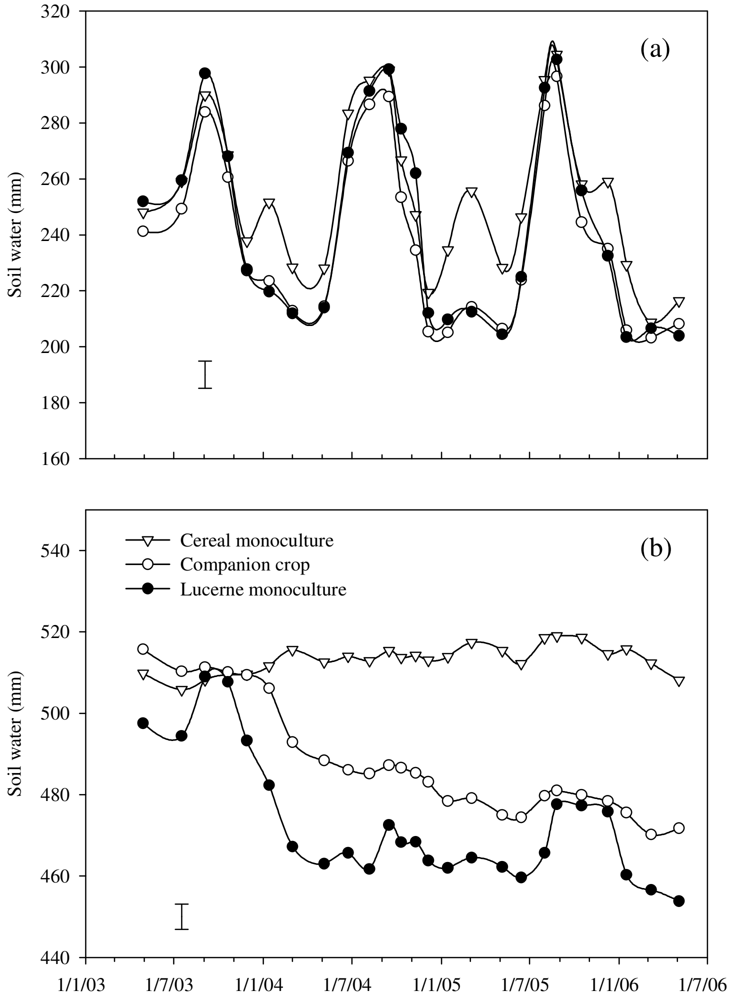

Fig 2. Fitted spline models of mean volumetric soil water content (from 29 April 2003 to 4 May 2006) for the grouped depths 0.2 to 1.0 m (a) and 1.2 to 2.8 m (b) under the cereal, companion crop and lucerne treatments

Discussion

The role of companion cropping for improving rainfall utilisation and biomass production

While cereal and lucerne production is individually compromised under companion cropping, our study shows conclusively that this practice promotes more efficient utilisation of rainfall because of greater combined (cereal and lucerne) annual biomass production in comparison with respective monocultures. Lucerne monocultures produce most of their annual biomass over the mid spring through to early summer period (Hirth *et al*. 2001), while annual cereals like wheat produce most of their biomass from tillering to anthesis (French and Schultz 1984) coinciding with late winter to mid spring in Southern Australia. Companion cropping provides a farming system where plant growth can opportunistically respond to rainfall throughout the year.

The additional growth promoted through companion cropping may be an attractive option for livestock production systems common on mixed farms. This work demonstrates that growing more dry matter through companion cropping is possible, but more research would be useful to identify ways of profitably utilising this additional biomass production.

When does the association with lucerne negatively impact on companion crop performance? Despite the advantage of more efficient rainfall utilisation, the challenge remains to produce economically viable products from companion cropping. Our study along with others (Egan and Ransom 1996; Humphries *et al*. 2004; Harris *et al*. 2007) suggest that cereal grain is unlikely to be that product, as competition with lucerne often prevents cereals from achieving potential grain yields.

Zimdahl (1999) defined competition occurring, “when two or more organisms seek what they want or need and the supply falls below the combined demand”. In our study we attempted to investigate the effect of resource supply (water and N) on companion crop performance. Past research had reported that companion crop dry matter taken at cereal anthesis were similar to cereals growing in monoculture, and that the competition between species was having the greatest effect on companion crop grain yields during the post anthesis period (Egan and Ransom 1996). In addition N was applied to test the hypothesis that N utilisation by lucerne was a constraint to cereal growth in the presence of lucerne. Hirth *et al.* (2001) measured significantly lower soil mineral N at the autumn break under lucerne pastures compared with annual pastures in four out of five years. Although the authors do not speculate why this result occurred, it was probably due to lucerne's largely continuous active growth immobilising available mineral N. Angus *et al*. (2000) had also concluded that N availability was likely to be a limiting factor to crop growth in the presence of lucerne, particularly when there was adequate soil water supply.

Based on the evidence presented by Egan and Ransom (1996), we designed the experiment with the intention of delivering resources later in the growing season, on the premise that competition for soil water during the post anthesis period was largely compromising companion crop grain yields. However, the data from our study suggests that the competitive effects on companion crop performance were occurring much earlier in the growing season. Cereals growing with lucerne produced fewer tillers, spikes and consequently cereal biomass compared with cereals growing in monoculture. The data collated by Harris *et al*. (2007) are consistent with this observation and although Humphries *et al*. (2004) did not directly measure tiller and spike density they did report a 50% decline in cereal biomass production over the winter period from companion cropping. This reduction in companion crop populations and biomass ultimately translated into lower grain yields, and many other studies have also shown a link between vigorous early cereal growth and subsequent grain yield (Acevedo and Ceccarelli 1987; Turner and Nicolas 1987; Palta and Fillery 1995).

What is the likely resource or resources contributing to this negative expression in companion crop grain yield?

The current study provided evidence that competition early in the growing season, soon after cereal seedling emergence, also contributed to the poorer performance by the companion crop. This finding means that our experimental design restricted our capacity to assess the role of resource supply at this critical period, and therefore we can only speculate as to the reason for reduced tillering in companion crops compared with cereal monocultures.

Applying N resulted in the same cereal responses irrespective of lucerne presence, so it appears that most of the N applied to the companion crop, was taken up by the cereal. This is further supported by the absence of a lucerne biomass response to N application in the companion crop treatment whereas the response was evident in the lucerne monoculture. However, we have evidence that the companion crop treatment has a greater demand for N over the winter period, reflected by the greater combined cereal and lucerne biomass and consequently herbage N uptake. In all years, after suppressing the lucerne before sowing the companion crop, there was initially rapid lucerne regrowth before growth slowed over the winter period. This initial lucerne regrowth may have resulted in soil N uptake, potentially reducing the pool of available N and depriving the companion crop of the same N supply available to the cereal monoculture. This would help to explain why the cereal response to applied N was the same irrespective of the presence of lucerne, because when N was applied later in the winter period, lucerne growth and demand for N was negligible. This theory assumes that lucerne was not sourcing its entire N requirements from the atmosphere (Whitehead 1995). The observed biomass response to applied N in the lucerne monoculture supported this notion. We also explored the possibility that companion cropping might compromise tiller survival, but found in 2005 when tiller density was monitored, that there was no difference in tiller survival in the companion crop and cereal monoculture treatments. Although we acknowledge that 2005 had a wet spring (164 mm recorded over September and October), and under drier conditions tiller survival in companion crops maybe more effected.

Early limited supply of available N may not be the only reason for reduced tiller formation in companion crops. Competition for soil water is a possibility. However, this was unlikely in the current study as soil water content in the top metre of the profile was increasing under all treatments over each winter period. Conversely, competition for light is another possible factor contributing to reduced tiller formation (Puckeridge and Donald 1967; Puckeridge 1968). Light can affect tillering through two mechanisms; firstly the quantity of photosynthetically active radiation (PAR) intercepted by individual cereal plants; and secondly the quality of light, or the ratio of red : far red light reaching the base of individual cereal plants (Evers *et al*. 2006). Knauber and Banowetz (1992) reported reduced tillering in wheat exposed to high far red irradiance. Competition for light increases as plant density increases, and in the case of companion cropping the presence of lucerne contributes to a greater plant density compared with the cereal monoculture. The initial rapid regrowth of lucerne shortly after sowing could have shaded neighbouring cereal seedlings altering either the quantity or quality of light intercepted by the companion crop.

Separating the individual effects that N and light have on tiller formation in companion crops is impossible in the field; such an assessment would need to be performed in an environment where resource supply can be controlled. Whilst a definitive answer regarding reduced tillering in companion crops can not be provided, this finding does have agronomic implications. Agronomic strategies that reduce rapid lucerne regrowth after suppression and early delivery of greater quantities of N to the companion crop may encourage greater tiller formation. Alternatively higher cereal sowing rates maybe another option for achieving higher cereal populations in companion crops. Consequently this may in turn allow the companion crop to perform on a comparable level with the cereal monoculture in terms of cereal populations, and depending on late growing season conditions, potentially close the grain yield gap at cereal maturity. In our study low harvest index in 2005, indicates that post anthesis stress can still contribute to reduced companion crop performance and should not be overlooked.

Additional water supplied late in the 2004 growing season and its interaction with N resulted in the same cereal grain yield responses, irrespective of whether lucerne was present. This tends to suggest that once the companion crop gains the competitive advantage over lucerne most of the resource supply is utilised by the cereal component. However with only one year’s data, we believe further observations are needed before this theory can be accepted.

Does companion cropping compromise lucerne's capacity to dry subsoils?

Our study shows that lucerne's association with a companion crop does to a degree, compromise its capacity to extract soil water from deep in the soil profile. Ridley *et al*. (2001) reported the major period for increased soil water extraction under lucerne was from late spring to mid summer, with additional drying from deeper layers in the autumn. Despite the companion crop treatment producing greater lucerne biomass over the summer period in 2004/05 and 2005/06, the soil profile remained significantly wetter. Hoffman *et al*. (2003) reported that topsoil moisture largely contributes to lucerne biomass production, and that subsoil moisture (> 0.6 m) even in plentiful supply, does not result in substantial biomass production. Our data shows that companion cropping significantly reduced aboveground lucerne biomass production over the growing season, and was likely to have equally compromised below ground biomass accumulation. We speculate that lucerne root proliferation may have been reduced in association with the cereal crop, resulting in less subsoil water extraction.

Conclusion

Our study demonstrated that the combined activity of cereal and lucerne growing simultaneously can be more efficient at capturing and converting rainfall into total annual biomass, compared with a cereal or lucerne growing alone. While this partnership does appear to compromise lucerne's potential to ameliorate dryland salinity to a degree, it does provide greater environmental protection compared with a continuous annual plant system. However, the negative effect on companion crop grain yield from the association with lucerne remains a constraint. We have identified that companion crops produce fewer tillers compared with cereals growing in monoculture, and suggest that competition for N and light, prior to cereal stem elongation are likely causes. In addition, we suggest agronomic strategies that limit lucerne regrowth shortly after sowing the companion crop combined with additional fertiliser N, may encourage greater tiller formation in companion crops, and potentially close the grain yield gap with equivalent cereals growing in monoculture. Alternatively higher sowing rates may also achieve greater cereal density in the presence of lucerne. However, we still acknowledge that late growing season conditions will have a large influence on companion crop grain production. For this reason we have proposed other applications for companion cropping, including a means for providing extra feed for livestock production systems on mixed farms.

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Chapter 4. Companion crop performance in the absence and presence of agronomic manipulation

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Running title: Fertiliser, herbicide and crop type effects on cereal-lucerne companion crops.

Co-author declarations

JR Hirth

11 November 2010

To whom it may concern.

This letter is to confirm that my contribution to the publication listed below, of which I was a co-author with Rob Harris, in terms protocol development, interpretation of the data, and suggested editing of the paper/manuscript, was in the order of 5%.

Harris RH, Hirth JR, Crawford MC, Bellotti WD, Peoples MB and Norng S (2007). Companion crop performance in the absence and presence of agronomic manipulation. *Australian Journal of Agricultural Research* **58**, 690-701.

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

Yours sincerely,

Jeff Hirth.

MC Crawford

I give written permission for the paper “Companion crop performance in the absence and presence of agronomic manipulation” to be included in Rob’s PhD Thesis.

I made a minor contribution to the work in the area of hypothesis formulation, protocol developments and editing of the paper.

Yours Sincerely

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WD Bellotti

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To whom it may concern,

Contribution to publications by Mr Rob Harris included in his thesis to be submitted for the award of Doctor of Philosophy

This note is to confirm that my contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Hirth JR, Crawford MC, Bellotti WD, Peoples MB, Norng S (2007a) Companion crop performance in the absence and presence of agronomic manipulation. *Australian Journal of Agricultural Research*. 58, 690-701.

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

Yours sincerely,

Professor Bill Bellotti
Vincent Fairfax Chair in Sustainable Agriculture and Rural Development

MB Peoples

28 November 2008

To whom it may concern

This note is to confirm that my contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Hirth JR, Crawford MC, Bellotti WD, Peoples MB and Norng S (2007). Companion crop performance in the absence and presence of agronomic manipulation. *Australian Journal of Agricultural Research* 58: 690-701.

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

Yours sincerely

Mark B Peoples
Deputy Chief
CSIRO Plant Industry

S Norng

I give Rob Harris permission for the paper “Companion crop performance in the absence and presence of agronomic manipulation” to be included in his PhD Thesis.

I carried out the REML statistical analysis for the soil water data presented in the paper, and provided guidance regarding soil water data interpretation.

Yours Sincerely

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Abstract

A field experiment located in southern New South Wales compared the component yields of cereal-lucerne companion crops (cereals sown into established lucerne), with the yields of cereal and lucerne monocultures. In-crop lucerne herbicide suppression, cereal crop types (wheat and barley) and top-dressed nitrogen (N) was evaluated for the potential to improve cereal production in the presence of lucerne. Plant populations and biomass, cereal grain yields and grain quality (protein, screenings and contamination) were measured. Over the three-year study cereals sown into established lucerne (4 years of age at the commencement of the experiment) yielded 17% less ($P<0.05$) grain than the cereal monoculture. Companion cropping also resulted in a 71% reduction ($P<0.05$) in lucerne biomass over the growing season compared with the lucerne monoculture, but a 3-fold ($P<0.05$) increase in total (cereal and lucerne) biomass production. There were no differences between wheat and barley crops in the presence of lucerne, although extensive lodging in the 2003-barley monoculture did result in a significant main treatment (+/0 lucerne and +/0 in-crop lucerne suppression) by crop type (wheat and barley) interaction in grain yield, but not cereal biomass. N top-dressed after tillering onto cereal-lucerne companion crops did not increase grain yield, although did increase cereal biomass in 2003. Whilst in-crop lucerne suppression did not increase cereal grain yields, it did increase ($P<0.05$) cereal biomass and reduced lucerne biomass at cereal maturity and contamination (lucerne pods and flowers) of the cereal grain. However this practice reduced ($P<0.05$) lucerne populations, and therefore potentially threatens the longer-term viability of lucerne stands more research is recommended to develop less detrimental strategies for achieving effective in-crop lucerne suppression. This study combined with results from others, suggest that rainfall was a major factor determining cereal responses in the presence of lucerne, and although there were responses in cereal biomass to additional N and herbicide suppression, these strategies appear to only have potential under favourable growing season condition.

Additional keywords: herbicide suppression; N application; companion crops; *Medicago sativa*; lucerne; barley; wheat; inter-cropping; over-cropping.

Introduction

Companion cropping is defined as growing two or more different crops simultaneously on the same area of ground (Willey 1979; Francis 1986). The component crops (individual crops that make up the mixture) can be sown at different times, although their growth patterns overlap for a significant part of the year. In this paper, cereal-lucerne companion cropping is defined as the sowing of an annual cereal directly into an existing lucerne stand (Harris *et al*. 2003; Robertson *et al*. 2004). This combination of cereals and lucerne is also referred to as inter-cropping (Egan and Ransom 1996) or over-cropping (Humphries *et al*. 2004).

Integrating lucerne into cropping systems can provide environmental benefits that conventional cropping systems based on annual plants can not. Ridley *et al.* (2001) reported for a four-year period, average vertical drainage below the root zone under annual crops and pastures of 49 and 35 mm/year respectively, compared with no drainage under a lucerne pasture. They concluded that lucerne created extra soil water storage by extracting soil water when the annuals were senescing (late spring to midsummer), with additional extraction from deeper soil layers from mid summer until autumn. Other Australian studies have made similar conclusions (Crawford and Macfarlane 1995; Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ward *et al.* 2002). Under the original deep-rooted native vegetation, soil profiles were dried to greater depths over summer and were able to store the winter rainfall that was in excess of plant demand, resulting in only small losses of water to the groundwater (Peck and Williamson 1987). Thus, integrating a perennial like lucerne into farming systems, has the potential to mimic the water-use patterns of the original native vegetation whilst maintaining farm income.

One well-documented approach to integrate lucerne into cropping systems is to temporally phase the crops with the lucerne, typically as a 3-5 year phase of annual crops followed by a 3-5 year lucerne phase (Hirth *et al.* 2001). This approach can be expensive as it involves the cost of the removal and re-establishment of successive lucerne phases, and runs the risk of removal and/or re-establishment failures. The cereal-lucerne companion crop system reduces the frequency of lucerne removal and potentially provides additional green forage for livestock between annual crops. In addition, maintaining a lucerne phase for a longer period may potentially decrease the chances of substantial drainage losses, but no work has confirmed whether the association with a cereal might compromise lucerne subsoil drying capacity.

Whilst lucerne's ability as a continuous phase to dry soil profiles to depth can be beneficial for reducing the risk of dryland salinity, the implications on the performance of companion grain crops are generally not favourable. The annual crops can experience direct competition for essential resources such as sunlight, water and nutrients, with detrimental effects on their grain yields (Robertson *et al*. 2004). Egan and Ransom (1996) reported that cereals sown into young lucerne stands yielded 6 to 62% less grain than stand-alone cereals in North Central Victoria. Humpheries *et al*. (2004) reported similar grain yield reductions (13 to 63%) where wheat was sown into lucerne over two seasons in Southern Australia. Whilst grain yield reductions from cereal-lucerne companion crops can be large, there is evidence that agronomic strategies may lessen grain yield losses. Angus *et al*. (2000) suggested that provision of additional N when companion cropping in wet environments might reduce the grain yield gap between companion and monoculture crops.

Phase farming with lucerne can also reduce grain yields. Various Australian studies have reported that the yields of first crops sown after lucerne were strongly dependent on growing-season rainfall (Holford and Doyle 1978; Angus *et al*. 1996; Hirth *et al*. 2001). When cropping began in a wet year, grain yields were similar to, or greater than continuous annual cropping, or annual pasture-crop sequences, but were substantially lower when cropping began in a dry season due to differences in soil water content at sowing.

If cereal-lucerne companion cropping is to become a more reliable cropping system for managing excess soil water and reducing the threat of dryland salinity, then the grain yield reductions commonly associated with this practice need to be better managed. This paper will begin by reporting the effects that companion cropping has on both cereal and lucerne production in the absence of agronomic intervention. Then progress to discuss the potential role that agronomic strategies might play by attempting to reduce the competitive effects that lucerne can have on cereal yields. These strategies include in-crop lucerne suppression, tactical N application and crop type (wheat and barley). We also report the impact that the cereal companion crop has on lucerne's ability to maintain an adequately dry soil profile at the beginning of each winter.

Materials and Methods

Experimental site

The experiment was conducted from 2002 to 2004 at Burraja (146°37'E, 35°87'S) in the southern Riverina of New South Wales, Australia, on a slightly acidic (pH_w 6.7, 0-15 cm) Eutrophic, Red Chromosol soil (Isbell 1996).

Paddock history

In October 1998 lucerne (*Medicago sativa* cv. Aquarius) was sown at 6 kg/ha after 2.4 t/ha of lime was applied and incorporated a month earlier. Over the following three seasons the lucerne was rotationally grazed at 15 DSE/ha and winter-cleaned every year with a paraquat/diquat (230 g / 270 g of ai/ha) and diuron (1000 g of ai/ha) tank mix to eliminate annual grasses and broadleaf weeds.

Experimental design

Seven main treatments were established in 2002, and replicated three times in a randomised complete block design. Treatments included a lucerne monoculture and six cropping treatments, including two cereal monocultures, two cereal-lucerne companion crops (cereal/lucerne), and two cereal-lucerne companion crops receiving in-crop lucerne suppression (cereal/supp lucerne). In 2002, wheat (*Triticum aestivum*), 2003 barley (*Hordeum sativum*), and 2004 wheat was sown in one of the cereal monoculture, cereal/lucerne, and cereal/supp lucerne treatments, while barley-wheat-barley was sown in the other corresponding treatments. Whilst these sequences of cereal crops are not commonly practiced in the surrounding district, it was the view of the authors that less competitive crops such as oilseeds and pulses would be exposed to unsatisfactory levels of competition, and therefore more prone to failure. Individual plots were 40 by 16 m in dimension. In 2003 and 2004 each main plot was divided into two sub-plots, with one sub-plot top-dressed with N after the completion of crop tillering. The application of N before cereal stem-elongation was considered too early, increasing the risk of too much early biomass production and exhausting soil water reserves before grain filling.

Lucerne removal

On 5 April 2002, the plots allocated to cereal monoculture treatments had a mix of glyphosate (540 g of ai/ha) and clopyralid (150 g of ai/ha) applied to remove the lucerne. Subsequently the entire plots of all cereal monoculture treatments were cultivated, in an attempt to achieve complete lucerne removal on the 20 May 2002. During the 2002-growing season some remaining lucerne plants (5 plants/m^2) emerged in the cereal monoculture treatments and another application of glyphosate (540 g of ai/ha) and clopyralid (150 g of ai/ha) was applied on 20 April 2003.

Soil sample collection and preparation for mineral N analysis

Soil mineral N (NH_4^+ + NO_3^-) was measured before the seasonal break in each year under the lucerne and cereal monoculture and cereal/lucerne treatments. In 2002, three soil cores (internal diameter 42 mm) were collected from randomly selected positions within each plot, while in 2003 and 2004, three soil cores were taken randomly from within each sub-plot. Cores were taken to a depth of 1.2 m and divided into 0.1 m increments to 0.2 m depth and 0.2 m increments thereafter, and bulked for each depth in each plot or sub-plot. Samples were oven dried at 40°C for 48 hours and passed through a 2 mm sieve prior to analysis for soil mineral N.

Crop establishment

Shortly after the seasonal break, all treatments were sprayed with paraquat/diquat (338 g / 288 g of ai/ha) to suppress lucerne and eradicate annual weeds prior to sowing. In all years, cv. Schooner barley and cv. Galaxy H45 wheat were sown, except in 2004, when cv. Diamondbird wheat was sown. All cereal crops were sown at 100kg/ha using a Duncan™ triple disc seeder to minimise damage to lucerne crowns in the companion cropping treatments. N and phosphorus were applied as DAP (18 and 20 kg/ha, respectively) with the seed in all years. The site was sown on 23 May, in both 2002 and 2003, and on 28 May 2004.

In-crop germinations of annual ryegrass (*Lolium rigidum*) and wild oats (*Avena fatua*) were controlled by the application of tralkoxydim (200 g of ai/ha) plus supercharge® adjuvant on 20 June 2003. In 2004, Diclopfop-methyl (469 g of ai/ha) was applied on 1 July 2004 to control the same weeds. All treatments sown to wheat received Propiconazole (125 g of ai/ha) on 13 October 2003 and 30 September 2004 to control outbreaks of stripe rust (*Puccinia striiformis*).

In-crop lucerne suppression

The in-crop lucerne suppression treatments received 30-45 g/ha of clopyralid at a water rate of 50 L/ha, on 21 August 2002, 4 September 2003 and 30 August 2004.

N management

Urea was top-dressed at 60 kg N/ha to all additional N sub-plots, on 28 August 2003 and 30 August 2004 when cereal crops completed tillering. Urea was also top-dressed to all plots at 40 kg N/ha on 28 June 2004, as there was concern of poor seedling vigour after emerging through the heavy stubbles from the previous year's crop.

Biomass measurements

Lucerne and cereal biomass were measured when cereal crops reached first node, anthesis and maturity growth stages, but lucerne biomass was not measured over the period from cereal crop maturity to the sowing of subsequent cereal crops. In 2002, five 0.5 m^2 quadrats were randomly placed within each plot, and three 0.5 m^2 quadrats in each sub-plot, in 2003 and 2004. Plant material within each quadrat was cut to 2 cm above ground level and bulked on plot or sub-plot basis. Samples taken from the cereal/lucerne and cereal/supp lucerne treatments were sorted into cereal and lucerne biomass, and all samples oven dried at 70^{o}C until constant weight.

Crop population measurements

In each year, seedling density was recorded at the second leaf stage of crop growth by counting cereal plants on both sides of a 0.5 m stick, randomly placed 20 times within each plot. Spike density was measured by counting fully emerged cereal ears collected from the biomass samples at crop anthesis.

Lucerne population measurements

Lucerne plant and stem densities were counted five times over the duration of the experiment. At each sampling, ten to fifteen, 0.5 m^2 quadrats were randomly placed within each plot, and lucerne plants and stems greater than 3 cm in length were counted.

Grain harvest measurements

In 2002, grain yield was measured by mechanically harvesting four 1.45 m wide strips from each plot, while in 2003 and 2004, one 1.45 m strip was harvested from each subplot. A sub-sample of grain was retained for quality assessment.

Cereal grain quality measurements

The contamination of grain with lucerne pods and flowers was determined by counting their presence in a hectolitre (hL) of grain sample. Grain screenings were determined by passing wheat and barley grain through a 2 mm and 2.2 mm sieves respectively. Grain protein was calculated by multiplying grain N concentration by 5.7.

Soil water measurements

Soil water content was measured with a calibrated neutron moisture meter (CPN Corporation Martinez, CA) (Greacen 1981) from 31 May 2002 to 6 December 2004. One 2.8 m long aluminium access tube (diameter 50 mm) with the lower end sealed was placed close to the centre of each of the cereal monoculture, cereal/lucerne and lucerne monoculture treatments sub-plots not receiving top-dressed nitrogen. Measurements were taken at 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.6, 2.0 and 2.5 m depths, at the sowing of cereal crops, mid-winter, early spring, cereal anthesis, cereal maturity and once or twice over each summer period.

Calibration of the neutron moisture meter

The neutron moisture meter was calibrated twice on separate occasions at each depth increment at times representative of wet and dry soil conditions. Probe readings in access tubes located close to the field experiment were collected and converted into count ratios by dividing the count number by a shield count taken on the day of measurement. Three soil cores (diameter 42 mm) were taken to 2.6 m depth, within 0.5 m of each access tube, and divided into the corresponding probing depths of 0.1-0.3, 0.3-0.5, 0.5-0.7, 0.7-0.9, 0.9-1.1, 1.1-1.3, 1.5-1.7, 1.9-2.1 and 2.4-2.6 m and bagged separately. Soil samples were oven dried at 105°C for 48 hours to determine bulk densities and volumetric water contents. The experimental neutron probe count ratios were regressed against volumetric soil water contents. One equation was sufficient as soil water was unaffected by depth, as bulk density below 0.1 m was constant, and the following calibration equation was derived:

Volumetric soil water content = (0.2074 x count ratio) - 0.0623 ($R^2 = 0.82$)

Chemical analysis

Soil mineral N concentrations were determined using the method of Rayment and Higginson (1992) via an automated colorimetric procedure and dual-channel auto analyser. The mean bulk density of soils collected when calibrating the neutron probe, was used to calculate mineral N per unit volume. Grain N concentrations were measured using a LECO CNS2000 analyser apparatus.

Statistical analysis

Statistical analyses were performed to determine the impact of companion cropping on the productivity of both the cereal and lucerne components, as well as on lucerne's ability to maintain dry subsoils, and the impact of in-crop lucerne suppression, crop type (wheat and barley) and additional N to enhance cereal productivity. The plant populations, biomass, grain yield and grain quality data were analysed using analysis of variance (ANOVA) appropriate for a completely randomised block design to assess the significant difference amongst treatments. Soil water data was analysed by fitting a linear mixed model for each individual depth using Residual Maximum Likelihood (REML) to determine treatment differences over time. The analysis also included fitting a cubic spline of time to investigate non-linear trends. Verbyla *et al.* (1999) provides a detailed explanation of the method. Linear regression analysis was also conducted to determine a relationship between rainfall and companion crop performance from data collected from this study and other Australian studies. All statistical analyses were performed using GENSTAT 7 Release 7.2 (Genstat 2004).

Results

Rainfall

In 2002 and 2004, annual rainfall was 188 and 135 mm less respectively, than the long-term mean of 506 mm (90 year average). In 2003 rainfall was 34 mm above the long-term mean. Growing season (April to October) rainfall was 174 and 102 mm below the long-term mean of 324 mm in 2002 and 2004, respectively; but in 2003 it was 65 mm above the long-term mean (Figure 1).

Lucerne populations

Over the period of the experiment, there was a decline ($P<0.05$) in both lucerne plant and stem density from companion cropping (cereal/lucerne and cereal/supp lucerne treatments), and this decline was more severe where in-crop suppression was performed (cereal/supp lucerne treatment) (Table 1). Lucerne plant densities at the start of the experiment (13 May 2002) ranged from 10-13 plants/m^2 across the lucerne monoculture, cereal/lucerne and cereal/supp lucerne treatments. By 15 January 2005, densities had declined to 4-8 plants/m^2, with the cereal/supp lucerne treatment having 4 and 3 fewer ($P<0.05$) plant/m^2 than the lucerne monoculture and cereal/lucerne treatments respectively.

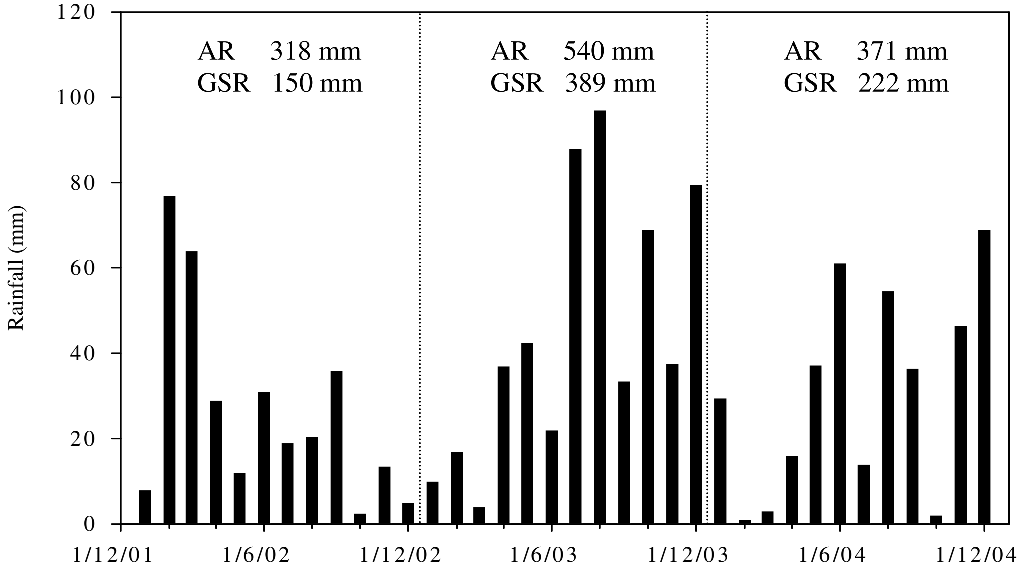

Fig 1. Monthly rainfall (mm) for Burraja, from 2002 to 2004. AR denotes annual rainfall, GSR denotes growing season rainfall.

Initially there were no differences in lucerne stem densities on 13 May 2002 (Table 1), but by 25 October 2002, the cereal/supp lucerne treatment had lower ($P<0.05$) stem densities compared with the lucerne monoculture and cereal/lucerne treatments, (71 and 52/m^2 fewer stems respectively). By 1 May 2003 stem populations had recovered in the cereal/supp lucerne treatment to densities comparable with the lucerne monoculture and cereal/lucerne treatments, with an average density of 164 stems/m^2 across the three treatments.

On 11 August 2004 and 15 January 2005 there were lower ($P<0.05$) stem densities in the cereal/lucerne and cereal/supp lucerne treatments compared with the lucerne monoculture. By 15 January 2005, there were 108 and 185 less stems/m^2 in the cereal/lucerne and cereal/supp lucerne treatments respectively, compared with the lucerne monoculture. Furthermore on both 11 August 2004 and 15 January 2005, there were fewer ($P<0.05$) stems in the cereal/supp lucerne treatment compared with the cereal/lucerne treatment, with 38 and 76 less stems/m^2 on these respective dates.

Table 1. Lucerne plant and stem densities in the lucerne monoculture, cereal/lucerne and cereal/supp lucerne treatments, on five occasions from 2002 to 2005

Mean of the wheat and barley crops and the two N rates for the cereal/lucerne and cereal/supp lucerne treatments

Mean of the two N rates for the lucerne monoculture

	lucerne monoculture	cereal/lucerne	cereal/supp lucerne	l.s.d ($P<0.05$)	Mean of all treatments
Plant density (plants/m^2)	10	9	8	1	
Stem density (stems/m^2)	183	137	103	19	
Date			*Plant density (plants/m^2)*		
13 May 2002	13	10	11	n.s	11
25 October 2002	13	12	9	n.s	11
1 May 2003	9	10	9	n.s	10
11 August 2004	8	7	5	n.s	6
15 January 2005	8	7	4	1	6
l.s.d ($P<0.05$)	n.s	n.s	n.s		1
			Stem density (stems/m^2)		
13 May 2002	143	138	142	n.s	140
25 October 2002	206	187	135	45	170
1 May 2003	166	168	159	n.s	164
11 August 2004	190	95	57	45	99
15 January 2005	209	100	24	45	91
l.s.d ($P<0.05$)	47	47	47		21

n.s indicates no significant difference

Autumn soil mineral N

No differences in soil mineral N accumulation were measured under all treatments for all sampling dates (Table 2). However differences ($P<0.05$) were found between sampling dates, with higher levels measured in autumn (April-May) compared with post harvest sampling in December 2002 and 2003.

Table 2. Soil mineral N (kg N/ha) measured under the lucerne monoculture, cereal/lucerne and cereal monoculture near the seasonal break in all years, and after grain harvest in 2002 and 2003.

Mean of the wheat and barley crops and the two N rates for the cereal/lucerne and cereal monoculture treatments

Mean of the two N rates for the lucerne monoculture

Date	lucerne monoculture	Cereal /lucerne	cereal monoculture	l.s.d ($P<0.05$)	Mean of all treatments
30 April 2002	68	72	62	n.s	67
3 December 2002	36	31	57	n.s	41
21 April 2003	95	80	95	n.s	90
10 December 2003	18	23	33	n.s	25
29 April 2004	52	28	57	n.s	46
l.s.d ($P<0.05$)	n.s	n.s	n.s		19

n.s indicates no significant difference

Cereal populations

No differences in seedling densities were observed between the treatments over the three years (Table 2). However over the duration of the experiment, spike density at cereal anthesis was greater ($P<0.05$) in the cereal monoculture relative to the cereal/lucerne and cereal/supp lucerne treatments. In the absence of suppression, companion cropping reduced spike density by 104 spikes/m^2 and with suppression by 70 spikes/m^2, compared with the cereal monoculture. In-crop suppression of lucerne did not encourage greater spike density.

Table 3. Cereal densities, grain yields, harvest index (grain yield/cereal biomass at maturity) and grain quality of the cereal/lucerne, cereal/supp lucerne and cereal monoculture treatments.

Mean of the wheat and barley crops and the two N rates

	cereal/ lucerne	cereal/ supp lucerne	cereal monoculture	l.s.d (*P*<0.05)	Mean of all treatments
Seedling density (plants/m^2)	128	131	126	n.s	
Spike density (plants/m^2)	351	385	455	39	
Grain yield (kg/ha)	2796	3028	3349	302	
Harvest index	0.33	0.33	0.31	n.s	
Grain protein (%)	12.0	11.8	12.5	n.s	
Screenings (%)	11	10	10	n.s	
Contamination (/hL)	57	16	na	9	
Year			*Seedling density (plants/m^2)*		
2002	112	100	111	n.s	108
2003	125	128	116	n.s	123
2004	146	163	152	n.s	154
l.s.d (*P*<0.05)	n.s	n.s	n.s		10
			Spike density (plants/m^2)		
2002	38	49	148	n.s	78
2003	431	446	538	n.s	472
2004	427	493	526	n.s	482
l.s.d (*P*<0.05)	n.s	n.s	n.s		36
			Grain yield (kg/ha)		
2002	203	226	655	n.s	361
2003	5021	5344	5660	n.s	5342
2004	1868	2112	2385	n.s	2121
l.s.d (*P*<0.05)	n.s	n.s	n.s		281
			Harvest index		
2002	0.186	0.216	0.247	n.s	0.217
2003	0.430	0.396	0.341	0.062	0.389
2004	0.297	0.314	0.312	n.s	0.308
l.s.d (*P*<0.05)	0.074	0.074	0.074		0.037
			Grain protein (%)		
2002	15.1	15.0	15.3	n.s	15.1
2003	9.6	9.5	10.6	n.s	9.9
2004	12.8	12.5	12.9	n.s	12.7
l.s.d (*P*<0.05)	n.s	n.s	n.s		1.0
			Screenings (%)		
2002	25	24	19	n.s	23
2003	2	2	5	n.s	3
2004	12	11	12	n.s	12
l.s.d (*P*<0.05)	n.s	n.s	n.s		4

Table 3 continued

			Contamination (/hL)		
2002	89	70		n.s	80
2003	53	2		n.s	28
2004	44	2		n.s	23
l.s.d ($P<0.05$)	n.s	n.s			13

n.s indicates no significant difference, na indicates no assessment undertaken

The impact of crop type (wheat and barley) and additional N

A significant interaction was found between crop type (wheat and barley) and main treatment (+/0 lucerne and +/0 in-crop lucerne suppression), but only in grain yield (Table 4). Barley growing in monoculture did not yield more grain than barley growing in the cereal/lucerne or cereal/supp lucerne treatments; conversely wheat growing in monoculture did out yield wheat growing in both the companion cropping treatments. However, as the effect only occurred in relation to grain yield, we have presented the mean of both wheat and barley crops for all measures of cereal productivity hereafter.

Significant interactions were not found between crop type (wheat and barley) and main treatment (+/0 lucerne and +/0 in-crop lucerne suppression) and additional N; nor was there an interaction between main treatment and additional N over the duration of the experiment for all measures of cereal and lucerne productivity (data not shown). However, the addition of N did effect cereal production across the experiment (mean of all treatments). Additional N resulted in a 19% and 14% increase ($P<0.05$) in harvest cereal biomass and total biomass respectively, across all treatments in 2003, but had no effect in 2004 (Table 5).

Table 4. Interaction between main treatment (+/0 lucerne +/0 in-crop lucerne suppression) and crop (wheat versus barley) in all measures of cereal productivity at cereal maturity in the cereal/lucerne, cereal/supp lucerne and cereal monoculture treatments.

Mean of the two N rates

crop	cereal/lucerne	cereal/supp lucerne	cereal monoculture	l.s.d (*P*<0.05)
		Cereal biomass (kg DM/ha)		
barley	7342	7951	9924	n.s
wheat	7655	9048	10606	n.s
l.s.d (*P*<0.05)	n.s	n.s	n.s	
		Grain yield (t/ha)		
barley	2951	3146	3141	n.s
wheat	2641	2909	3557	380
l.s.d (*P*<0.05)	n.s	n.s	363	
		Harvest Index		
barley	0.356	0.350	0.312	n.s
wheat	0.300	0.305	0.310	n.s
l.s.d (*P*<0.05)	n.s	n.s	n.s	
		Grain protein (%)		
barley	11.5	11.4	12.1	n.s
wheat	12.5	12.2	12.8	n.s
l.s.d (*P*<0.05)	n.s	n.s	n.s	
		Screenings (%)		
barley	13	13	13	n.s
wheat	8	7	8	n.s
l.s.d (*P*<0.05)	n.s	n.s	n.s	
		Contamination (/hL)		
barley	51	14		n.s
wheat	63	18		n.s
l.s.d (*P*<0.05)	n.s	n.s		

n.s indicates no significant difference

Table 5. The effect of N application on cereal and lucerne biomass at cereal maturity, grain yield, harvest index (grain yield/cereal biomass at maturity) and grain quality

Mean of all treatments and wheat and barley crops

	N+	N0	l.s.d (*P*<0.05)
Lucerne biomass (kg DM/ha)	1129	1051	n.s
Cereal biomass (kg DM/ha)	11175	9891	487
Total biomass (kg DM/ha)	10385	9228	459
Grain yield (kg/ha)	3709	3754	n.s
Harvest index	0.324	0.373	0.028
Grain Protein (%)	12.5	10.2	0.4
Screenings (%)	11	4	2
Contamination (/hL)	24	27	2
Year		*Lucerne biomass (kg DM/ha)*	
2003	1474	1349	n.s
2004	785	752	n.s
l.s.d (*P*<0.05)	n.s	n.s	
		Cereal biomass (kg DM/ha)	
2003	14184	11476	828
2004	6843	6365	n.s
l.s.d (*P*<0.05)	853	853	
		Total biomass (kg DM/ha)	
2003	14071	12114	621
2004	6699	6343	n.s
l.s.d (*P*<0.05)	629	629	
		Grain yield (kg/ha)	
2003	5308	5057	n.s
2004	1911	2069	n.s
l.s.d (*P*<0.05)	n.s	n.s	
		Harvest index	
2003	0.379	0.447	n.s
2004	0.283	0.328	n.s
l.s.d (*P*<0.05)	n.s	n.s	
		Grain Protein (%)	
2003	10.2	9.0	0.8
2004	14.5	10.8	0.8
l.s.d (*P*<0.05)	0.7	0.7	
		Screenings (%)	
2003	3	1	n.s
2004	17	6	3
l.s.d (*P*<0.05)	4	4	
		Contamination (/hL)	
2003	28	28	n.s
2004	20	26	n.s
l.s.d (*P*<0.05)	n.s	n.s	

n.s indicates no significant difference

Additional N had no effect on grain yield, but did result in a 12% and 25% increase (*P*<0.05) in grain protein in 2003 and 2004 respectively (Table 5). Top-dressing N, also had negative effects on cereal production, with a 15% decline (*P*<0.05) in harvest index across all years and cereal treatments, and grain screenings were 11% higher (*P*<0.05) in 2004.

Lucerne and cereal biomass

The lucerne monoculture generally produced more (*P*<0.05) above ground lucerne biomass than the cereal/lucerne and cereal/supp lucerne treatments over time (Table 6). Exceptions were, biomass cuts taken at cereal anthesis and cereal maturity in 2002. Over the duration of the experiment lucerne biomass at cereal grain maturity was 71% and 86% less (*P*<0.05) in the cereal/lucerne and cereal/supp lucerne treatments respectively, compared with the lucerne monoculture. In-crop lucerne suppression resulted in a 53% decline (*P*<0.05) in lucerne biomass across all years by cereal maturity in the cereal/supp lucerne treatment compared with the cereal/lucerne treatment, but biomass cuts taken at cereal first node and cereal anthesis showed no effect of suppression.

Over the three years, the cereal monoculture produced more (*P*<0.05) above ground cereal biomass at cereal anthesis and cereal maturity than the cereal/lucerne and cereal/supp lucerne treatments, but no differences occurred at cereal first node (Table 6). At cereal maturity there was 27 and 17% less (*P*<0.05) cereal biomass in the cereal/lucerne and cereal/supp lucerne treatments respectively, compared with the cereal monoculture. Initially in-crop lucerne suppression did not result in additional cereal biomass production, however by cereal maturity, the cereal/supp lucerne treatment had produced 12% more (*P*<0.05) cereal biomass than the cereal/lucerne treatment over all years of the experiment (Table 6).

Total (lucerne and cereal) above ground biomass production was greater (*P*<0.05) in the cereal monoculture compared with the other treatments when cereals reached anthesis and maturity, but only greater than the lucerne monoculture when cereals were at first node in all years of the experiment (Table 6). Over the three years by cereal maturity, the cereal monoculture produced 74, 20 and 14% more ($P<0.05$) total biomass during the cereal-growing season than the lucerne monoculture, cereal/lucerne and cereal/supp lucerne treatments, respectively. In contrast, total biomass production over the cereal-growing season in the lucerne monoculture was less ($P<0.05$) than the cereal monoculture, cereal/lucerne and cereal/supp lucerne treatments over the three years of the experiment (Table 6).

Cereal grain production and quality

Over the duration of the experiment the cereal/lucerne and cereal/supp lucerne treatments yielded 17 and 10% less ($P<0.05$) grain respectively, than the cereal monoculture (Table 3). Harvest index, grain protein and screenings were largely unaffected by the presence of lucerne. However, a significant main treatment (+/0 lucerne and +/0 in-crop lucerne suppression) by year interaction in relation to harvest index was found, where the cereal monoculture suffered from a low ($P<0.05$) harvest index in comparison with the cereal/lucerne and cereal/supp lucerne treatments in 2003 only.

Grain contamination by lucerne pods and flowers, were higher ($P<0.05$) in the cereal/lucerne treatment compared with the cereal/supp lucerne treatments in all years (Table 3). Over the period of the experiment the cereal/supp lucerne treatment had 41 fewer ($P<0.05$) lucerne pods and flowers/hL, compared with the cereal/lucerne treatment. Furthermore in-crop lucerne suppression did not appear as effective in 2002 compared with the following years.

Table 6. Aboveground lucerne, cereal and total (lucerne and cereal) biomass (kg DM/ha) production for all treatments at cereal first node, anthesis and maturity over the 2002-2004 growing seasons.

Mean of the wheat and barley crops and the two N rates for the cereal/lucerne, cereal/supp lucerne and cereal monoculture treatments

Mean of the two N rates for the lucerne monoculture

Cereal growth stage		cereal monoculture	cereal/lucerne	cereal/supp lucerne	lucerne monoculture	l.s.d ($P<0.05$)
First node	Lucerne biomass		499	412	976	99
	Cereal biomass	1729	1259	1369		157
	Total biomass	1729	1758	1781	976	186
Anthesis	Lucerne biomass		806	609	2761	248
	Cereal biomass	9105	7005	7604		743
	Total biomass	9105	7811	8213	2761	623
Maturity	Lucerne biomass		754	357	2627	260
	Cereal biomass	10288	7499	8500		737
	Total biomass	10288	8253	8857	2627	646
First node	Year			*Lucerne biomass*		
	2002		349	369	634	168
	2003		694	631	1031	168
	2004		453	236	1262	168
	l.s.d ($P<0.05$)		196	196	196	
				Cereal biomass		
	2002	1108	455	403		n.s
	2003	1516	996	1090		n.s
	2004	2563	2327	2615		n.s
	l.s.d ($P<0.05$)	n.s	n.s	n.s		

Table 6 continued

				Total biomass		
	2002	1108	805	773	634	n.s
	2003	1516	1690	1721	1031	523
	2004	2563	2780	2850	1262	523
	l.s.d ($P<0.05$)	607	607	607	607	
Anthesis				*Lucerne biomass*		
	2002		477	621	1034	497
	2003		1325	974	3293	497
	2004		451	237	3093	497
	l.s.d ($P<0.05$)		506	506	506	
				Cereal biomass		
	2002	2327	976	908		1403
	2003	13401	10568	10924		1403
	2004	8103	6457	7633		1403
	l.s.d ($P<0.05$)	1487	1487	1487		
				Total biomass		
	2002	2517	1453	1528	1034	1452
	2003	13401	11893	11898	3293	1452
	2004	8103	6908	7870	3093	1452
	l.s.d ($P<0.05$)	1505	1505	1505	1505	
Maturity				*Lucerne biomass*		
	2002		405	424	794	n.s
	2003		1179	491	3716	527
	2004		505	190	2454	527
	l.s.d ($P<0.05$)		530	530	530	

Table 6 continued

			Cereal biomass		
2002	2670	1077	1176		1480
2003	16635	11841	13819		1480
2004	7693	6367	6842		n.s
l.s.d ($P<0.05$)	1475	1475	1475		
			Total biomass		
2002	2784	1481	1600	794	1584
2003	16635	13020	14310	3716	1584
2004	7693	6872	7032	2454	1584
l.s.d ($P<0.05$)	1560	1560	1560	1560	

n.s indicates no significant difference

Soil water distribution over time and depth

Significant changes ($P<0.05$) in volumetric soil water contents over time, were found at depths 0.4, 0.6, 0.8, 1.0 and 1.2 m over the duration of the experiment, under the lucerne monoculture, cereal/lucerne and cereal monoculture treatments (Table 7). However, differences over time, were not found at greater depths (>1.2 m), nor at 0.2 m depth.

To examine temporal changes in volumetric soil water content under the different treatments, fitted spline models were divided into “recharge” (RC1 and RC2) and “de-watering” (DW1 and DW2) periods (Figure 2) including only the depths where significant changes in soil water content were observed. There was no significant rate of change in volumetric soil water content between treatments from 31 May 2002 to 4 September 2003, which included the first recharge period (RC1). In the first de-watering period (DW1: 4 September 2003 - 7 May 2004) the lucerne monoculture and cereal/lucerne treatments had a greater ($P<0.001$) rate of soil water extraction, with an additional 5.2 and 5.7 mm, respectively compared with the cereal monoculture. At the end of the second recharge period (RC2: 7 May - 5 August 2004), the cereal monoculture treatment had a greater ($P<0.001$) rate of recharge, with 1.4 and 1.8 mm of additional soil water accumulation compared with the lucerne monoculture and cereal/lucerne treatments respectively. Over the final de-watering period (DW2: 5 August - 6 December 2004), both the lucerne monoculture and cereal/lucerne treatments had a greater ($P<0.001$) rate of soil water extraction, an additional 2.2 mm of soil water removed by both treatments, compared with the cereal monoculture.

Table 7. Fixed terms included in the chosen fitted spline model for volumetric soil water content data collected under the lucerne monoculture, cereal/lucerne and cereal monoculture treatments.

	Treatment			Time			Treatment x Time		
Depth (m)	Wald Statistic	d.f.	P-value	Wald Statistic	d.f.	P-value	Wald Statistic	d.f.	P-value
0.2	1.01	2	0.603	381.37	1	<0.001	21.98	2	<0.001
0.4	7.66	2	0.022	27.58	1	<0.001	9.30	2	0.010
0.6	56.39	2	<0.001	10.58	1	0.001	15.77	2	<0.001
0.8	17.09	2	<0.001	14.40	1	<0.001	17.12	2	<0.001
1.0	8.88	2	<0.001	9.30	1	0.002	15.93	2	<0.001
1.2	111.55	2	<0.001	10.35	1	0.001	23.18	2	<0.001
1.6	0.85	2	0.652	1.65	1	0.211	19.01	2	<0.001
2.0	0.22	2	0.895	3.40	1	0.065	0.28	2	0.870
2.5	0.65	2	0.721	1.68	1	0.195	0.09	2	0.956

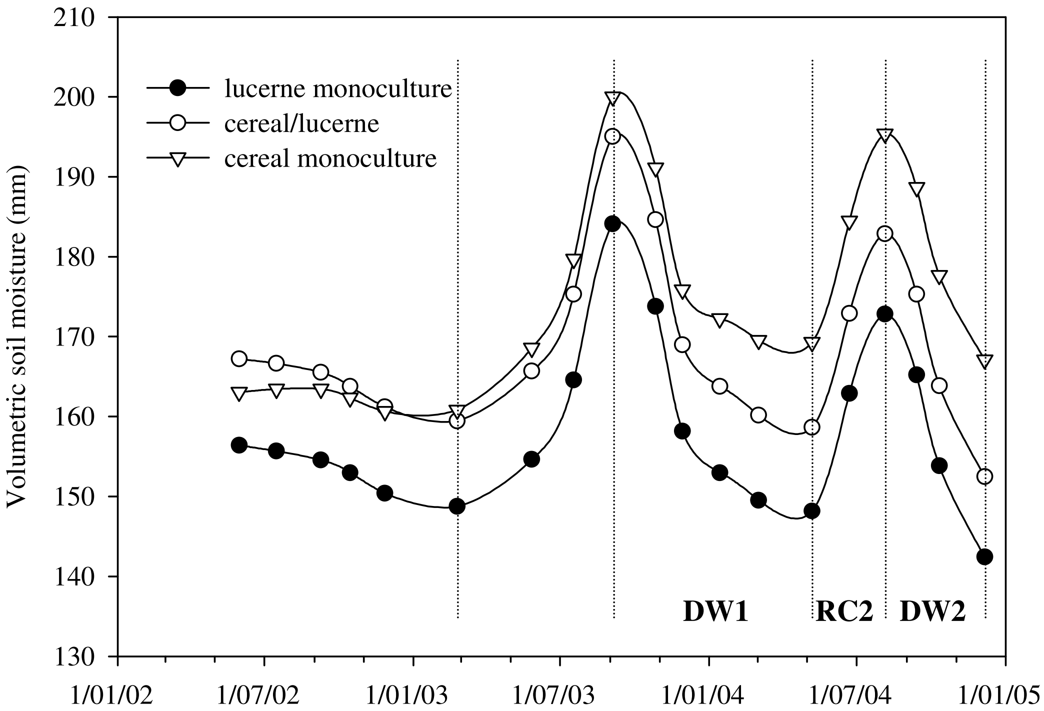

Fig 2. Fitted spline models of mean volumetric soil water content (from 31 May 2002 to 6 December 2004) for the depth interval 0.4 to 1.2 m under the lucerne monoculture, cereal/lucerne and cereal monoculture treatments. Recharge periods: RC1 24 February 2003 - 4 September 2003, RC2 7 May - 5 August 2004. De-watering periods: DW1 4 September 2003 - 7 May 2004, DW2 5 August - 6 December 2004.

Discussion

Companion cropping effects on lucerne and cereal production in the absence of agronomic manipulation

Over the three years of the experiment, the productivity of the mature lucerne stand (4-6 years of age) was reduced by the presence of cereal companion crops. Although Humphries *et al.* (2004) do not specifically refer to reductions in lucerne biomass in the presence of wheat, their data shows a greater variation, ranging from 15 to 90% reductions over the study period. The range of lucerne biomass reductions reported in this study reflected the impact of the seasonal conditions on cereal performance, and therefore on the level of direct competition from the cereal companion crops, as well as direct seasonal affects on lucerne productivity.

In all years the difference in lucerne biomass between the cereal/lucerne treatment and the lucerne monoculture increased from the time of first cereal node through to cereal anthesis, except in 2003 when the difference continued to increase after cereal anthesis. In both 2002 and 2004, less than 3 mm of rainfall was recorded in October, and this is the most likely explanation for the decline in lucerne production in the late spring. Conversely in October 2003, 69 mm of rainfall was recorded, which would have contributed to the continued lucerne growth in the lucerne monoculture. The growth response of the cereal companion crop to October rainfall suggest that the crop utilised more of the rainfall than the neighbouring lucerne plants, effectively preventing the lucerne from producing further biomass in the cereal/lucerne treatment. During this period cereals appear to be more competitive than lucerne capturing most of the available resources.

Cereal grain yield reductions from companion cropping in our experiment, were within the ranges previously reported by Egan and Ransom (1996) and Humphries *et al*. (2004). In all years lucerne significantly reduced companion crop yields, relative to the cereal monoculture. This was despite an incomplete kill of lucerne plants in the cereal monoculture plots prior to the 2002 crop, which meant that this treatment was effectively a low lucerne density companion crop in the first year. Other authors (Ransom and Egan 1998; Bullied *et al.* 1999; Angus *et al.* 2000; Davies *et al*. 2005) have also reported difficulties in successfully removing lucerne prior to a cropping phase. The low density of lucerne carried over into the cereal monoculture (5 plants/m^2) may have influenced cereal yield, and it is possible that the presence of lucerne plants in this treatment resulted in an underestimation of the impact of companion cropping. Conversely the use of cultivation to remove lucerne prior to imposing the cereal monocultures may have stimulated additional soil N mineralisation, and potentially enhanced the subsequent performance of cereals.

The effect of rainfall on companion crop grain yield could not be fully explored in the context of our study three-year study. Therefore we have combined the data presented here with additional results derived from Humphries *et al*. (2004) and Egan and Ransom (1996) against potential wheat yield formulated by French and Schultz (1984) to evaluate the likely impact of rainfall on companion crop performance. This analysis indicated a strong positive relationship (P=0.002) between growing season rainfall and increasing companion crop yield (Figure 3), but also highlights that companion cropping generally inhibits cereals from achieving their water-limited potential yield. Whilst this form of analysis demonstrates the biophysical constraints of growing season rainfall on companion crop success, it does not indicate the "break even" threshold where grain yield reductions become economically acceptable.

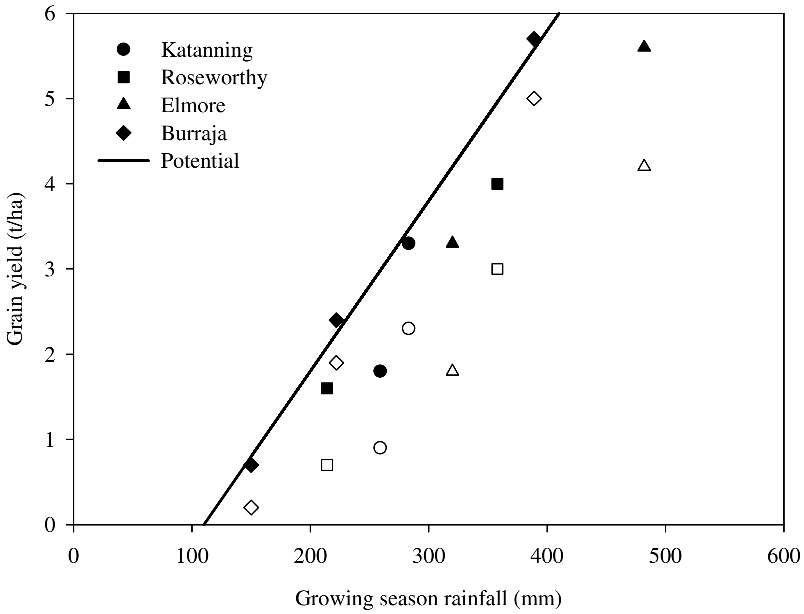

Fig 3. Comparison of potential (formulated by French and Schultz 1984 for wheat) versus actual cereal grain yields both without lucerne (solid symbol) and with lucerne (open symbol). Katanning and Roseworthy data from Humphries *et al.* (2004), Elmore data from Egan and Ransom (1996). Grain yields from the cereal monoculture and companion crop treatments at Katanning were the mean of the two rates of N fertiliser. At Katanning and Roseworthy the companion crop grain yield was the mean of all the lucerne variety / companion crop treatments. Grain yields from the cereal monoculture and companion crop treatments at Elmore were the mean of the Meering and Rosella wheat variety treatments. At Burraja the grain yields from the cereal monoculture and companion crop treatments were the mean of the wheat and barley crops.

In our experiment, companion cropping did not affect cereal grain protein. The same observation was made by Egan and Ransom (1996) who reported similar grain protein levels in both companion and stand-alone cereals, whereas Angus *et al.* (2000) showed a 0.3% reduction in protein content from companion cropping. The data reported by Humphries *et al.* (2004) show that there were no consistent effects. The data suggest no clear impact of lucerne companion cropping on cereal grain protein.

Results from our study and Humphries *et al*. (2004) indicated significant reductions in cereal biomass throughout the growing season occurred in the presence of lucerne. This contrasts with Egan and Ransom (1996), who found that apart from the dry year of 1994, the biomass of cereal companion crops at cereal anthesis were similar to that of cereal growing in monoculture. They concluded that competition during the post-anthesis period was likely to have the greatest impact on companion crop performance. In our study, significant differences in cereal biomass occurred from the first node stage of cereal crop development. Humphries *et al*. (2004) made the same observation in August 2002, when they reported a 50% reduction in the biomass of companion cropped wheat, compared with the wheat monoculture.

In our study, cereal seedling densities across all treatments were the same in all years. However, spike densities were significantly greater in the cereal monoculture compared with the companion crop treatments by cereal anthesis, suggesting that cereals growing with lucerne do not form as many fertile tillers. This result supports the suggestion made by Humphries *et al*. (2004) that competition for light and/or nutrients within companion crops could substantially retard early wheat growth and subsequent reproductive development.

The effect of agronomic manipulation on lucerne and cereal productivity in companion crops

In the first year of the experiment, in-crop suppression of lucerne did not improve cereal performance nor decrease lucerne production. The dry conditions experienced in 2002, would have reduced the efficacy of the clopyralid herbicide, and at the time of application the lucerne was showing signs of water stress. In the following year, in-crop suppression initially had no effect on lucerne biomass, but by cereal grain maturity had significantly reduced lucerne biomass. These data imply prolonged (several months) effects of residual clopyralid herbicide on lucerne can occur, if conditions are favourable. Clopyralid is an auxin mimicking synthetic plant growth hormone; it disrupts plant growth by binding to molecules that are normally used as receptors for the natural growth hormone auxin (Tu *et al*. 2001). When applied at low doses it causes initially uncontrolled and disorganised plant growth that leads to some lucerne plant tissue death namely leaf and some stems, but has little effect on neighbouring cereals. Clopyralid has a half-life of two months in the soil and does not bind to the soil and is highly mobile (Riaz Ahmad James and Anis Rahman Holland 2003), therefore rainfall events encouraging clopyralid uptake over its half-life period may have continued effects on lucerne growth. We conclude that soil moisture conditions could be crucial in determining the relative effectiveness of in-crop lucerne suppression.

Whilst suppression reduced lucerne and increased cereal biomass production by cereal maturity, it did not increase cereal grain production. The main benefit of in-crop lucerne suppression was to improve grain quality through delayed lucerne maturity and less lucerne pod and flower contamination of the harvested cereal grain. However, short-term gains in grain quality may be negated by accelerated declines in lucerne persistence and production, our experiment showed a significant reduction in lucerne stem densities between 2003 and 2004 under suppression. Our present knowledge of the effects of in-crop suppression on lucerne is limited and further research is needed to develop less detrimental strategies to produce quality cereal grain without jeopardising lucerne populations in companion cropping systems.

In designing the experiment we had hypothesised that earlier maturing cereals would perform better as a companion crop, by reducing the likelihood of post-anthesis water stress; a constraint suggested by Egan and Ransom (1996). Our grain yield data suggested that barley responded differently to the presence of lucerne in comparison with wheat, but on close examination this difference was only found between the wheat and barley monocultures, and the cereal biomass data did not emulate the grain yield data. This discrepancy was probably due to excessive crop lodging in the barley monoculture in 2003.

The application of N to cereals growing with and without lucerne did not increase cereal grain yields. However, the application of N in 2003 did increase cereal biomass at grain harvest across all cropping treatments. This suggests that in terms of cereal biomass irrespective of whether lucerne was present, cereal crops responded the same way to additional N. Although the likelihood of a main treatment (+/0 lucerne and +/0 in-crop lucerne suppression) by additional N interaction affecting cereal productivity may have been greater, had we seen differences in available soil N at sowing.

The question remains, why didn't the additional cereal biomass at maturity translate into greater grain yields? Additional N resulted in lower harvest index, and higher grain protein and grain screenings suggesting that post-anthesis water stress from N and not the presence of lucerne was causing "haying-off" (van Herwaarden *et al*. 1998), especially in 2004 when there was a dry finish to the growing season. In 2003, the combination of top-dressing N and favourable late growing season rainfall resulted in extensive crop lodging especially in the barley crop, and therefore the potential increase in grain yield was never realised. A criticism of the N management in our study relates to the timing of applications, in both 2003 and 2004, the N was applied after the first cereal-node growth stage. Given that reduced tillering in the companion crops was observed in this experiment, earlier applications of N might have had a positive impact on tiller density and perhaps subsequent grain yields. Therefore, we have enough evidence to conclude that additional N has the potential to increase companion crop grain yields where application is accompanied by optimal late growing season rainfall.

Impact of companion cropping on soil water contents

Companion cropping did not appear to compromise lucerne's soil water extraction patterns when compared with the lucerne monoculture. However, this result must be put into the context that soil water contents remained unchanged below 1.2 m throughout the experiment, even under the cereal monoculture. This finding reflects both the seasonal conditions experienced over the experiment, and the fact that the lucerne stand was already four years old and had dried the subsoil (>1.2 m) in the years prior to the start of the experiment, before imposing the cereal monoculture. Subsequent dry years over the study period, except 2003 when above average rainfall resulted from favourable late growing season rainfall which was used by cereal crops, meant that there was no recharge of soil water under all treatment below 1.2 m depth. The differences in soil water extraction may have been higher if the lucerne had been successfully removed from the cereal monoculture in the first year of the experiment. Therefore, given the dry climatic conditions and incomplete lucerne removal in the first year of the cereal monoculture, further data under wetter seasonal conditions are needed before firm conclusions about the impacts of companion crops on the soil water extraction capacity of lucerne can be confidently drawn.

On-farm implications

In our experiment, three consecutive cereal crops were sown into lucerne. This sequence of continuous cereal crops increases the risks of cereal-borne diseases affecting grain yields (Angus *et al*. 1991; Kirkegaard *et al*. 1994) and is not advocated for commercial farmers. There are farmers in central Victoria who are companion cropping lucerne on a commercial scale, some of which include canola (*Brassica napus*) and/or pulses in their crop sequences (Harris *et al*. 2003). Although farmers recognise grain yield reductions are a limitation; they adopt this practice because companion cropping allows them to increase cropping intensity, while maintaining a greater proportion of lucerne across their farms to combat the threat of dryland salinity. Another approach could involve a sequence of companion cropping in alternate years, with lucerne maintained as a pasture between each crop. This approach would provide the necessary disease break between cereal companion crops, provided invading annual grasses that host cereal-borne diseases are controlled during the lucerne phase (MacLeod *et al*. 1993).

The findings of this and other studies (Egan and Ransom 1996; Humphries *et al*. 2004) have highlighted grain yield reductions in companion cropping systems, which are likely to impact on farm incomes. However, to focus solely on reduced grain yields ignores other factors that contribute to the economics of the total companion cropping system. For example, the economic value of grazing lucerne-crop stubbles over the summer. At this stage we are unaware of any comprehensive economic analyses that examines companion cropping at a whole farm level. Such analyses would need to put a value on the quantity and nutritional quality of the summer feed supply, which may vary considerably, depending on the summer rainfall, as well as the savings in the reduced frequency of lucerne removal and re-establishment costs. Currently there are limited data (Humphries *et al*. 2004) that quantify the impacts of companion cropping on summer lucerne productivity, while there are no published data on livestock productivity between companion crops. However, there are simulation models currently under development that could be used in conjunction with historic rainfall records to undertake risk analyses of grain yield reductions (Robertson *et al*. 2004). These data are critical for future objective assessments of the impacts that companion cropping can have on farm incomes.

Whilst grain yield reductions appear at first to be a major limitation to the feasibility of companion cropping systems, we found that companion-cropping increased total biomass production from lucerne pastures over the growing season. This suggests that companion cropping may be used as a fodder crop in livestock enterprises by increasing the feed availability of lucerne pastures, and so allow additional livestock production on farms where grain production is not a high priority. This is in addition to the demonstrated role that lucerne has in reducing the likelihood of recharge to groundwater systems and the spread of dryland salinity.

This study shows that rainfall was the major factor determining cereal responses in the presence of lucerne, and that agronomic strategies like N fertilisation, herbicide suppression and crop maturity have limited impacts on the grain yields of cereal-lucerne companion crops.

However, improved timing of N application and herbicide suppression may enhance companion crop grain production, where there is favourable late growing season rainfall.

Disclaimer

The herbicide clopyralid used in our study for in-crop lucerne suppression was used for research purposes only, and is not currently registered for the suppression of lucerne. The authors and the organisations we represent do not endorse the use of this product for lucerne suppression.

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Chapter 5. Modelling simultaneous cereal and lucerne growth on the Riverine Plains

This Chapter is a manuscript intended for submission to either Crop and Pasture Science or Agricultural Systems.

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Running title: Simulating lucerne and cereal production grown together and separately.

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9 November 2010

To whom it may concern

This note is to confirm that my contribution to chapters 5 & 6 in the PhD Thesis of Robert Harris consisted of collaboration with Robert on APSIM model testing for his focus on lucerne-wheat companion cropping systems (Chapter 5). This collaboration included provision of advice on APSIM configuration, interpretation of model performance in comparison with experimental findings, and subsequent input on iterative changes to configuration in achieving acceptable model performance. I also provided input on Robert's deliberations and final critical evaluations of APSIM's performance. This was followed by provision of advice on use of the model in scenario analyses which Robert had envisaged and subsequently performed (Chapter 6). I estimate my contribution to these chapters as in the vicinity of 5%.

This note also confirms my permission for the manuscripts to be included in Robert's thesis.

Yours sincerely

Donald Gaydon
Senior Farming Systems Researcher
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WD Bellotti

24 November 2010

To whom it may concern,

Contribution to publications by Mr Rob Harris included in his thesis to be submitted for the award of Doctor of Philosophy

This note is to confirm that my contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Gaydon D, Bellotti WD, Unkovich MJ, Robertson MJ (2010 in prep) Modelling simultaneous cereal and lucerne growth on the Riverine Plains. *Crop and Pasture Science or Agricultural Systems.*

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

Yours sincerely,

Professor Bill Bellotti
Vincent Fairfax Chair in Sustainable Agriculture and Rural Development

MJ Unkovich

My contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Gaydon D, Bellotti WD, Unkovich MJ, Robertson MJ (2010 in prep) Modelling simultaneous cereal and lucerne growth on the Riverine Plains. *Crop and Pasture Science or Agricultural Systems.*

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

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To whom it may concern: I contributed to hypothesis formulation, protocol development, interpretation of the data, contribution to the underlying structure of the paper/manuscript and suggested editing of the paper for chapter 5 of this thesis. My contribution would amount to less than 5% of the overall piece of work.

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Abstract

This paper compares data collected from a field experiment in NE Victoria, with simulated wheat (*Triticum aestivum*) and lucerne (*Medicago sativa*) grown simultaneously (companion crop) and in monoculture, with (N+) and without (N0) the addition of fertiliser N, using the Agricultural Production Systems Simulator (APSIM). Detailed field measurements of soil water, soil mineral N and soil C were used to parameterise the growth environment, as well as specified management inputs, in an attempt to simulate part of a field experiment. The observed cereal and lucerne aboveground biomass and cereal grain yield data was used to assess the accuracy of model estimations. Initially root mean squared error (RMSE) was used to quantify the overall magnitude of error between simulated and observed data, then time-series plots accompanied by two-tailed t-tests were used to determine if corresponding simulated output fell within the "normal population" distribution defined for each observed sampling point. APSIM satisfactorily simulated cereal production in monoculture for both rates of N application, with an RMSE of <28% and <23% of the observed mean, for cereal biomass and cereal grain yield respectively. In comparison the RMSE was greater in simulations of cereals growing with lucerne, as lucerne growth was over-estimated and cereal growth under-estimated in the final year. When autumn soil N was reset to observed field values in the companion crop simulations, RMSE declined for both rates of N, to <39% and <30% of the observed mean for cereal biomass and cereal grain yield respectively, providing evidence that N supply can affect the fate of the companion cereal. The resets of autumn soil N appeared necessary, as the model may have over-estimated lucerne soil N uptake over the summer/autumn period preceding the companion cereal and this seems the likely reason for the soil N resets. APSIM also reliably predicted lucerne production in monoculture and in the companion crop stubble over the summer autumn period; but estimations particularly in the absence of N fertiliser, may have been improved with detailed temporal field measurements of lucerne N fixation.

Additional keywords: lucerne, wheat, companion crop, APSIM, model.

Introduction

Companion cropping (also known as inter-cropping, over-cropping or pasture cropping) is defined as growing two or more crops simultaneously on the same area of ground (Willey 1979). Component crops (individual crops that make up a mixture of crops) are not necessarily sown at the same time, but their growth needs to coincide for a significant period of time. Mixtures of annual cereal crops sown directly into existing lucerne (*Medicago sativa*) stands are an example of companion cropping.

Mixed plant communities can provide better use of growth resources (Willey 1979). Therefore farming systems with mixed plant communities might be more resilient to climate change than monocultures, due to a greater capacity to maximise production from variable rainfall. Cereal crops sown into established lucerne stands could potentially capture and utilise greater quantities of rainfall through continued transpiration over twelve months of the year, thereby providing dual income streams to mixed farming systems through grain production and out of season feed supply.

Whilst research has shown lucerne can increase water use in dryland cropping systems (Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ridley *et al*. 2001; Ward *et al.* 2002) many field based studies have also reported reductions in cereal crop grain yields from associated competition with lucerne (Egan and Ransom 1996; Humphries *et al*. 2004; Harris *et al*. 2007a Harris *et al*. 2007b, Harris *et al*. 2008) raising doubt about the viability of this practice. However, past research has tended to focus on grain yield reductions with little consideration given to the additional benefits of lucerne production in the companion crop stubble over summer. For instance, Harris *et al*. (2008) measured up to 3.9 tonnes of lucerne DM/ha in companion crop stubble over one summer period, highlighting the possibility that subsequent summer lucerne production providing additional grazing opportunities, might compensate for lost grain production in some seasons. Furthermore, Harris *et al*. (2008) also reported improved companion crop grain production from additional top-dressed N suggesting that an improved understanding of the system and different management could limit cereal yield declines and improve the viability of companion cropping.

Some Australian studies have reported the use of APSIM (Agricultural Production System Simulator) for extrapolation of findings beyond season and site specific field based research (Probert *et al*. 1995; Asseng *et al*. 1998a). APSIM is the most advanced cropping system computer model used in Australia to study interactions between climate, soil and plant growth, while providing the flexibility to stipulate specific management interventions that can impact on these interactions.

APSIM simulations have already been tested against field observations for both wheat (Keating *et al*. 1995; Asseng *et al*. 1998b; Yunusa *et al*. 2004; Lilly and Kirkegaard 2007) and lucerne (Robertson *et al*. 2002; Dolling *et al*. 2005) grown in monoculture, with satisfactory agreement between predicted and measured data. Only Robertson *et al*. (2004) has attempted to compare simulated associated wheat and lucerne production against observed field data in companion cropping systems; and while their results appear to show reasonable agreement, there is no apparent analysis expressing the level of precision between simulated and observed data.

Whilst simulation modelling can potentially provide greater insight into the longer-term effects of seasonal variation and management inputs on associated cereal and lucerne performance; undertaking such an analysis would be premature without first validating the model in a companion cropping situation. In this paper we statistically compare the difference between simulated and observed data over time to determine if APSIM can simulate cereal and lucerne growth in monoculture and in mixture.

Material and Methods

This paper presents both observed and simulated data for cereal and lucerne aboveground biomass, cereal grain yield, soil mineral N and soil water over time. We also use observed soil water content, soil mineral N, crop and lucerne stem population data for model parameterisation. All of the observed data was collected from a field experiment detailed in Harris *et al*. (2008).

Experimental data

The field experiment was conducted from April 2003 to May 2006 at North Boorhaman (146^{o}23'E, 36^{o}10'S) in North East Victoria, on a slightly acidic (pH 6.4 in $CaCl_2$, 0-12 cm) Calcic, Mottled-Subnatric, Red Sodosol soil (Isbell 1996). Temporal observed data from dryland cereal monoculture companion crop and lucerne monoculture treatments.

In the Harris *et al*. (2008) field experiment , lucerne (*Medicago sativa*) cv. Pioneer 54Q53 was sown on 10 August 2002, and in the following autumn six treatments were established, initially replicated three times in the first year, but in later years four times. Harris *et al*. (2008) describes the six treatments, but in this paper we present data for only three treatments, the dryland lucerne monoculture, cereal monoculture and cereal-lucerne companion crop treatments.

Lucerne was removed from the plots allocated to cereal monoculture treatments on 10 April 2003 from replicates 1-3, and 5 May 2004 from replicate 4. Shortly after the autumn seasonal break, all treatments were sprayed with paraquat/diquat to suppress lucerne and eradicate weeds prior to sowing. A sequence of wheat (*Triticum aestivum*) - triticale (*Triticosecale*) - wheat was sown in the cereal monoculture and companion crop treatments. Main plots were divided into two sub-plots; with one sub-plot randomly allocated top-dressed N.

Harris *et al*. (2008) provides details regarding the collection of field observed data, except for lucerne stem populations and soil mineral N. Lucerne stem populations were counted six times over the duration of the experiment, at each sampling, ten 0.5 m^2 quadrats were randomly placed within each sub-plot and the number of lucerne stems greater than 3 cm in length counted. Soil mineral N (NH_4^+ + NO_3^-) was measured at the beginning of the growing season (April) in all years and at the end of the growing season (December) in all years except 2005. On each occasion three soil cores (external diameter 42 mm) were collected randomly from within each sub-plot. Cores were extracted to a depth of 1.2 m, divided into 0.1 m increments to 0.2 m depth and 0.2 m depth thereafter, and then bulked for each depth in each sub-plot. Soil samples were oven dried at 40°C for 48 hours, and passed through a 2 mm sieve prior to measuring mineral N concentrations on extracts determined via an automated colorimetric procedure and dual-channel auto analyser (Rayment and Higginson 1992).

Climatic data was obtained from the SILO database (http://www.bom.gov.au/SILO) for the Peechelba East (146°27'E, 36°17'S) weather station, located approximately 7 km south of the experimental site. Manually collected daily rainfall data from the experimental site was exported into the MET file for the period of the experiment.

Simulation model

The APSIM model has been developed to simulate biophysical processes in farming systems by providing a framework for biological, environmental and management modules to be 'plugged in' to a simulation engine which communicates with the independent modules to produce output (McCown *et al*. 1996). APSIM can be used to simulate crop development, growth, yield, and N accumulation on an area basis, in response to temperature, radiation, photoperiod, soil water, and N supply, all on a daily time-step (Robertson *et al*. 2002). Model details can be found in Keating *et al*. (2003) or at http://www.apsim.info/.

In our study APSIM was configured to perform six simulations; two where lucerne was grown in monoculture; another two where wheat was grown in monoculture; and a further two more where lucerne and wheat were grown together (companion crop). One of each of the lucerne monoculture, wheat monoculture and companion crop simulations received additional top-dressed N, the others no top-dressed fertiliser N. The modules used with APSIM5.3 for all simulations were *manager* and *fertilise*, which describe specific agronomic practices and fertiliser management; the environmental modules *surface organic matter*, modified *soil* module and a *met* file, which describe the specific soil and climatic conditions under which the field experiment was conducted; the plant modules *lucerne* (Robertson *et al.* 2002; Dolling *et al.* 2005) and *wheat* (Probert *et al.* 1995; Keating *et al.* 1995); an additional *weed* module was plugged into the cereal monoculture simulations to mimic use of soil water and N by summer weeds over the fallow period between wheat crops. The *canopy* module was included in the companion crop simulations to simulate competition for light by taking into account the differential height and leaf areas of the different species (Carberry *et al.* 1996). Soil water and N are allocated to the roots of each species on an alternating day by day basis (Robertson *et al.* 2004).

The lucerne monoculture and companion crop simulations were set to commence on 1 August 2002 shortly before the lucerne was established in the corresponding field experiment. The cereal monoculture simulations were started from 23 April 2003, the date when soil mineral N and soil water was first measured and lucerne had been removed before sowing in the corresponding field experiment. All simulations ended on 10 May 2006, soon after field observations ceased.

Model parameterisation

Model parameterisation was based on actual experimental events, inputs and collected field data to quantify the growth environment, so that APSIM could simulate cereal and lucerne growth under field experimental conditions and management practices. In the lucerne monoculture and companion crop simulations, winter dormant lucerne (cv. Kaituna) was used because phenological parameters for the actual lucerne grown in the field (cv. Pioneer 54Q53) had not been developed. Lucerne sowing was set to 10 August 2002, at a depth of 2 mm and with 20 kg/ha of NH_4^+-N fertiliser. Lucerne populations were set at 200 (monoculture) or 150 stems/m^2 (companion crop), reflecting the mean populations measured over time under these treatments in the corresponding field experiment.

In the cereal monoculture and companion crop simulations wheat was sown in all years, as phenological parameters for triticale had not been developed and cv. whistler had the closest matching phenology to the triticale cv. Kosciusko sown in 2004. Wheat sowing was set to 27 April 2003, 3 June 2004, and on 2 June 2005 at densities measured in the field experiment (126, 101 and 164 plants/m^2 respectively), with 20 kg of N/ha of NH_4^+-N fertiliser applied at seeding each year.

The soil water parameters drained upper limit (DUL), lower limit (LL15) (Table 1) and crop LL for wheat and lucerne (Table 2) were derived from repeated soil water measurements over time by neutron moisture meter in the corresponding field experiment, which identified when the soil profile was at it wettest (DUL) in late winter (August 2003 and 2005), and at its driest (crop LL) generally coinciding with maximum crop biomass production after anthesis for both cereals (December 2004 and 2005) and lucerne (March – April 2006). Saturation (SAT) and the proportion of soil water that drains in a day (swcon, Probert *et al.* 1998) were derived from measured bulk density data for each soil layer (Dalgliesh and Cawthray 1998). The root exploration factor (XF) and the proportion of daily soil water removed through root extraction from a given soil layer (KL) were adjusted to reflect the temporal root advancement and soil water extraction patterns from the measured soil water data for both wheat and lucerne (Table 2). Values for summer and winter soil evaporation (U and Cona) were the same used by Verburg *et al.* (2007), who simulated the effects of lucerne phase farming on soil water storage in North East Victoria. The labile organic matter fraction (Fbiom, Table 1) and the non-labile organic matter fraction (Finert) were calculated from the methods presented in Probert *et al*. (1998) (Table 1).

Table 1. Soil parameters determined from the Red Sodosol soil at North Boorhaman.

BD, bulk density, SAT, saturation, DUL, drained upper limit, LL15, lower limit at 15 bar, Fbiom, labile pool of organic matter, Finert non- labile pool of organic matter.

Depth m	BD g/cm^3	SAT mm/mm	DUL mm/mm	AirDry mm/mm	LL15 mm/mm	Fbiom	Finert	Organic C %
0-0.1	1.3	0.3	0.27	0.02	0.05	0.04	0.1	2.30
0.1-0.3	1.5	0.3	0.27	0.02	0.05	0.02	0.5	0.40
0.3-0.5	1.7	0.35	0.32	0.13	0.20	0.02	0.7	0.20
0.5-0.7	1.7	0.35	0.33	0.15	0.23	0.02	1	0.25
0.7-0.9	1.7	0.35	0.32	0.15	0.24	0.02	1	0.25
0.9-1.1	1.7	0.35	0.29	0.15	0.26	0.02	1	0.25
1.1-1.3	1.7	0.33	0.29	0.15	0.26	0.02	1	0.25
1.3-1.5	1.7	0.33	0.29	0.15	0.26	0.02	1	0.25
1.5-1.7	1.7	0.33	0.29	0.15	0.26	0.02	1	0.25
1.7-1.9	1.7	0.33	0.29	0.15	0.27	0.02	1	0.25
1.9-2.1	1.7	0.33	0.29	0.15	0.27	0.02	1	0.25
2.1-2.3	1.7	0.33	0.28	0.15	0.26	0.02	1	0.25
2.3-2.5	1.7	0.33	0.28	0.15	0.26	0.02	1	0.25
2.5-2.7	1.7	0.33	0.28	0.15	0.26	0.02	1	0.25

Soil water content and soil mineral N (NH_4 and NO_3) data (Table 2) measured during the field experiment around the 2003 seasonal break, were used as starting values to initialise the cereal monoculture simulations. However, starting values for soil mineral N and soil water content used to initialise the lucerne monoculture and companion crop simulations could only be estimated from observed data collected at corresponding times in the subsequent years of the field experiment, along with assumptions of elevated soil mineral N levels after a long chemical fallow period before lucerne establishment (Table 2). Starting surface organic matter for the cereal monoculture simulations was set at 500 kg/ha of lucerne residue, with a C:N ratio of 15, while in the lucerne monoculture and companion crop simulations surface organic matter values were set at 200 kg/ha of grass residue with a C:N ratio of 100.

Table 2. Plant soil water and soil initialising parameters; for wheat growing in the cereal monoculture and companion crop treatments; for lucerne growing in the lucerne monoculture and lucerne growing in the companion crop treatments; and for the broadleaf summer weed growing in the cereal monoculture treatment.

LL, crop lower limit, PAWC, plant available water content, KL, proportion of soil water extracted from a given layer in a single day, XF, root extraction factor.

	Plant parameters						Initialising soil parameters		
Depth m	LL mm/mm	KL	XF	LL mm/mm	KL	XF	soil water mm/mm	NO_3 kg N/Ha	NH_4 kg N/Ha
	Wheat			*Summer broadleaf weed*			*cereal monoculture simulations*		
0-0.1.0	0.050	0.06	1.0	0.050	0.06	1.0	0.12	37.3	3.0
0.1-0.3	0.050	0.06	0.8	0.050	0.06	1.0	0.16	11.8	1.7
0.3-0.5	0.200	0.05	0.3	0.200	0.02	0.3	0.26	8.80	2.0
0.5-0.7	0.260	0.04	0.3	0.260	0.00	0.0	0.26	2.80	1.7
0.7-0.9	0.260	0.03	0.3	0.260	0.00	0.0	0.27	1.10	1.5
0.9-1.1	0.275	0.03	0.3	0.275	0.00	0.0	0.28	0.60	1.4
1.1-1.3	0.270	0.00	0.0	0.270	0.00	0.0	0.28	0.60	1.2
1.3-1.5	0.280	0.00	0.0	0.280	0.00	0.0	0.29	0.00	0.0
1.5-1.7	0.280	0.00	0.0	0.280	0.00	0.0	0.29	0.00	0.0
1.7-1.9	0.280	0.00	0.0	0.280	0.00	0.0	0.29	0.00	0.0
1.9-2.1	0.280	0.00	0.0	0.280	0.00	0.0	0.29	0.00	0.0
2.1-2.3	0.280	0.00	0.0	0.280	0.00	0.0	0.28	0.00	0.0
2.3-2.5	0.280	0.00	0.0	0.280	0.00	0.0	0.29	0.00	0.0
2.5-2.7	0.280	0.00	0.0	0.280	0.00	0.0	0.29	0.00	0.0

Table 2 continued

		Lucerne			*Lucerne in companion crop*			*Lucerne monoculture and companion crop simulations*	
0-0.1	0.05	0.10	1.0	0.050	0.10	1.0	0.24	42.0	8.4
0.1-0.3	0.05	0.10	1.0	0.050	0.10	1.0	0.25	19.0	2.1
0.3-0.5	0.20	0.08	0.8	0.200	0.08	0.8	0.32	17.7	2.1
0.5-0.7	0.26	0.08	0.8	0.260	0.08	0.8	0.33	11.1	1.5
0.7-0.9	0.26	0.06	0.6	0.260	0.06	0.6	0.32	6.3	1.4
0.9-1.1	0.26	0.06	0.6	0.260	0.06	0.6	0.31	4.3	1.4
1.1-1.3	0.25	0.05	0.5	0.265	0.05	0.5	0.30	3.5	1.4
1.3-1.5	0.25	0.05	0.5	0.270	0.05	0.5	0.29	0.0	0.0
1.5-1.7	0.25	0.05	0.3	0.270	0.05	0.3	0.29	0.0	0.0
1.7-1.9	0.26	0.05	0.3	0.265	0.05	0.3	0.29	0.0	0.0
1.9-2.1	0.26	0.03	0.3	0.265	0.03	0.3	0.29	0.0	0.0
2.1-2.3	0.26	0.03	0.2	0.265	0.03	0.2	0.28	0.0	0.0
2.3-2.5	0.26	0.03	0.2	0.265	0.03	0.2	0.28	0.0	0.0
2.5-2.7	0.26	0.03	0.2	0.270	0.03	0.2	0.28	0.0	0.0

Management logic and modifications to the lucerne and weed modules

In the Harris *et al.* (2008) field experiment, lucerne was suppressed in both the lucerne monoculture and companion crop treatments on the same day as the cereal crops were sown (Table 3). In APSIM, this activity was simulated via the management logic by cutting lucerne to ground level, but not removing biomass, and then setting lucerne radiation use efficiency (rue) to 0 for a period of 14 days, to emulate the suppressed lucerne growth in the field experiment.

During the field experiment the lucerne treatment was mechanically slashed after some of the biomass sampling cuts (Table 3). In APSIM this was described in the management logic by cutting lucerne to a height of 20 mm but not removing biomass, as plant material was left on the surface after slashing in the corresponding field experiment.

In the Harris *et al.* (2008) field experiment, urea was top-dressed at 60 kg N/ha to all sub-plots allocated to receive additional N, in 2003 and 2004, but in 2005, urea was top-dressed at 100 kg N/ha (Table 3). Urea was also top-dressed to all plots at 40 kg N/ha on 29 June 2004. This was simulated in APSIM in the management logic by specifying that "urea_N" was the fertiliser applied, along with the specific N rate used on the corresponding dates.

Both Robertson *et al.* (2002) and Dolling *et al.* (2005) reduced rue to simulate lucerne growth over the autumn-winter period, and to represent the increased storage of carbohydrates in the root reserves during this period (Khaiti and Lemaire 1992; Brown *et al.* 2006). In our study we also reduced rue (Table 4) over the autumn winter period, to the same values used by Dolling *et al.* (2005), the only other study to compare simulated and observed lucerne biomass production in southern Australia. In APSIM rue was reduced in the management logic from day 45 to day 227 in all years.

Table 3. Input parameters associated with management of the cereal monoculture, companion crop and lucerne monoculture treatments

Lucerne sowing dates in the lucerne monoculture and companion crop treatments	Cereal sowing dates in the cereal monoculture and companion crop treatments	Pre-crop lucerne suppression in the lucerne monoculture and companion crop treatments	N application dates in all treatments	Cutting dates in the lucerne monoculture	Grazing dates in all treatments
10 Aug. 2002	27 Apr. 2003	27 Apr. 2003	23 July 2003	14 Sep. 2004	15 Dec. 2003
	3 June 2004	3 June 2004	29 June 2004[A]	20 Oct. 2004	12 Jan. 2004
	2 June 2005	2 June 2005	30 Aug. 2004	24 Oct. 2005	2 Mar. 2004
			12 Aug. 2005		4 May 2004
					5 Dec. 2004
					13 Jan. 2005
					4 Mar. 2005
					6 May 2005
					6 Dec. 2005
					14 Jan. 2006
					8 Mar. 2006
					4 May. 2006

[A] N applied in all simulations

Table 4. Lucerne and summer broadleaf weed parameters for different stages of growth, for radiation use efficiency (rue) and transpiration efficiency coefficient (TEC).

	Lucerne				*Summer broadleaf weed*	
Stage of growth	Seedling rue (g/MJ)	Regrowth[A] rue (g/MJ)	Regrowth[B] rue (g/MJ)	TEC ($g/m^2/mm$)	Growth rue (g/MJ)	TEC ($g/m^2/mm$)
Germination	0.00	n.a.	n.a.	0.000	0.00	0.000
Emergence	0.65	1.80	1.40	0.006	1.30	0.003
Juvenile	0.65	1.80	1.40	0.006	1.30	0.003
Flower initiation	0.50	1.40	1.10	0.005	1.30	0.003
Flowering	0.35	0.80	0.60	0.003	1.30	0.003
Start of Grain Filling	0.10	0.40	0.30	0.001	1.30	0.003
End of Grain Filling	0.10	0.10	0.10	0.000	1.30	0.003

n.a., not applicable, [A]Regrowth after cutting or lucerne suppression, [B]Regrowth during autumn or winter

In the Harris *et al*. (2008) field experiment, heliotrope (*Heliotropium europaeum*) invasion of the cereal monoculture stubble resulted in transpiration over the summer fallow period needing to be simulated. To capture this effect in APSIM, the *weed* module was modified to simulate the growth of a summer broadleaf weed with transpiration efficiency and rue consistent with its C3 photosynthetic pathway (Table 4). In the management logic of APSIM, summer weed growth was initiated if a single rainfall event exceeded 25 mm between day 335 and day 40 of the following year, with the summer broadleaf weed 'sown' to a depth of 40 mm at 50 plants/m^2, and a maximum rooting depth of 0.5m. The summer broadleaf weed was terminated when it reached either harvest_ripe stage of growth or day 60.

During the field experiment, all treatments were grazed (Table 3) after lucerne biomass sampling over summer, between cereal crops. APSIM simulated this activity in the management logic by grazing all live plant material, i.e. lucerne in the lucerne monoculture and companion crop treatments and summer weeds in the cereal monoculture, to a height of 20 mm and removing 70% of plant biomass. In addition surface organic matter was also grazed to emulate some cereal stubble breakdown resulting from grazing livestock.

Initially the model was run by setting the soil N levels in accordance with field observed values from the first year (Table 5) and allowing the model to run through the 3 years without adjustment. However, due to the large divergence in soil N between the observed and simulated values in the final year of the companion crop simulations, the soil N levels in the model were set each year to the observed values. Resetting soil mineral N in the companion crop and lucerne simulations were carried out to adjust soil N levels in line with measured values (Table 5) from the corresponding field experiment. The resetting was necessary particularly in the companion crop simulations to ensure that the cereal crop growing in the presence of lucerne was given the opportunity to respond in a similar manner to the observed response.

Statistical analysis

The magnitude of difference between simulated (S) and observed (O) data was quantified using root mean squared error (RMSE) as described by Wallach and Goffinet (1989). In addition, two tailed t-tests were used to define the 'normal' population distribution around the observed mean at 95% confidence limits at each sampling point through time, and presented as time series plots in this paper. Satisfactory agreement was achieved when simulated output fell within the population distribution. If the simulated data fell beyond the lower or upper 95% confidence limits it was considered an underestimation or overestimation respectively.

Table 5. Measured soil mineral N ($N0_3$ and NH_4) values (kg N/ha) from the field experiment used to reset the companion crop and lucerne N0 and N+ simulations

Depth (m)	23 April 2003		26 April 2004		26 April 2005	
Companion crop simulations						
N0						
	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4
0-0.1	42.0	8.4	20.4	2.6	22.1	2.3
0.1-0.3	19.0	2.1	4.0	1.2	4.1	1.5
0.3-0.5	17.7	2.1	0.6	1.2	1.8	1.4
0.5-0.7	11.1	1.5	0.4	1.2	1.2	1.3
0.7-0.9	6.3	1.4	0.4	1.2	2.5	1.2
0.9-1.1	4.3	1.4	0.4	1.2	3.5	1.2
1.1-1.3	3.5	1.4	0.4	1.2	3.5	1.2
N+						
	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4
0-0.1	42.0	8.4	19.5	25.8	23.2	3.3
0.1-0.3	19.0	2.1	3.5	1.3	6.1	1.6
0.3-0.5	17.7	2.1	0.6	1.2	3.0	1.3
0.5-0.7	11.1	1.5	0.4	1.2	2.4	1.3
0.7-0.9	6.3	1.4	0.4	1.2	3.8	1.7
0.9-1.1	4.3	1.4	0.4	1.2	4.3	1.6
1.1-1.3	3.5	1.4	0.4	1.2	3.5	1.2
Lucerne simulations						
N0						
	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4
0-0.1	42.0	8.4	31.2	1.1	16.2	7.8
0.1-0.3	19.0	2.1	4.1	1.2	2.2	1.6
0.3-0.5	17.7	2.1	0.8	1.2	1.2	1.5
0.5-0.7	11.1	1.5	0.5	1.2	1.3	1.2
0.7-0.9	6.3	1.4	0.5	1.2	1.9	1.2
0.9-1.1	4.3	1.4	0.9	1.2	1.6	1.2
1.1-1.3	3.5	1.4	1.2	1.2	1.2	1.2
N+						
	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4
0-0.1	42.0	8.4	38.1	4.1	5.5	2.5
0.1-0.3	19.0	2.1	3.1	1.4	1.3	1.8
0.3-0.5	17.7	2.1	0.7	1.7	0.7	1.7
0.5-0.7	11.1	1.5	0.7	1.8	0.4	1.2
0.7-0.9	6.3	1.4	0.6	1.8	0.4	1.2
0.9-1.1	4.3	1.4	0.7	2.0	0.5	1.2
1.1-1.3	3.5	1.4	0.8	2.1	0.5	1.2

Results

Simulated and observed cereal production in the presence and absence of lucerne

Generally there was satisfactory agreement between observed and simulated cereal biomass in the presence and absence of lucerne, providing autumn soil N was reset in the companion cropping simulations. For the cereal monoculture the RMSE was 28% and 26% of the observed mean, for the N0 and N+ cereal monoculture simulations respectively (Table 6). However, resetting autumn soil N in each year of the companion crop N0 and N+ simulations resulted in a reduction in RMSE from 52% to 39% and 63 to 28% of the observed mean respectively. The time series plots showed that without resetting soil N in the companion crop N0 and N+ simulations, APSIM under-estimated cereal biomass at maturity by 4889 kg DM/ha and 9163 kg DM/ha respectively, in the final year (Figures 1e to 1h).

Simulated cereal grain yield were satisfactory, given that the RMSE was 23% and17% of the observed mean in the cereal monoculture N0 and N+ simulations respectively (Table 6). Similarly to the cereal biomass without resetting autumn soil N in each year of the companion crop N0 and N+ simulations, APSIM underestimated grain yield by 1790 kg/ha and 3433 kg/ha in the final year (Figures 2e to 2h). Resetting the soil N to observed field values at the beginning of each season improved the RMSE from 49% to 20% and 62% to 30% of the observed mean in the companion crop N0 and N+ simulations respectively (Table 6).

Table 6. Root mean squared error (RMSE) between observed and simulated cereal and lucerne production, and soil water content, in the cereal monoculture, companion crop and lucerne monoculture treatments for both rates of N.

Treatment	Additional N	*N*	Observed mean	Observed Range Max	Min	RMSE	RMSE with reset N[#]
Cereal biomass (kg DM/ha)							
Cereal monoculture	N0	33	5884	11658	722	1619	
	N+	33	7885	17192	1112	2049	
Companion crop	N0	33	4496	15222	824	2347	1761
	N+	33	6526	14434	824	4137	1815
Grain yield (kg/ha)							
Cereal monoculture	N0	11	3372	4156	2762	780	
	N+	11	4372	5348	3071	738	
Companion crop	N0	11	2405	3478	1845	1171	475
	N+	11	3402	4478	2143	2124	1025
Lucerne biomass (kg/ha)							
Companion crop	N0	66	993	3366	158	1064	586
	N+	66	850	2746	158	1156	499
Lucerne monoculture	N0	66	1502	7510	96	927	927
	N+	66	1961	10486	96	1280	1280
Soil mineral N (kg/ha)							
Cereal monoculture	N0	15	39	82	20	15	
	N+	15	53	99	18	22	
Companion crop	N0	15	49	199	15	36	
	N+	15	56	199	18	41	
Lucerne monoculture	N0	15	53	199	16	37	
	N+	15	56	199	14	40	
Companion crop	N0	6*	18	22	15		5
with reset N	N+	6*	21	25	18		12
Lucerne monoculture	N0	6*	28	39	16		15
with reset N	N+	6*	38	88	15		41
Soil water (mm) 0.1-1.1 m							
Cereal monoculture	N+	75	249	201	304	13	
Companion crop	N+	75	241	184	311	23	23
Lucerne monoculture	N+	75	241	187	314	23	23
Soil water (mm) 1.1-2.7 m							
Cereal monoculture	N+	75	461	448	470	8	
Companion crop	N+	75	435	417	460	7	7
Lucerne monoculture	N+	75	422	393	473	15	15

[#] resets of autumn soil mineral N on 23 Apr.03, 26 Apr. 04 and 26 Apr. 05.

*excluding both observed and simulated autumn soil mineral N data.

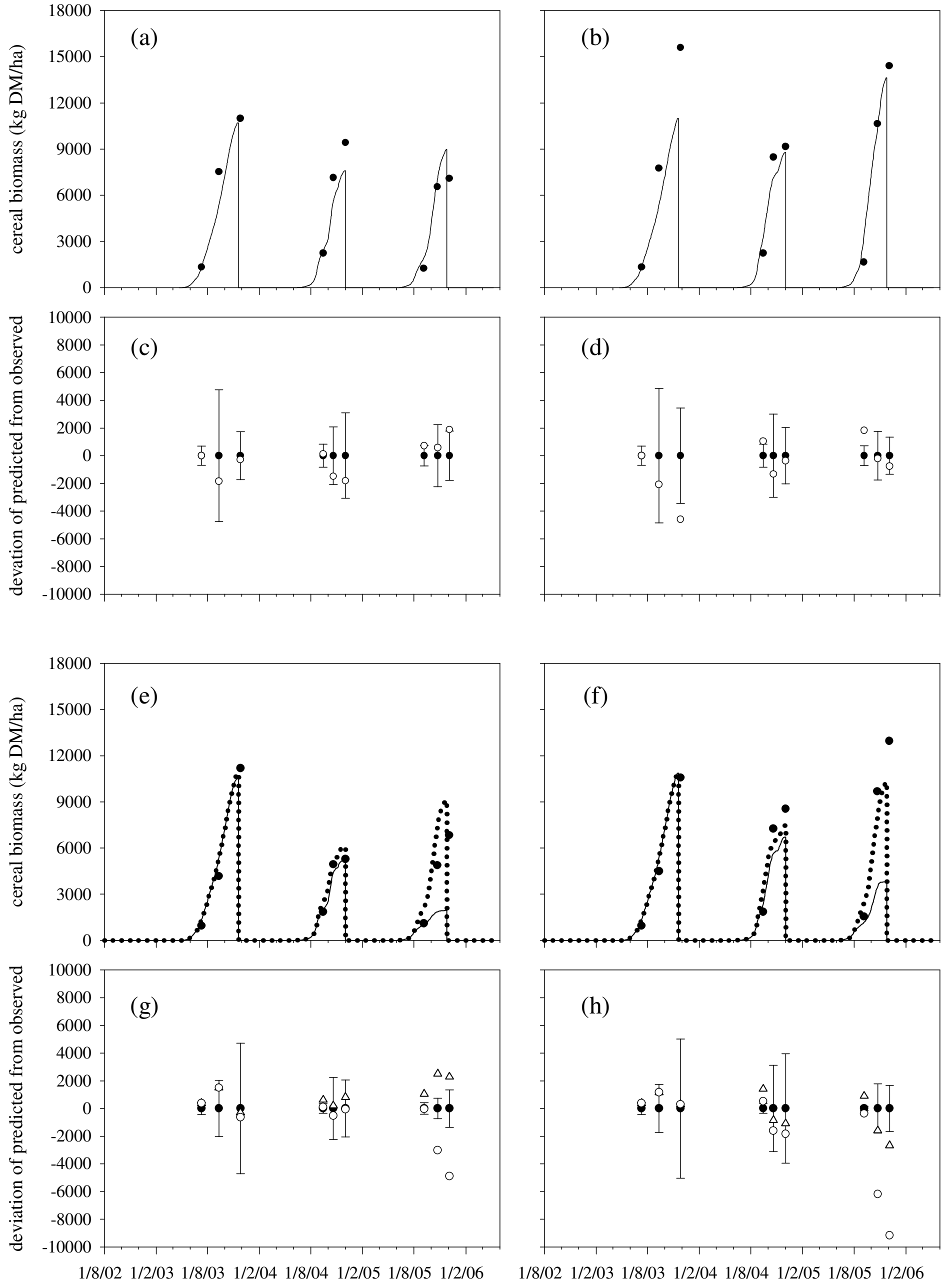

Fig 1. Time series plots of observed mean (scatter plots) and simulated (line) cereal biomass production in the cereal monoculture (a and b) and companion crop (e and f) treatments. Respective vertically corresponding graphs (c, d, g and h) show deviation of predicted (open symbol) from the observed mean (closed symbol) with the vertical line around the observed mean representing the 'normal' population distribution at 95% confidence limits. Additional simulations (broken line) in graphs e and f, and the corresponding open triangle symbols in graphs g and h, are estimations where autumn soil N was reset in each year of the companion crop simulations. Graphs a, c, e and g represent N0, and graphs b, d, f and h represent N+ simulations.

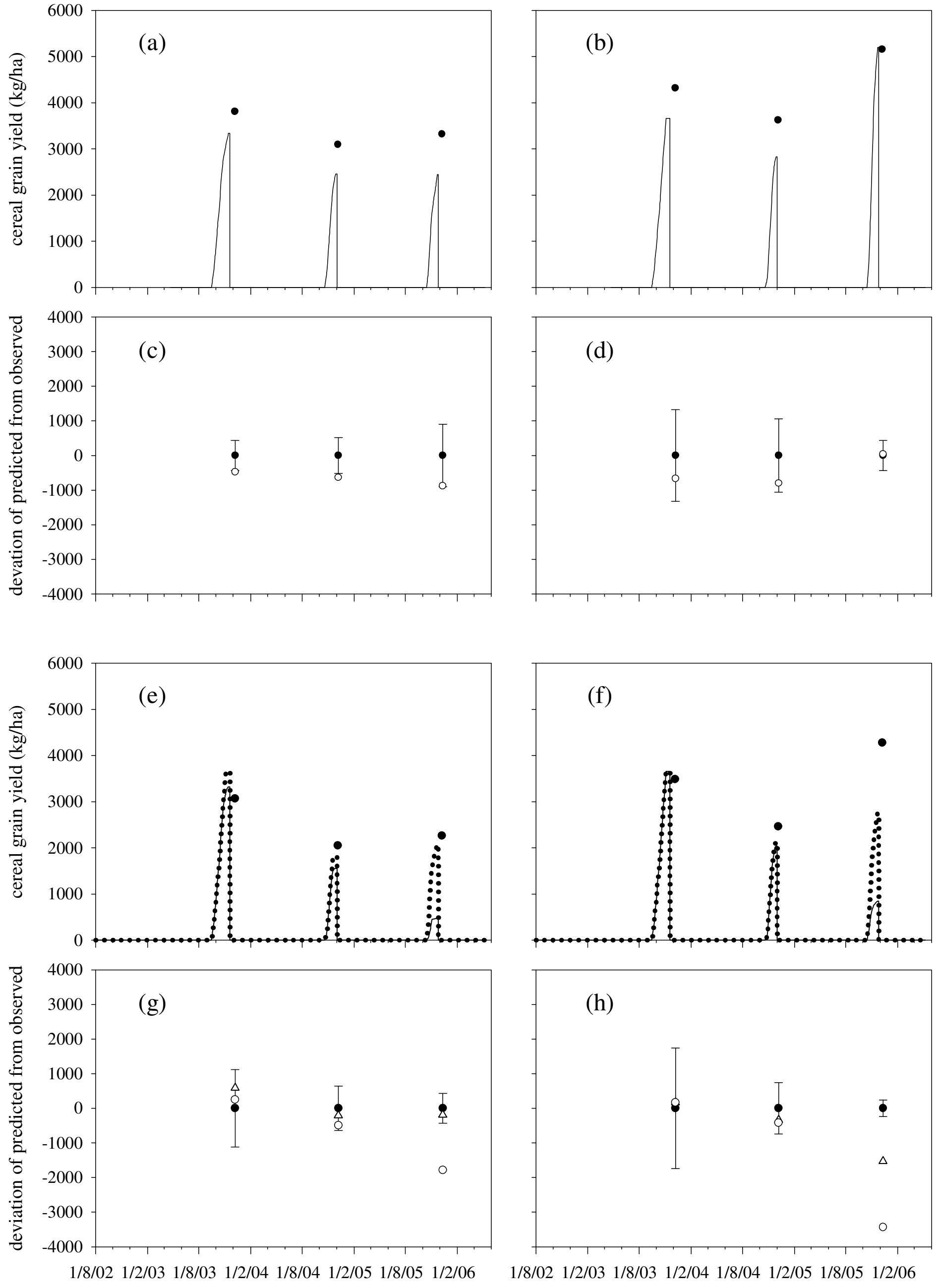

Fig 2. Time series plots of observed mean (scatter plots) and simulated (line) cereal grain yield in the cereal monoculture (a and b) and companion crop (e and f) treatments. Respective vertically corresponding graphs (c, d, g and h) show deviation of predicted (open symbol) from the observed mean (closed symbol) with the vertical line around the observed mean representing the 'normal' population distribution at 95% confidence limits. Additional simulations (broken line) in graphs e and f, and the corresponding open triangle symbols in graphs g and h, are estimations where autumn soil N was reset in each year of the companion crop simulations. Graphs a, c, e and g represent N0, and graphs b, d, f and h represent N+ simulations.

Simulated and observed lucerne production in the presence and absence of a cereal crop

Resetting autumn soil N in each year of the lucerne monoculture simulations had no effect on improving the accuracy of simulated lucerne biomass production. Irrespective of autumn soil mineral N resets, the RMSE remained unchanged, at 62% and 65% of the observed mean for the lucerne monoculture N0 and N+ simulations respectively (Table 6). Conversely, resetting autumn soil mineral N in the companion crop simulations resulted in a substantial improvement in APSIM estimations of lucerne biomass production (Table 6). The time series plots showed that without autumn soil N resets in the companion crop N0 and N+ simulations, APSIM overestimated lucerne biomass production in the final year at cereal maturity by 3524 kg DM/ha and 3926 kg DM/ha respectively (Figure 3a to 3d).

Most of the APSIM estimations of lucerne growth over the summer autumn period in the companion crop simulations fell within the "normal" population distribution, particularly in the N+ simulation. APSIM overestimated summer/autumn lucerne biomass production by 424 and 577 kg DM/ha in the second and fourth summers respectively, in the companion crop N0 simulation (Figure 3a and 3c).

In contrast to the field data, simulated lucerne biomass production in monoculture showed little response to the application of N (Figures 3e to 3h). Averaged over all years, cumulative winter/spring production was overestimated by 251 kg DM/ha in the N0 and underestimated by 719 kg DM/ha in the N+ lucerne monoculture simulations. Simulations of cumulative summer/autumn production average over all years was overestimated by 87 kg DM/ha and 111 kg DM/ha in the lucerne monoculture N0 and N+ simulations respectively.

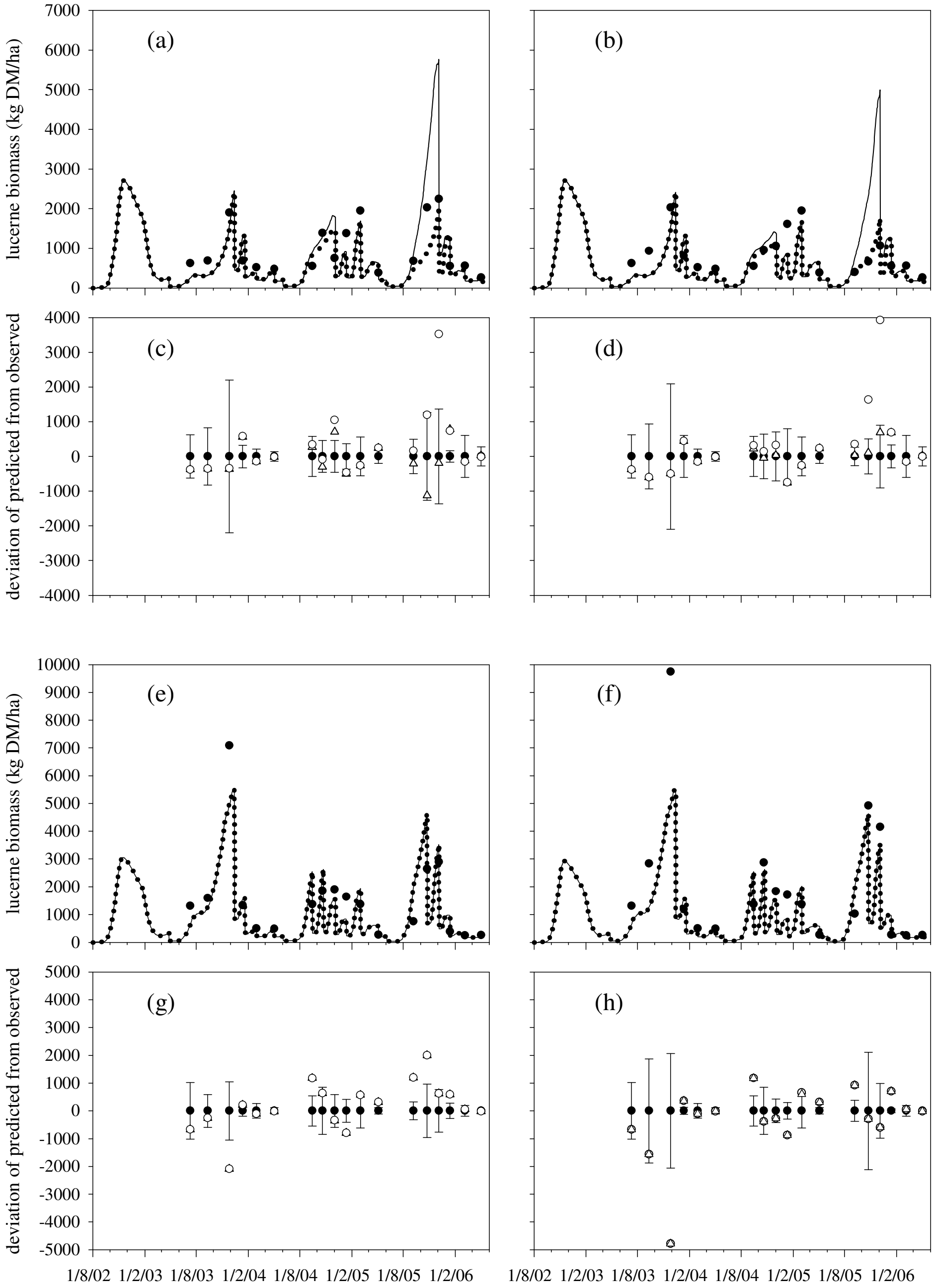

Fig 3. Time series plots of observed mean (scatter plots) and simulated (line) lucerne production in the companion crop (a and b) and lucerne monoculture (e and f) treatments. Lucerne biomass simulated with (unbroken line) and without (broken line) resets of autumn soil mineral N in both the companion crop and lucerne monoculture simulations. Respective vertically corresponding graphs (c, d, g and h) show deviation of predicted (open symbol) from the observed mean (closed symbol) with the vertical line around the observed mean representing the 'normal' population distribution at 95% confidence limits. The open symbols are estimations from simulations with (triangle) and without (circle) resets of autumn soil mineral N in both the companion crop and lucerne monoculture simulations. Graphs a, c, e and g represent N0, and graphs b, d, f and h, represent N+ simulations.

Simulated and observed soil mineral N and soil water content under cereal and lucerne grown separately and in mixture

Comparison of simulated and observed soil mineral N in both the cereal monoculture N0 and N+ simulations, resulted in a RMSE of 37% and 41% of the observed mean respectively (Table 6); also supported by the time series plots showing simulated outputs falling within the "normal" population distribution on all sampling dates (Figures 4a to 4d). In contrast the estimated soil mineral N in the companion crop and lucerne monoculture simulations were less reliable, with the proportion of RMSE to the observed means greater (>69%), than the cereal monoculture simulations (Table 6). Introducing resets of autumn soil mineral N in each year reduced the proportion of RMSE to the observed mean, in the companion crop N0 simulation but not the companion crop N+ or the lucerne monoculture simulations (Table 6).

The time series plots showed that without resets of autumn soil N, APSIM tended to underestimate soil mineral N in the autumn of the third and final year of the companion crop simulations (Figures 4e to 4h). Without resetting autumn soil mineral N in the companion crop N0 simulation, estimated soil mineral N averaged across the third and final year, was 30 kg/ha below the observed mean (Figures 4e to 4h). Irrespective of autumn soil N resets in the companion crop N+ simulation, the time series plots showed satisfactory agreement between observed and simulated mineral N data. The time series plots also show that resetting autumn soil N provided no improvement in estimated soil mineral N at cereal maturity under both the lucerne monoculture N0 and N+ simulations (Figures 4i to 4l).

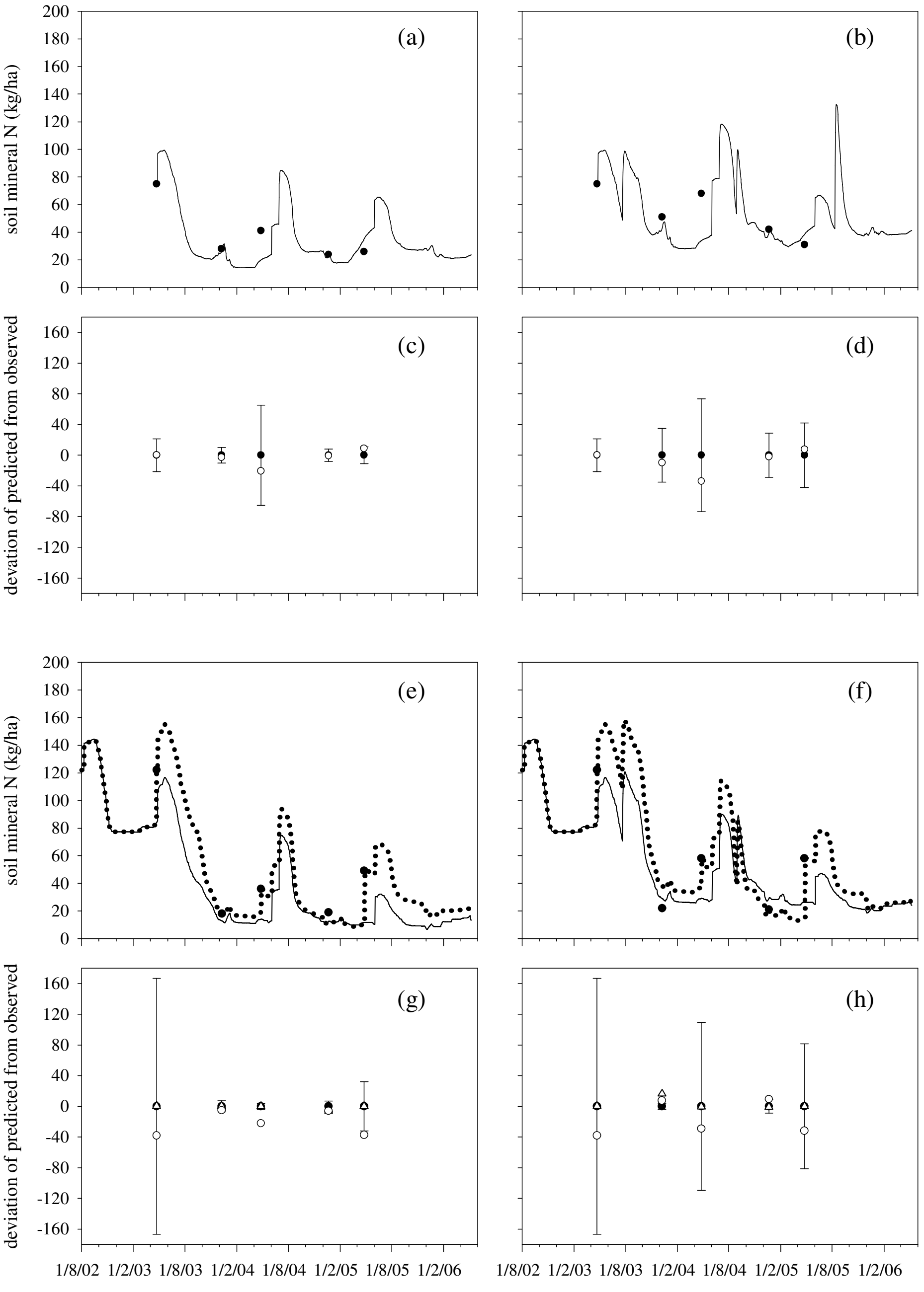

Fig 4. continued next page

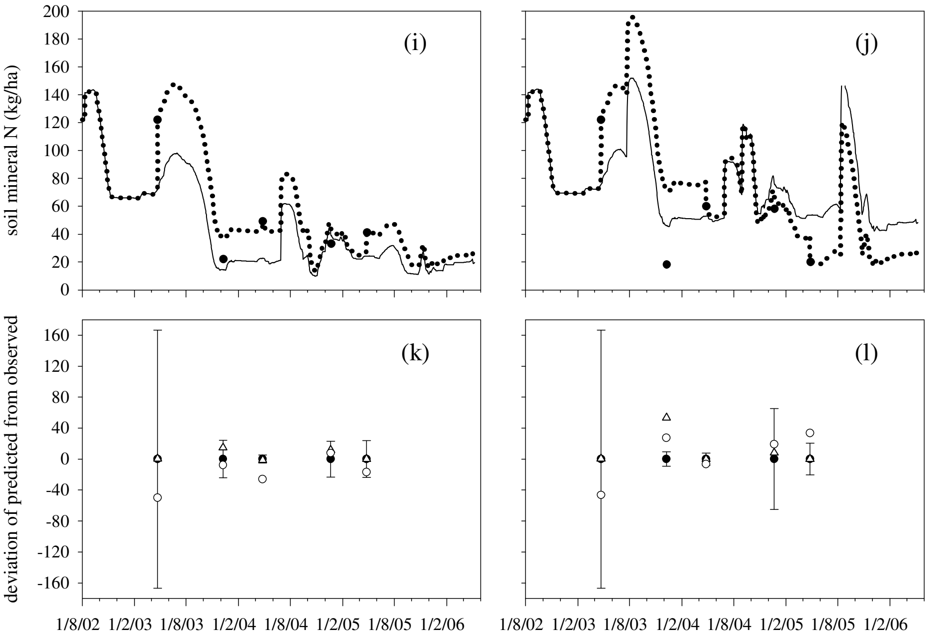

Fig 4. Time series plots of observed mean (scatter plots) and simulated (line) soil mineral N in the cereal monoculture (a and b), companion crop (e and f) and lucerne monoculture (i and j) treatments. Respective vertically corresponding graphs (c, d, g, h, k and l) show deviation of predicted (open symbol) from the observed mean (closed symbol) with the vertical line around the observed mean representing the 'normal' population distribution at 95% confidence limits. Additional simulations (broken line) in graphs e, f, i and j, and the corresponding open triangle symbols in graphs g, h, k and l, are estimations where autumn soil N was reset in each year of the companion crop and lucerne monoculture simulations. Graphs a, c, e, g, i and k represent N0, and graphs b, d, f, h, j and l represent N+ simulations.

The comparison of simulated and observed soil water data at both depths increments, showed the RMSE for the cereal monoculture, companion crop and lucerne monoculture simulations were 5%, 10% and 10% respectively, of the observed mean in the 0.1- 0.9 m depth increment; while the RMSE was 2%, 2% and 4% respectively, of the observed mean in the 0.9 – 2.7 m depth increment (Table 6). Resetting autumn soil N in each year, had no affect on estimated soil water in both the companion crop and lucerne monoculture simulations at both depth increments.

The time series plots showed that over the winter period of the second and third years, APSIM underestimated soil water content under the companion crop and lucerne monoculture simulations at the 0.1 – 0.9 m depth increment (Figures 5b and 5e). Over both periods, APSIM under-predicted average soil water content by 35 mm (companion crop) and 40 mm (lucerne monoculture simulations) for each sampling date. Furthermore, APSIM tended to overestimate average soil water content by 10 mm after harvest, in the 0.1-0.9 m layer under the cereal monoculture simulation. Generally all simulations behaved consistently with the observed data, with both data sets responding to rainfall and evapotranspiration (Figures 5a to 5i). At the deeper soil layer, most of APSIM estimations of soil water content (Figures 6a to 6f) fell within the "normal" population distribution.

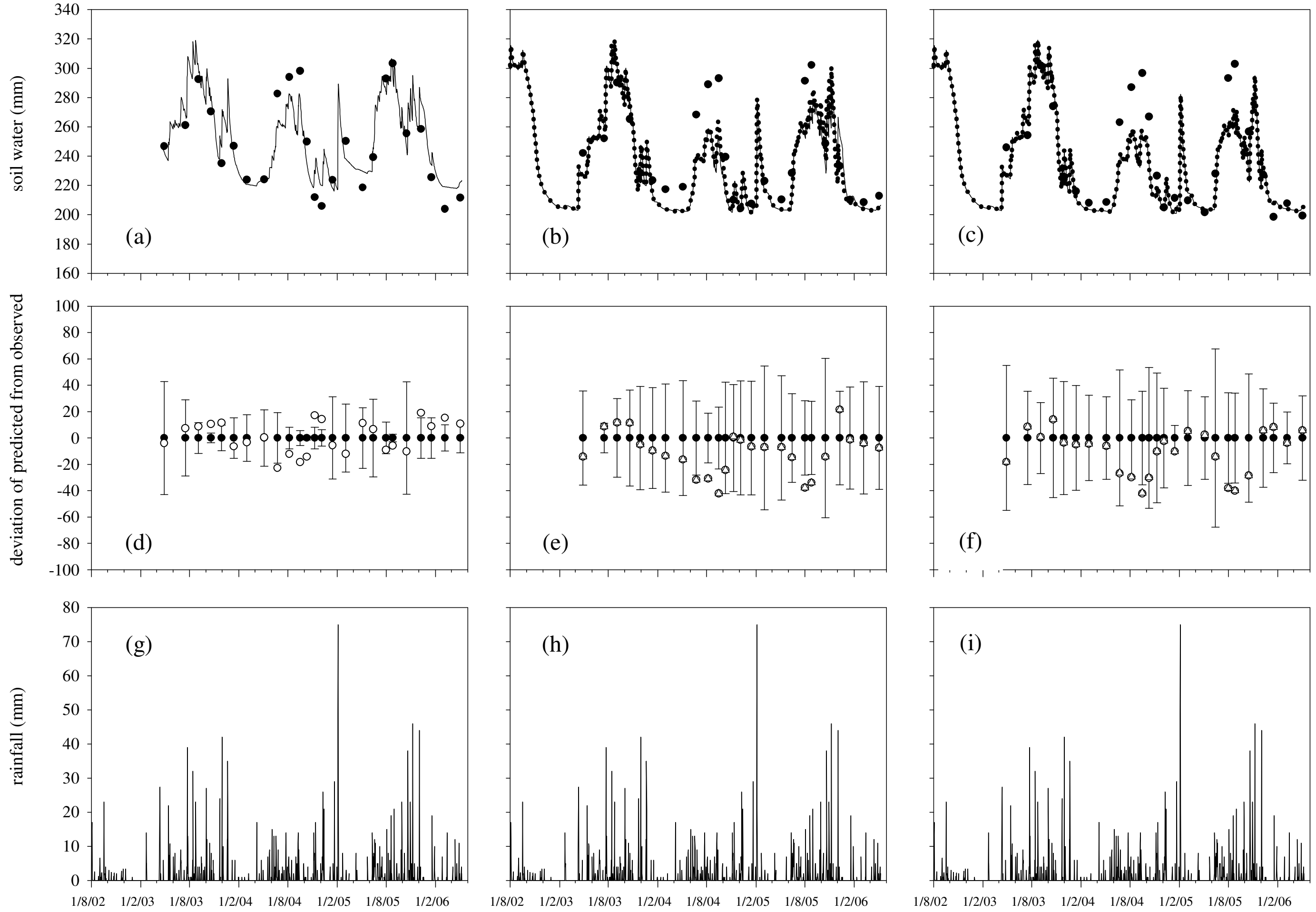

Fig 5. Time series plots of observed mean (scatter plots) and simulated (line) soil water content between 0.1 – 0.9 m depth under the cereal monoculture (a) companion crop (b) and lucerne monoculture (c) treatments. Respective vertically corresponding graphs d, e and f show deviation of predicted (open symbol) from the observed mean (closed symbol) with the vertical line around the observed mean representing the 'normal' population distribution at 95% confidence limits. Additional simulations (broken line) in graphs b and c, and the corresponding open triangle symbols in graphs e and f, are estimations where autumn soil N was reset in each year of the companion crop and lucerne monoculture simulations. Graphs g h and i represent daily rainfall measured at North Boorhaman from the 1/08/2002 to 31/05/2006.

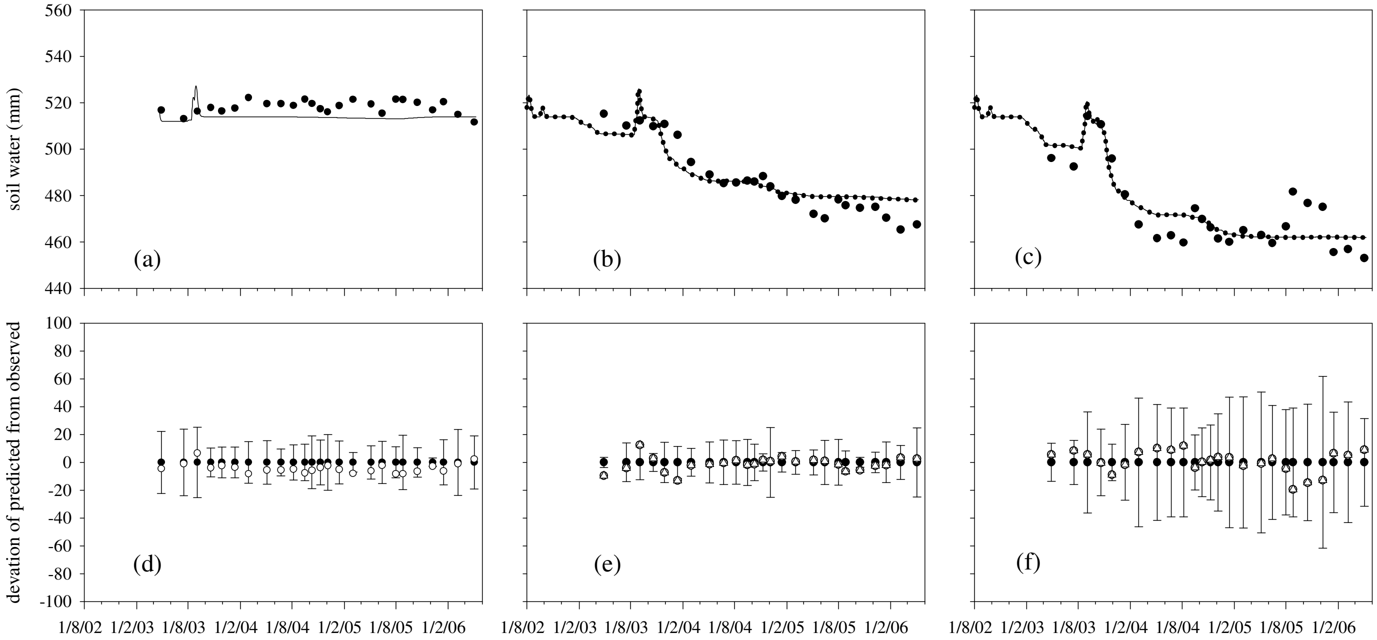

Fig 6. . Time series plots of observed mean (scatter plots) and simulated (line) soil water content between 0.9 – 2.7 m depth under the cereal monoculture (a) companion crop (b) and lucerne monoculture (c) treatments. Respective vertically corresponding graphs d, e and f show deviation of predicted (open symbol) from the observed mean (closed symbol) with the vertical line around the observed mean representing the 'normal' population distribution at 95% confidence limits. Additional simulations (broken line) in graphs b and c, and the corresponding open triangle symbols in graphs e and f, are estimations where autumn soil N was reset in each year of the companion crop and lucerne monoculture simulations

Discussion

Evaluation of APSIM for simulating companion cropping

The data presented in this paper emphasises the importance of accurate simulation of soil mineral N, because initial simulated competition between the cereal and lucerne components appears to be largely driven by access to soil N early in the growing season. If the simulated soil mineral N is low, APSIM will assume plant N uptake exhausts soil mineral N and thereafter lucerne demand for N is satisfied through N fixation, resulting in continued lucerne canopy development and capture of solar radiation at the expense of the companion cereal, largely denied access to N (Figure 7). When autumn soil mineral N was reset to reflect field conditions the competitive advantage remained with the cereal component, consistent with field observations.

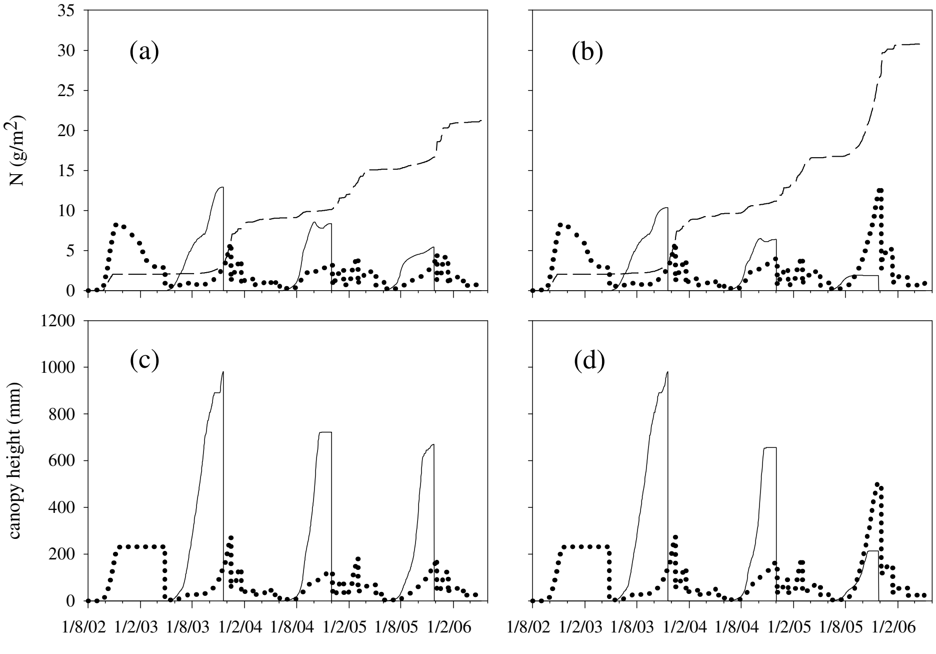

Fig 7. Simulated wheat (unbroken line) and lucerne (dotted line) plant N uptake (a and b) and canopy height (c and d) and cumulative lucerne N fixation (medium dash line). Mean of the companion crop N0 and N+ simulations with (a and c) and without (b and d) autumn soil N resets.

The observed autumn soil mineral N levels were higher than simulated by APSIM in the companion crop simulations. Field measurements of autumn soil N showed that most (>85%) of the mineral N was contained in the 0-0.1 m soil layer. This discrepancy may have resulted from soil N spared under low density lucerne stands in the corresponding field experiment. Dear *et al*. (2001) found greater soil mineral N under sparse (5-10 plants/m^2) lucerne monoculture stands compared with low density phalaris (5-10 plants/m^2) or dense (40 plants/m^2) lucerne stands over the autumn/winter period; attributing the superior ability of phalaris to compensate for low plant density by increasing individual plant size and consequently exploiting a larger surface soil volume and taking up more soil N than low density lucerne stands. In a companion cropping situation, presumably the companion cereal with a similar fibrous root system (higher root length density) and planted at a high density would be more effective at scavenging top soil mineral N. APSIM may have overestimated root exploration by the lucerne and therefore soil N uptake over the summer/autumn period, as lucerne plant densities ranged from 12 to 8 plants /m^2 (or 200-150 stems/m^2) over the lifespan of the corresponding field experiment.

The theory concerning the overestimated lucerne root exploration, conflicts with the apparent agreement between simulated and observed soil water content, giving rise to another possible explanation. Lemaire *et al*. (2005) published data supporting the idea that lucerne leaf growth drives the dynamics of shoot N accumulation, they showed a linear relationship ($y=1.769x + 0.641$, $R^2 = 0.929$) between shoot N uptake and leaf area index (LAI) under field conditions. When the Lemaire *et al*. (2005) relationship was applied to APSIM simulated LAI, a substantial decrease in lucerne N uptake was found (Figure 8). A reduction in simulated lucerne N uptake could result in less demand for soil N over the summer/autumn period and could possibly emulate the “spared” autumn soil N observed in the corresponding field experiment.

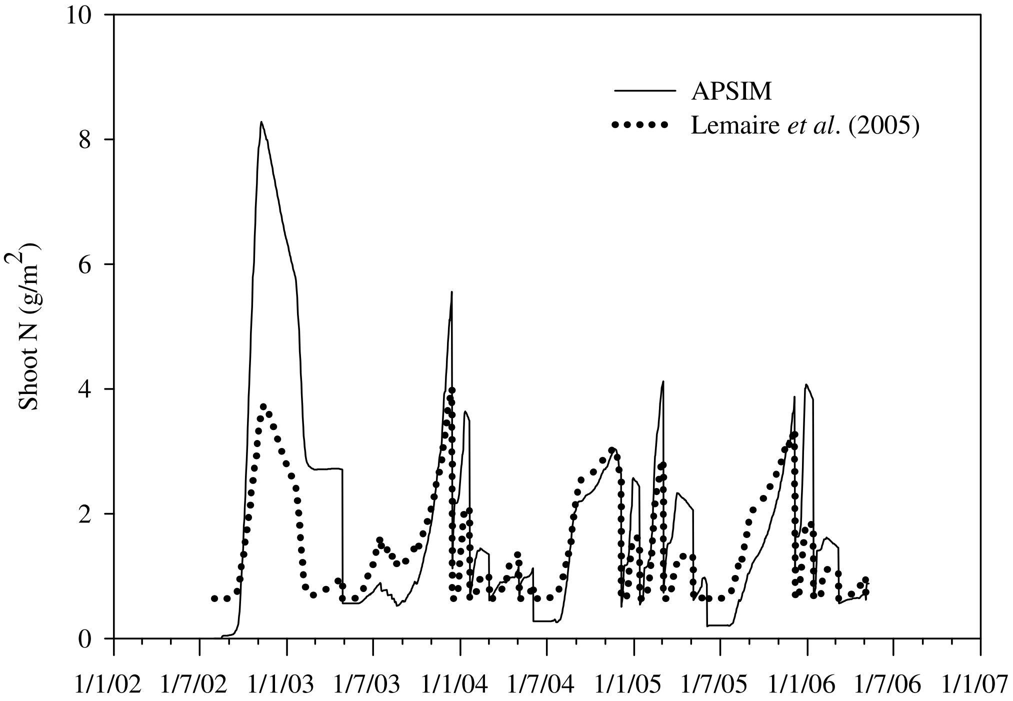

Fig 8. Comparison of APSIM estimated shoot N uptake (solid line) with the Lemaire *et al.* (2005) (broken line) relationship for calculating shoot N uptake of lucerne growing in the companion crop treatments. Mean of companion crop N0 and N+ simulations.

Despite the companion crop simulations in the absence of autumn soil N resets giving an untrue reflection of what unfolded in the field, it does give further insight into the effect that resource supply can have on competition, regarding one component gaining competitive advantage over another. APSIM suggests that N supply plays a critical role in determining the fate of the companion cereal. In support of APSIM's estimation, the corresponding field experiment (Harris *et al.* 2008) and other field based studies (Humphries *et al.* 2004; Harris *et al.* 2007a) have shown significant reductions in either cereal tiller formation or winter cereal biomass production in the presence of lucerne. Harris *et al.* (2008) ruled out competition for soil water before cereal stem elongation (Z31), and produced data showing greater combined demand and therefore competition for N in companion crops than cereal and lucerne grown in monoculture. They could not dismiss competition for light (either the quantity or quality of light intercepted) contributing to suppressed cereal production in the presence of lucerne. On the basis of the hypothetical scenario of low soil mineral N; we surmise that N supply might initially influence associated lucerne and cereal canopy development and thereafter determine which component achieves superior light interception and consequently greater subsequent access to the majority of resources (Figure 7).

Evaluation of APSIM for simulating cereal and lucerne production in grown monoculture

Although assessing the accuracy of APSIM to simulate lucerne and cereal production as monocultures is not the main focus of this paper, it remains an important consideration, especially when using monocultures as a benchmark to compare separate component yields in a companion crop system. The data presented in this paper is largely in accord with authors have who previously reported satisfactory model performance for simulating wheat growth and development across southern Australia (Asseng *et al*. 1998a; Asseng *et al*. 1998b; Yunusa *et al*. 2004; Lilley and Kirkegaard 2007).

Previous authors have also reported satisfactory model performance for simulating lucerne growth (Robertson *et al*. 2002; Zahid *et al*. 2003; Dolling *et al*. 2005). However, in our study, APSIM appeared less reliable at predicting lucerne growth compared with wheat in monoculture or companion crop. The main concern was the absence of a predicted response to N application. The simulation data showed that irrespective of soil mineral N, lucerne biomass in monoculture simulations remained unaffected by soil mineral N, because any shortfall in soil N could be satisfied through N fixation. However, APSIM N fixation parameter may have been too high for this environment. In the corresponding field experiment, the initial acid (4.3 $CaCl_2$) topsoil conditions may have reduced rhizobia survival (Coventry *et al*. 1985) and therefore lucerne N fixation, and this could have contributed to the apparent N fertiliser response expressed in the observed data. This theory may also help to explain the over-predicted summer/autumn lucerne biomass production in the companion crop N0 simulation. We conducted a hypothetical simulation where the lucerne N fixation parameter was reduced, resulting in a lower estimation of lucerne biomass in the absence of fertiliser N, but the companion crop N+ simulated output remained unchanged from the original N fixation parameter (data not shown). Measurements of lucerne N fixation in the corresponding field experiment could have improved model parameterisation and estimations of lucerne production.

Whilst we have highlighted potential weaknesses in parameterisation of the lucerne model, we also have doubts about the accuracy of the observed data in the first year of the lucerne monoculture. On close inspection of the data in the first year, between the second and third lucerne biomass cuts (late winter and spring), the growth rates equate to 71 and 90 kg DM/ha/day for the N0 and N+ applications respectively, which is considerably higher than the 51 kg DM/ha/day previously reported over spring, in this environment (Hirth *et al*. 2001). This outcome was a reflection on poor management of the lucerne monoculture treatment, in which individual plants became severely lignified and lodged, proving not only difficult to accurately sample, but unrealistic of how commercial lucerne stands are managed in a farming systems context. When the third observed sampling point in the first year of observations and corresponding simulated data was removed in both the N0 and N+ comparisons, the RMSE improved (828 kg DM/ha and 774 kg DM/ha respectively). Furthermore the simulated daily lucerne growth rate was much closer to the field values previously reported by Hirth *et al*. (2001) for North East Victoria.

Calibration of APSIM using field measured soil water and soil mineral N data

The performance of APSIM can not be evaluated on the basis of the soil water and soil mineral N data, because they were used to parameterise the model. However, the close agreement between simulated and observed soil water data provides sufficient confidence in the model setup. Although the agreement between simulated and observed soil mineral N was not as accurate as the soil water; clearly the resets of autumn soil N were required to provide a realistic estimation of what actually unfolded in the corresponding field experiment. We propose that any long-term simulations investigating the outcomes of companion cropping, particularly under low levels of soil mineral N, will need to introduce a correction factor (or reset of autumn soil N) to accommodate for suspected excessive simulated lucerne soil N uptake over the summer/autumn period.

Conclusion

APSIM satisfactorily simulated cereal production in the presence of lucerne, providing autumn soil N was reset in each year. The model probably over-predicted lucerne soil N uptake over the summer/autumn period, and this seems the most likely reason necessitating the autumn soil N resets. Providing autumn soil N is reset to accommodate for this weakness in the model, from the data presented in this paper we suggest that APSIM will give adequate estimations of cereal production in the presence and absence of lucerne and N application. The model performance for estimating lucerne production in monoculture and in association with a companion cereal was largely sufficient, particularly when field sampling error/mismanagement was considered in the lucerne monoculture, and autumn soil N was reset in the companion crop simulations. However, we conclude that measurements of lucerne N fixation in the corresponding field experiment could have improved model parameterisation and predicted lucerne biomass production. Model performance indicates APSIM can be used to simulate longer term effects of rainfall distribution and management intervention on companion crop performance, thus helping identify the circumstances under which the practice might be feasible.

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Chapter 6. Estimated long-term trends in agronomic strategies for mitigating competition in companion cropping systems on the Riverine Plains

This Chapter is a manuscript intended for submission to either Crop and Pasture Science or Agricultural Systems.

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Running title: Simulated long-term climatic and agronomic effects on cereal production growing with and without lucerne.

Co-author declarations

D Gaydon

9 November 2010

To whom it may concern

This note is to confirm that my contribution to chapters 5 & 6 in the PhD Thesis of Robert Harris consisted of collaboration with Robert on APSIM model testing for his focus on lucerne-wheat companion cropping systems (Chapter 5). This collaboration included provision of advice on APSIM configuration, interpretation of model performance in comparison with experimental findings, and subsequent input on iterative changes to configuration in achieving acceptable model performance. I also provided input on Robert's deliberations and final critical evaluations of APSIM's performance. This was followed by provision of advice on use of the model in scenario analyses which Robert had envisaged and subsequently performed (Chapter 6). I estimate my contribution to these chapters as in the vicinity of 5%.

This note also confirms my permission for the manuscripts to be included in Robert's thesis.

Yours sincerely

Donald Gaydon
Senior Farming Systems Researcher
CSIRO Ecosystem Sciences

WD Bellotti

24 November 2010

To whom it may concern,

Contribution to publications by Mr Rob Harris included in his thesis to be submitted for the award of Doctor of Philosophy

This note is to confirm that my contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Gaydon D, Bellotti WD, Unkovich MJ, Robertson MJ (2010 in prep) Estimated long-term trends in agronomic strategies for mitigating competition in companion cropping systems on the Riverine Plains. *Crop and Pasture Science or Agricultural Systems.*

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

Yours sincerely,

Professor Bill Bellotti
Vincent Fairfax Chair in Sustainable Agriculture and Rural Development

MJ Unkovich

My contribution to the publications identified below, which I co-authored with Rob Harris, in terms of protocol development, data collection, data presentation, interpretation of the data, contribution to the underlying structure or content of the paper and suggested editing of the paper was in the order of 5%.

Harris RH, Gaydon D, Bellotti WD, Unkovich MJ, Robertson MJ (2010 in prep) Estimated long-term trends in agronomic strategies for mitigating competition in companion cropping systems on the Riverine Plains. *Crop and Pasture Science or Agricultural Systems.*

I formally give permission for the above publication to be included in Rob Harris's Doctor of Philosophy thesis.

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MJ Robertson

To whom it may concern: I contributed to hypothesis formulation, protocol development, interpretation of the data, contribution to the underlying structure of the paper/manuscript and suggested editing of the paper for chapter 6 of this thesis. My contribution would amount to less than 5% of the overall piece of work.

Yours sincerely

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Abstract

The simulation model APSIM (Agricultural Production Systems Simulator) and a long-term (1956-2007) climatic dataset was used to study competition in cereal growing with the perennial forage lucerne (*Medicago sativa*); and to determine the possible role of agronomic strategies for mitigating wheat productivity losses. Simulations were performed for wheat growing with (companion crop) and without (cereal monoculture) lucerne under historical rainfall on a red sodosol soil in NE Victoria. Wheat production was simulated at 170, plants/m^2 grown separately and with lucerne sown at a plant density of 150 stems/m^2. Both the wheat monoculture and companion crop simulations received N fertiliser at 0, 30, 60 or 90 kg N/ha, top-dressed at both 40 and 80 days after sowing. Additional companion crop simulations were performed, where each combination of rate and timing of N application occurred in the presence and absence of pre-crop lucerne suppression and in-crop lucerne suppression. Long-term comparisons showed that on average the cereal monoculture had an extra 81 mm (± 2 s.e.m) of extractable plant available soil water compared with that under companion cropping. Competition for available soil water appears the most likely cause for previous field observations of declines in companion cropped cereals prior to cereal stem elongation. Companion cropping performance is thus strongly influenced by the amount of in-crop rainfall. Growing season rainfall (GSR) with a decile of 3 or less ($\leq$298 mm of GSR), resulted in estimated grain yield reductions of up to 1860 kg/ha (± 67 s.e.m) in companion cropped cereal compared with the cereal monoculture. When GSR was decile 4 ($\leq$299 mm of GSR) or greater, the estimated difference in grain production between the cereal monoculture and companion cropped wheat never exceeded 932 kg/ha (± 68 s.e.m). The combination of pre-crop lucerne suppression and additional fertiliser N enhanced the companion wheat utilisation of in-crop rainfall. These strategies enabled the companion cereal to achieve canopy height advantage over the lucerne canopy for greater radiation interception and increased below ground resource capture and mitigated the effects of competition. However, improvements in companion cereal performance often led to a trade off in terms of decreased annual lucerne production, particularly from pre-crop lucerne suppression.

Additional keywords: *Medicago sativa*, wheat, companion crop, APSIM, model.

Introduction

Companion cropping is a practice where annual crops are sown directly into existing lucerne (*Medicago sativa*) stands; and is one approach available to farmers for integrating lucerne into cropping systems. Perennial herbaceous plants like lucerne offer greater year round plant transpiration, whilst maintaining, and in some cases improving farm income compared with annual pastures grown in rotation with annual crops (Ransom *et al*. 2006). Increasing the water use of farming systems is a key strategy for reducing the impact of agriculture on the surrounding landscape, by either using rainfall when and where it falls, or by increasing the soil's capacity to store excess rainfall for deferred subsequent plant use (Dunin *et al*. 1999), and consequently reducing water leakage below the root zone. Water leaking below the root zone can contribute to land degradation, such as dryland salinisation and soil acidification. Furthermore, cereal crops sown into established lucerne stands could potentially provide dual income streams to mixed farming systems through grain production and provision of better summer and autumn feed for livestock.

Whilst companion cropping presents many potential advantages, companion cereal yield reductions associated with competition from neighbouring lucerne, has often been identified as a major constraint, especially where companion cereals are grown for grain (Egan and Ransom 1996; Humphries *et al*. 2004). Past field research has attempted to identify the key factor or factors driving competition (Egan and Ransom 1996; Harris *et al*. 2008) but there is still substantial uncertainty regarding the specific mechanisms driving competition. Recent research has shown that under some circumstances agronomic intervention can help to mitigate competition and produce more favourable outcomes for companion crop performance (Harris *et al*. 2007b). However, these findings have been confined to a limited number of seasons, and questions remain regarding the factor or factors contributing to competition, and how agronomic strategies for mitigating competition might perform under a broader range of climatic conditions.

The broader literature suggests that the severity of competition in cereal and lucerne mixtures is likely to be determined by; the supply of environmental resources (water, soil nitrogen and solar radiation) which is effected by soil and atmospheric conditions; the growth patterns of the respective plant components which dictates their demand for resources, and the degree to which demand for resources overlap (Fukai and Trenbath 1993); the spatial arrangement (density and distribution) of the cereal with respect to lucerne (Egan and Ransom 1996; Latta and Lyons 2006); and finally canopy height and the components capacities to capture solar radiation. The longer term consequences of these complex interactions on companion cereal performance are very difficult to explore in field experiments due to temporal and resource constraints. However, recent developments in computer crop modelling offers the opportunity to explore cereal and lucerne interactions over many seasons to help examine how the severity of competition is affected by resource supply and how agronomic strategies might alter resource capture to produce more productive companion cereal crops.

The computer crop model APSIM (Agricultural Production System Simulator) has been used for extrapolation of findings beyond season and site specific field based research (Probert *et al*. 1995; Asseng *et al*. 1998). The model can simulate interactions between climate, soil and plant growth, while providing the flexibility to stipulate specific management strategies that can impact on these interactions. Recent research has validated APSIM's capacity to simulate competition in companion cropping systems throughout southern Australia (Robertson *et al*. 2004; Chapter 5), largely reporting satisfactory model performance. However in Chapter 5 concerns were raised about APSIM's capacity to simulate the longer-term N dynamics of companion cropping, concluding the need for regular re-setting of autumn soil N, to compensate for the model exhausting soil N more rapidly than field data showed.

This paper compares simulated wheat production in the absence and presence of lucerne over 52 seasons, to understand why yields of companion cereals are often lower than cereals growing in monoculture. Then compares trends in cereal and lucerne production from long-term companion cropping simulations in response to different lucerne suppression and N fertiliser strategies; to determine if, and under what circumstances these strategies might mitigate competition, and increase companion cereal yield.

Materials and Methods

Simulation model

The APSIM model simulates biophysical processes in farming systems by providing a framework for biological, environmental and management modules to be 'plugged in' to a simulation engine which communicates with the independent modules to produce output (McCown *et al*. 1996). APSIM simulates crop development, growth, yield, and nitrogen accumulation on an area basis, in response to temperature, radiation, photoperiod, soil water, and nitrogen supply, on a daily time-step (Robertson *et al*. 2002). Model details can be found in Keating *et al*. (2003) or at http://www.apsim.info/.

Chapter 5 evaluated the performance of APSIM for simulating cereal and lucerne production grown together and separately, after comparison with detailed field observations the RMSE was < 2049 kg DM/ha and <1045 kg grain/ha for cereal production in the presence of lucerne. However, APSIM tended to exhaust soil mineral N more rapidly under lucerne than the field data indicated, necessitating regular resetting of autumn soil N in long-term simulations, details of which are provided later. The data presented in this paper represents long-term simulations of cereal and lucerne growth on a slightly acidic (pH 6.4 in $CaCl_2$, 0-12 cm)

Calcic, Mottled-Subnatric, Red Sodosol soil (Isbell 1996) in north east Victoria. Climatic data was sourced from the SILO database (http://www.bom.gov.au/SILO) for the Peechelba East (146°27'E, 36°17'S) weather station, located approximately 7 km south of the field experiment reported in Harris *et al*. (2008).

In our study APSIM was configured to perform two simulations; wheat grown in monoculture (cereal monoculture), and wheat and lucerne grown together (companion crop). Both the cereal monoculture and companion crop simulations received N fertiliser at 0, 30, 60 or 90 kg N/ha, top-dressed at both 40 and 80 days after sowing. Additional companion crop simulations were performed, where each combination of rate and timing of N application received simulated +/0 pre-crop lucerne growth suppression and +/0 in-crop lucerne growth suppression. The long-term simulations of cereal biomass and grain yield in response to agronomic strategies (lucerne suppression, N rate and N timing) were then used to identify the optimally performing cereal monoculture and companion crop simulations for valid comparisons of both systems.

Model parameterisation

Long-term simulations using APSIM5.3 were set up using the same modules as described in Chapter 5 for the cereal monoculture and companion cropping systems. Model parameterisation remained the same as detailed by Chapter 5, except that sowing of cereal crops with fertiliser N, and pre-crop lucerne suppression were performed when cumulative rainfall was >15mm over a 10 day period between 15 April and 7 July. The wheat cultivar Diamondbird was sown in all years of the cereal monoculture and companion crop simulations, at a plant density of 170, plants/m^2. Top-dressed N was applied as “urea_N” at the corresponding rates (30N, 60N and 90N) and 40 and 80 days after sowing. Chapter 5 provides details regarding model parameterisation for pre-crop lucerne suppression. In-crop lucerne suppression was imposed by setting lucerne radiation use efficiency to 0 for 28 days on 31 August, to emulate the suppressed lucerne growth over spring in the companion crop system.

All simulations commenced on 1 August 1955 shortly before establishing lucerne cv. Kaituna, at 150, stems/m^2 in the companion crop simulation. A fallow period was simulated in the cereal monoculture before crops were sown in the autumn of 1956 in both the cereal monoculture and companion crop simulations. All simulations ended on 31 December 2007. Resetting soil mineral (NO_3^- and NH_4^+) N (Table 1) in all simulations was carried out every 2nd year on 25 April for all simulations, to maintain soil N at levels observed in the corresponding Harris *et al*. (2008) field experiment.

Table 1. Nitrate and ammonium concentrations for which autumn soil mineral N were reset every two years.

Depth (m)	NO_3^- (kg/ha)	NH_4^+ (kg/ha)
0-0.1	30	10
0.1-0.3	8	4
0.3-0.5	3	2.5
0.5-0.7	2	1
0.7-0.9	1	1
0.9-1.1	0.5	1
1.1-1.3	0.5	1
Total	45	20.5

Both the cereal monoculture and companion cropping systems had simulated grazing over the summer periods on 15 January, 1 March, 15 April and 11 December. Both systems were grazed to a height of 20 mm, and 70% of plant biomass was removed at each grazing. In addition, surface residues were also grazed to emulate some cereal stubble breakdown resulting from grazing livestock.

Results

Long-term performance of companion cropping in comparison with cereal monoculture

In 100% of years, the companion cereal crop produced less biomass than the cereal monoculture (Figure 1a); with an estimated long-term mean difference of 3799 kg DM/ha (± 247 s.e.m). Simulated grain yield data showed a similar trend (Figure 1b), with the estimated long-term mean yield difference between the companion crop and the cereal monoculture was 1489 kg/ha (± 84 s.e.m).

Simulated plant available water at sowing of the cereal crop (Z00), was always lower under companion cropping, compared with cereal grown in monoculture (Figure 1c). Long-term simulations showed that on average the cereal monoculture had an extra 81 mm (± 2 s.e.m) of plant available water at sowing, followed by diminishing difference in plant available water over the growing season, but that the soil remained largely drier under companion cropping (Figure 1d, 1e and 1f).

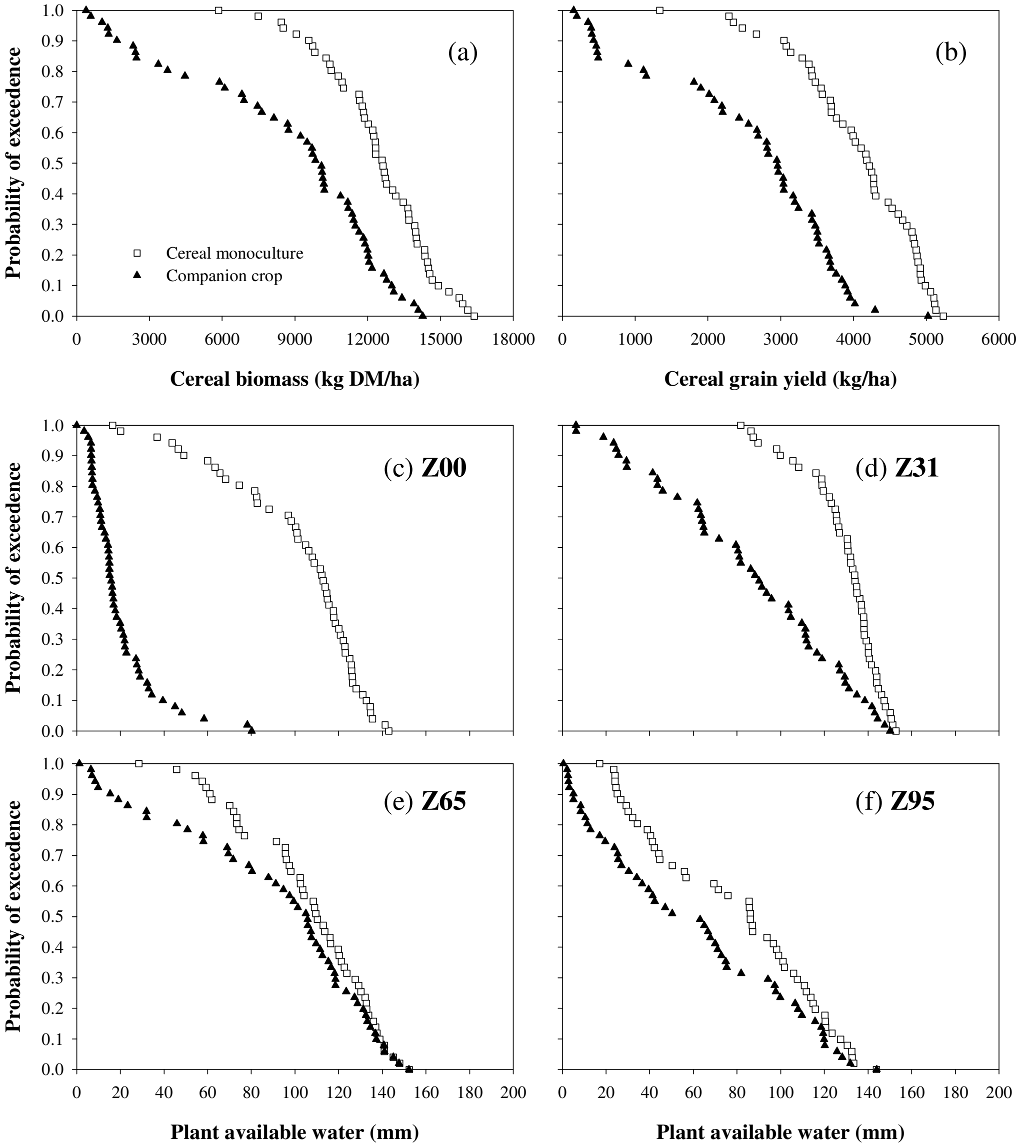

Fig 1. Simulated long-term (1956-2007) cereal biomass (a) and cereal grain yield (b) for cereal grown with and without lucerne, and the long-term effect of the cereal monoculture and companion cropping treatments on plant available water in the 0.1 to 1.1 m soil layer at cereal crop sowing (c, Z00) cereal first node (d, Z31) cereal anthesis (e, Z65) and cereal maturity (f, Z95). Both the cereal monoculture and companion crop systems received 60 kg N/ha at 40 Das. The companion crop system received pre-crop lucerne suppression.

Long-term simulations of water stress constraining cereal photosynthesis, showed the companion cereal experienced greater stress throughout the growing season, particularly early under both low (0N) and high (60N) N inputs (Figure 2a and 2b). However, water stress declined by mid winter, as rainfall replenished the soil profile and evaporative demand declined. In comparison, estimates of water stress constraining cereal photosynthesis in the monoculture, was not apparent until August (high N) or September (low N). While estimations of N stress constraining cereal photosynthesis showed a large decline under high compared with low N inputs, for both cereals growing with and without lucerne, the trends in simulated N stress were largely identical (Figure 2c and 2d).

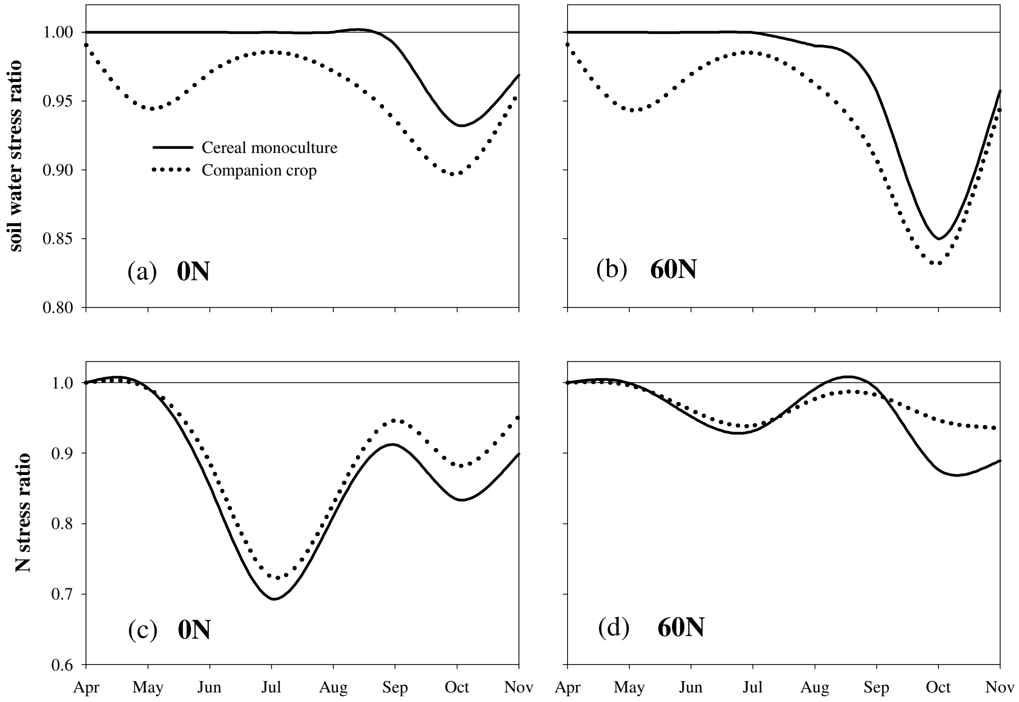

Fig 2. Simulated long-term (1956-2007) simulations of mean monthly wheat water (a and b) and N stress (c and d) factors for photosynthesis in cereals growing with and without lucerne over the growing season under 0N (a and c) and 60N (d and d) inputs. 1 indicates no stress, 0 complete stress. Soil water stress ratio is calculated by dividing actual soil water supply by the potential soil water supply. N stress ratio is calculated for the stover (stem and leaf) by (actual N concentration of the stover – minimum N concentration required by the stover) / (critical N concentration required by the stover – minimum N concentration required by the stover). The cereal monoculture and companion crop systems receiving 60N was applied at 40 Das. Both the high and low N input companion crop systems received pre-crop lucerne suppression.

Long-term simulations of cereal biomass and grain yield showed substantial response from applying N fertiliser to cereals growing in monoculture (Figure 3a and 3b). Applying an additional 30 kg N/ha, resulted in a long-term mean increase in cereal biomass of 2739 kg DM/ha (± 120 s.e.m) and grain yield of 1050 kg/ha (± 28 s.e.m) compared with no top-dressed N in the cereal monoculture. Simulated cereal biomass production from an extra 60 and 90 kg N/ha were almost identical, but grain yields showed a greater difference, with a long-term mean increase of 1825 kg/ha (± 46 s.e.m) and 2345 kg/ha (± 63 s.e.m), respectively, compared with no top-dressed N in the cereal monoculture.

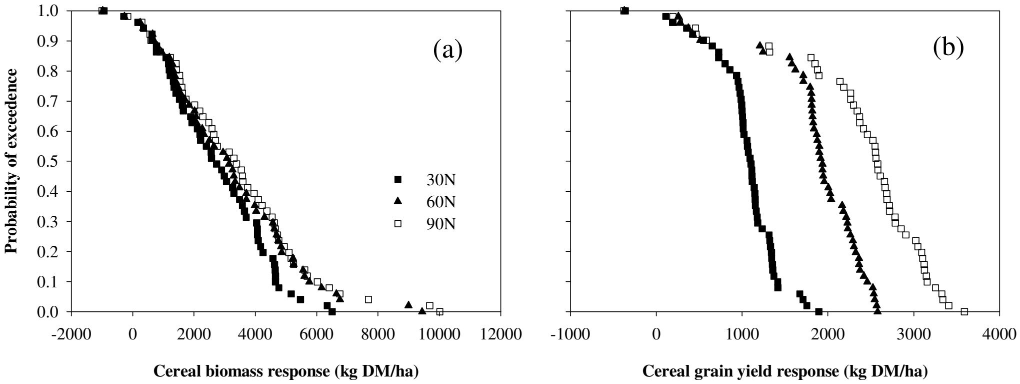

Fig 3. Simulated long-term (1956-2007) yield differences between 0N and different rates of additional top-dressed N in cereal biomass (a) and grain yield (b). Mean of all timings of N application.

The difference between simulated cereal productivity growing with and without lucerne was greater under less favourable growing season conditions (Figure 4). Under low rainfall conditions (Decile 1 to 3, 145 – 298 mm of GSR) long-term mean cereal biomass was reduced by 4935 kg DM/ha (± 252 s.e.m) and grain yield by 1860 kg/ha (± 67 s.e.m) in the companion crop compared with the cereal monoculture. Under favourable growing season conditions (decile >3, >298 mm of GSR) the differences in production were lower, as the companion crop produced on average 2017 kg DM/ha (± 277 s.e.m) less cereal biomass, and 932 kg/ha (± 68 s.e.m) less grain yield than the cereal monoculture.

Long-term response of companion cropping to lucerne suppression

There was no consistent trend in summer lucerne production in response to pre-crop lucerne suppression (Figure 5a), with a long-term mean difference of 23 kg DM/ha (± 18 s.e.m) between +/0 pre-crop lucerne suppression. However, there was a 90% probability that pre-crop lucerne suppression would reduce annual lucerne biomass production, with a long-term mean reduction of 1754 kg DM/ha (± 124 s.e.m) compared with no pre-crop lucerne suppression (Figure 5b). Suppressing lucerne at sowing resulted in greater simulated companion cereal productivity; with a greater than 96% probability of achieving extra cereal biomass and grain yield (Figure 5c and 5d). Simulated yields of cereals growing with pre-crop suppressed lucerne, estimated a long-term mean increase of 4585 kg of cereal DM/ha (± 237 s.e.m) and 1275 kg of grain yield/ha (± 70 s.e.m), compared with cereal growing without suppression.

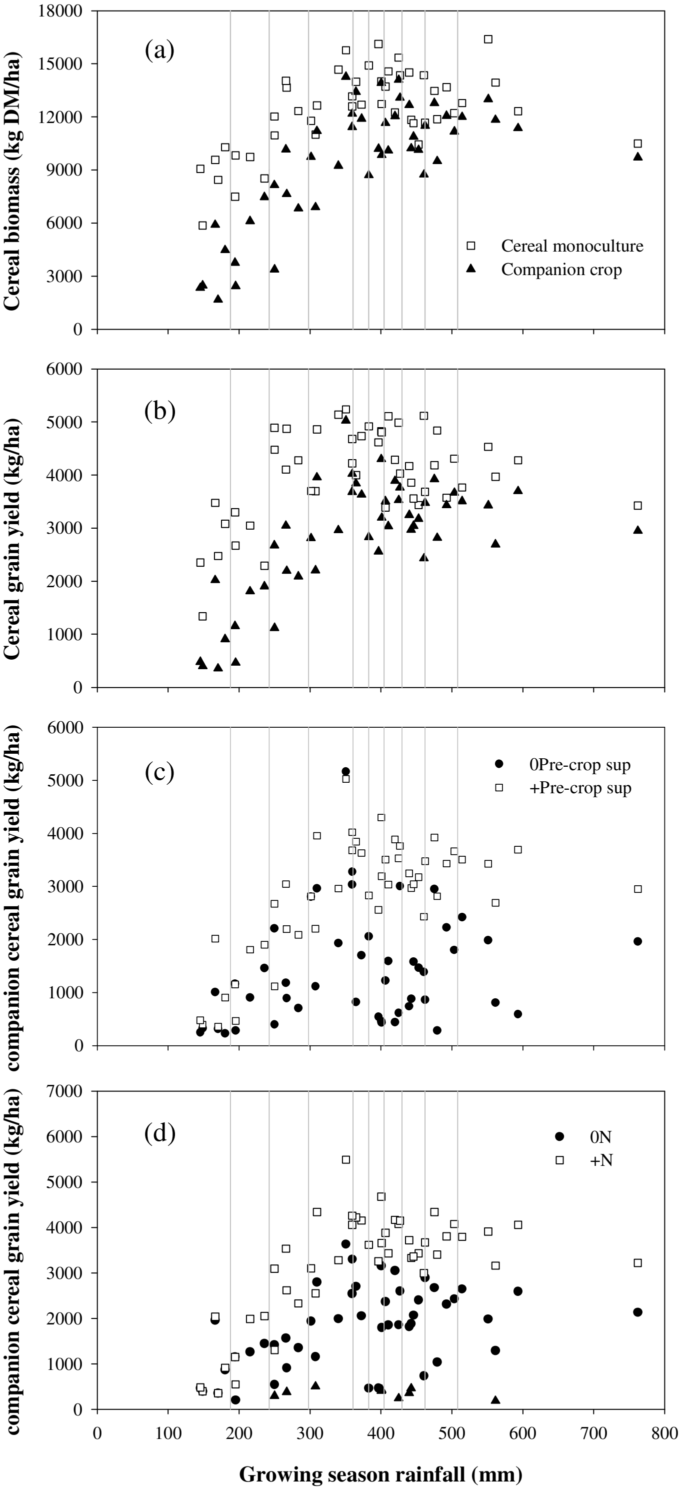

Fig 4. Simulated long-term (1956-2007) cereal biomass production (a) and grain yield (b) growing with and without lucerne; and companion cereal grain yield in the presence and absence of pre-crop lucerne suppression (c) with (mean of all rates of N) and without top-dressed N (d) in response to different quantities of GSR. Both the cereal monoculture and companion crop systems in graphs (a and b) received 60N at 40 Das. The companion crop system in graphs (a and b) also received pre-crop lucerne suppression. Vertical lines represent the boundary for each GSR decile.

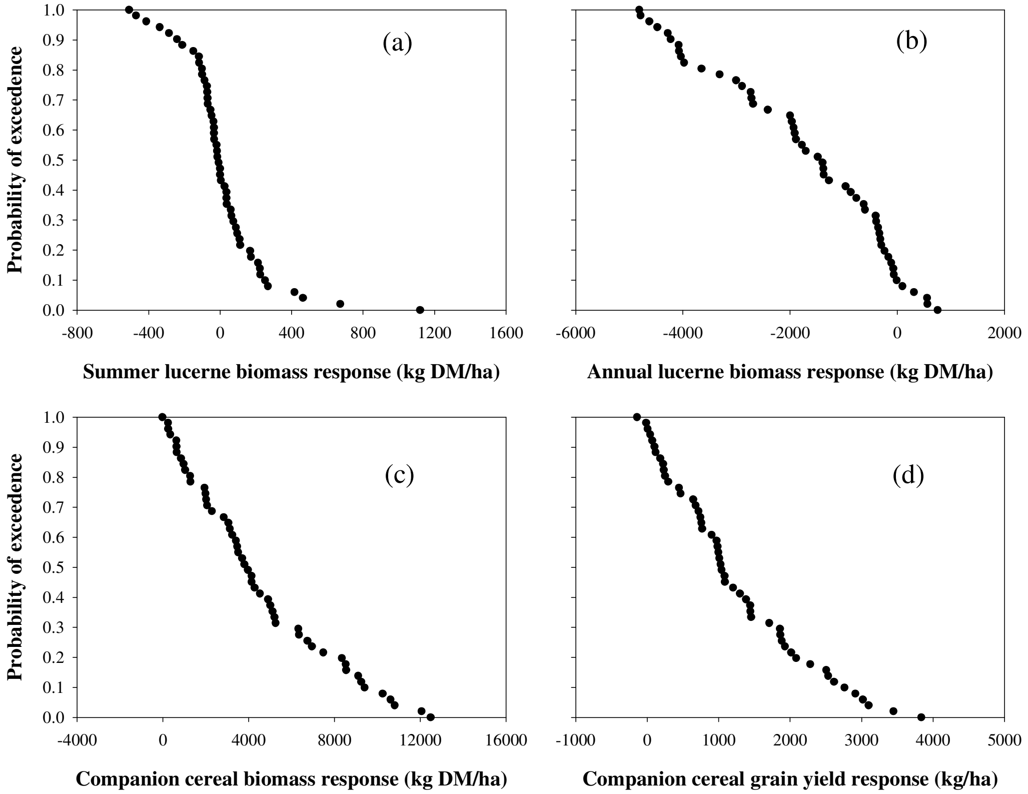

Fig 5. Simulated long-term (1956-2007) yield differences between 0/+ pre-crop lucerne suppression in summer (a) and annual (b) lucerne biomass, companion cereal biomass at maturity (c) and grain yield (d). Mean of all rates and timings of N application.

Averaged over 12 months, lucerne green cover percentage was 12% higher (Figure 6a) and cereal green cover percentage was 12% lower (Figure 6b) in cereals growing with unsuppressed lucerne, compared with cereals growing with pre-crop suppressed lucerne.

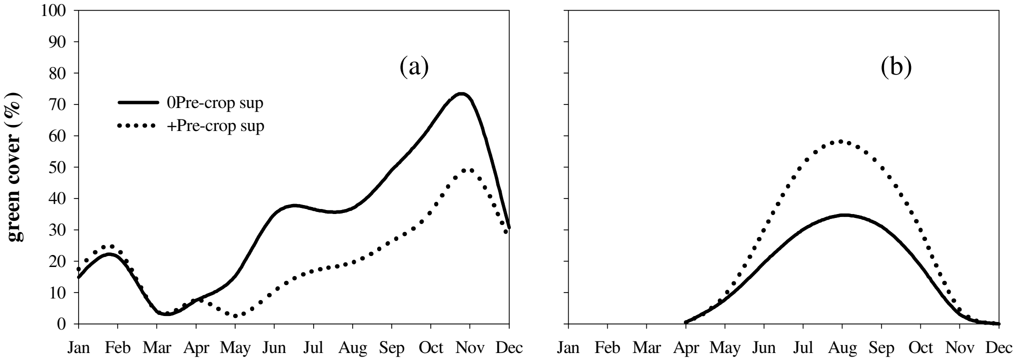

Fig 6. Long-term mean simulated monthly green cover percentage for lucerne (a) and cereal (b) growing with unsuppressed lucerne (solid line), and pre-crop suppressed lucerne (dotted line). Mean of all timings and rates of N fertiliser.

Simulated in-crop lucerne suppression had no affect on summer lucerne biomass and companion cereal productivity (Table 2). However, in-crop lucerne suppression reduced the estimated long-term annual lucerne biomass by 417 kg DM/ha (± 36 s.e.m) compared with cereals growing without in-crop lucerne suppression. There were also no differences in the rates and timings of N applications in combination with +/0 in-crop lucerne suppression (data not shown).

Table 2. Mean yield differences from long-term simulations (1955-2007) of summer and annual lucerne biomass, companion cereal biomass at maturity and grain yields from pre-crop lucerne suppression, and timing and rate of N application.

Treatment Structure	Suppression	N timing	N rate kg/ha	Summer[#] lucerne biomass kg DM/ha	Annual lucerne biomass kg DM/ha	Companion cereal biomass kg DM/ha	Companion cereal grain yield kg/ha
Suppression	In-crop*			-4	-417	26	-108
	Pre-crop			23	-1754	4585	1275
N timing				1	-120	499	79
N rate			30	-35	-315	1176	500
			60	-48	-364	1365	790
			90	-55	-386	1439	918
Suppression x N timing	0Pre-crop			-7	-82	231	61
	+Pre-crop			8	-159	767	96
Suppression x N rate	0Pre-crop		30	-22	-155	443	236
			60	-21	-146	414	269
			90	-25	-151	417	277
	+Pre-crop		30	-48	-474	1909	764
			60	-75	-582	2317	1311
			90	-85	-621	2461	1560
N timing x N rate		Early	30	-33	-404	1527	512
			60	-48	-444	1711	855
			90	-55	-457	1741	999
		Late	30	-37	-225	825	488
			60	-48	-283	1020	725
			90	-54	-315	1137	837

*mean of all combinations of timing and rate of N applications, [#]lucerne biomass production during the period between companion crops

Long-term response of companion cropping to different rates and timing of N application

Simulated summer lucerne productivity appeared unaffected by fertiliser N application, while there was a slight decline (<386 kg DM/ha) in the long-term mean annual lucerne biomass production (Table 2). Conversely, top-dressing with 30 kg N/ha resulted in a long-term mean increase of 1176 kg DM/ha (± 85 s.e.m) of companion cereal biomass; incremental gains in cereal biomass were smaller at higher rates of N, with estimated long-term mean increases of 1365 kg DM/ha (± 113 s.e.m) and 1439 kg DM/ha (± 122 s.e.m) for 60 and 90 kg N/ha respectively, compared with no top-dressed N (Table 2). Companion grain yields followed a similar trend to the companion cereal biomass, with a long-term mean increase of 500 kg/ha (± 24 s.e.m) of grain from the application of 30 kg N/ha, with smaller incremental gains of 790 kg/ha (± 80 s.e.m) and 918 kg/ha (± 49 s.e.m) of grain from 60 and 90 kg N/ha respectively, compared with no top-dressed N. The timing of N application appeared to have little effect on both simulated lucerne productivity and companion cereal grain productivity. However, the earlier application of N resulted in an estimated long-term mean increase of 499 kg DM/ha (± 54 s.e.m) of companion cereal biomass (Table 2). Furthermore, the different rates of N fertiliser were more responsive in terms of cereal biomass production, when applied early (40Das) rather than late (80Das).

Long-term effect of GSR on agronomic strategies for mitigating competition

Simulated pre-crop lucerne suppression and top-dressed N, resulted in a more pronounced relationship between GSR and companion cereal grain yield (Figure 4c and 4d). Although, the relationship tended to plateau once GSR exceeded 350 mm. The simulations suggest that increased companion cereal productivity from pre-crop lucerne suppression began to appear, once GSR exceeded 215 mm (within the 2nd decile of GSR) and increased companion cereal productivity from top-dressed N at 242 mm (decile ≥ 3 mm of GSR).

Interaction between pre-crop lucerne suppression and N application

In the absence and presence of pre-crop lucerne suppression, there was no apparent difference between early (40Das) and late (80Das) applications of N for all measures of lucerne and companion cereal grain productivity. However, cereals growing with pre-crop suppressed lucerne produced a higher cereal biomass response from the early application of N (Table 2).

No response to the application of N was apparent in the simulated summer lucerne biomass, either in the presence or absence of pre-crop lucerne suppression (Figure 7a and 7c). Annual lucerne productivity was slightly greater in the absence of pre-crop lucerne suppression, but there was no effect from the application of N (Figure 7b). Conversely under simulated pre-crop lucerne suppression there was a trend towards lower annual lucerne biomass from increasing inputs of N (Figure 6d and Table 2).

Companion cereals were more responsive to fertiliser N when lucerne growth was suppressed at sowing. Without suppression, improvements in companion cereal productivity were only found under higher GSR (decile ≥6, ≥383 mm of GSR), and no improvements in productivity were estimated beyond 30 kg N/ha (Figure 7e and 7f). In comparison simulated companion cereals growing with pre-crop suppressed lucerne had a 80% probability of achieving extra cereal biomass and grain yield from the addition of N fertiliser (Figure 7g and 7h). Top-dressing an additional 30 kg N/ha resulted in an estimated long-term mean increase of 1909 kg of cereal DM/ha (± 129 s.e.m) and 764 kg of grain/ha (± 33 s.e.m), compared with no top-dressed N. While the addition of 60 kg N/ha resulted in an estimated long-term mean increase of 2317 kg of cereal DM/ha (± 161 s.e.m) and 1311 kg of grain/ha (± 60 s.e.m), and for 90 kg N/ha, an extra 2461 kg cereal DM/ha (± 176 s.e.m) and 1560 kg/ha of grain (± 77 s.e.m) compared with no top-dressed N.

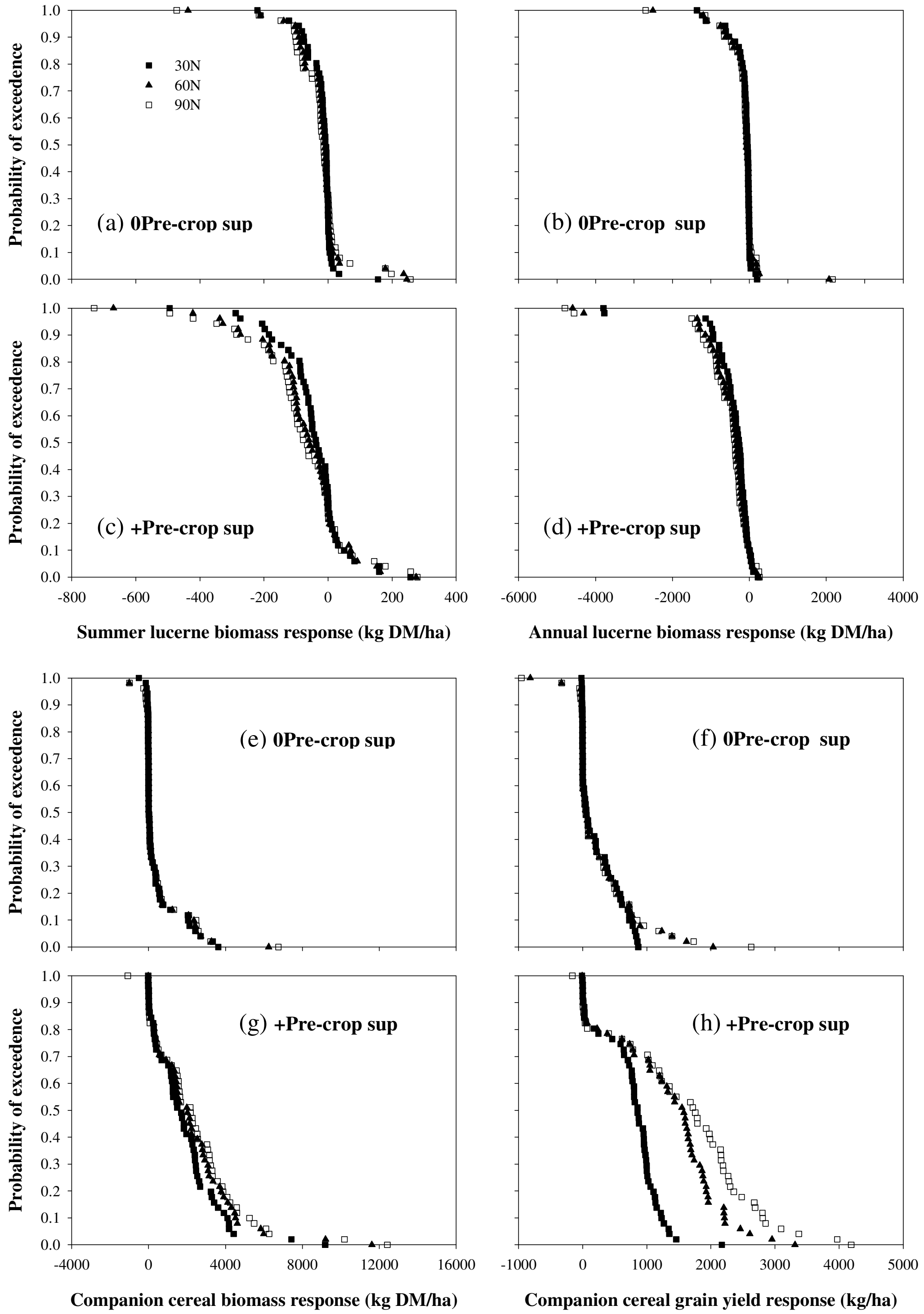

Fig 7. Simulated long-term (1956-2007) yield differences between 0N and different rates of additional top-dressed N in summer (a and c) and annual (b and d) lucerne biomass, companion cereal biomass at maturity (e and g) and grain yield (f and h) in the absence (a, b, e and f) and presence (c, d, g and h) of lucerne suppression at sowing of the companion crop.

Discussion

Why are the yields of companion cereals lower than cereal grown in monoculture?

Many studies have reported reductions in companion crop productivity in the presence of lucerne, compared with cereal grown in monoculture (Egan and Ransom 1996; Humphries *et al*. 2004; Harris *et al*. 2007b; Harris *et al*. 2008). Companion crop productivity is compromised early in the growing season prior to stem elongation (Humphries *et al*. 2004; Harris *et al*. 2007a; Harris *et al*. 2008). Harris *et al*. (2008) showed that cereals growing with lucerne produced fewer tillers and consequently cereal biomass compared with cereals grown in monoculture. They speculated that competition for N and light prior to cereal stem elongation were likely causes, producing evidence of a greater combined demand for N, compared with cereal grown in monoculture. Evidence presented in this paper show that lucerne consumes most of the plant available soil water over the preceding summer; reducing soil water supply to the companion cereal early in the growing season. Long-term trends in estimated water stress constraining cereal photosynthesis from April to July, prior to cereal stem elongation, would suggest that supply of soil water largely drives competition. Many studies have shown a link between early vigorous cereal growth and greater subsequent grain yield (Acevedo and Ceccarelli 1987; Turner and Nicolas 1987; Palta and Fillery 1995). The magnitude of grain yield reduction from companion cropping appears strongly influenced by the amount of in-crop rainfall, in combination with agronomic strategies that facilitate optimal companion cereal productivity.

The long-term simulations cast doubt about whether competition for N was a major contributing factor as suggested in the Harris *et al*. (2008) study. Comparison of long-term estimates of cereal N stress between the companion cereal and cereal monoculture, suggest that N response in the companion crop was more a reflection of low N status at the site, rather than necessarily a greater demand for N by cereals growing with lucerne. This conclusion may be construed as a product of model parameterisation with resetting of autumn soil mineral N to the same value every second year, under both the cereal monoculture and companion crop systems. However, the long-term simulated data and the Harris *et al*. (2008) field study measured the same magnitude of cereal response to top-dressed N irrespective of whether cereals were growing with or without lucerne. While the Harris *et al*. (2008) study may have shown greater demand for N early in the growing season, without any direct measure of lucerne N fixation, there may not have actually been greater combined demand for soil N by the companion cereal and lucerne. Furthermore, the Harris *et al*. (2008) field study did not measure soil water in the top 0-10 cm layer, which should have been considered before dismissing competition for soil water.

In the absence of pre-crop lucerne suppression, competition for light early in the growing can be a contributing factor in determining the companion cereals dominance, over the lucerne component. Simulations indicated that much of the potential benefits of N application for improving companion cereal performance were negated if the lucerne canopy achieved height dominance over the companion cereal canopy.

Authors are unaware of any field studies quantifying the effect of pre-crop lucerne suppression on associated annual winter crops. However, some parallels exist with the Eberlein *et al*. (1992) study, which reported that irrigation applied to corn growing with suppressed lucerne yielded as much, as corn grown in monoculture; but where suppression was not applied to lucerne, corn yield was reduced by 63% where irrigation was applied, and 96% in the absence of irrigation. Although the Eberlein *et al*. (1992) study does not provide an explanation of why the corn yield in the irrigated non-suppressed lucerne was penalised, when presumably there was adequate available moisture, their light interception data indicates competition for light, may have been a contributing factor.

Defining the circumstances under which lucerne suppression and N fertiliser can mitigate competition

The data presented in this paper supports the hypothesis of Angus *et al*. (2000) who suggested that additional N in wet cropping environments could improve companion crop performance. However, long-term simulations show that without pre-crop lucerne suppression and N fertiliser, the companion crop was unable to efficiently utilise, in-crop rainfall. Strategies that allow the companion crop to maintain canopy height and light dominance over lucerne will lead to greater subsequent resource capture and crop growth.

Simulation data suggest that the responsiveness of companion cereals to the application of N will depend on pre-crop lucerne suppression and in-crop rainfall. However, we acknowledge that soil N levels are likely to impact on cereal responses to fertiliser N, and that the regular resetting of autumn soil N in this study does not allow us to explore the longer-term effects of changes in soil N on companion cereal yield. Therefore within the levels of soil N, under which simulation were conducted in this study, responses in companion cereal yield from N application became apparent around the beginning of the 3rd decile of GSR for the North Boorhaman site. This finding highlights the potential for simulation modelling used in conjunction with long-term weather forecasts, as a risk management tool for estimating the outcome of N applied to companion crops.

Despite GSR having a substantial influence over the success of pre-crop lucerne suppression and N fertiliser for enhancing companion cereal yield, other management decisions could also play an important role in reducing the risk of failed companion crops. In our simulations we assumed companion cropping was performed in all years, but interviews with farmers practising companion cropping showed this is unlikely in reality (Harris *et al*. 2003). Evidence of low plant available water at sowing restricting companion crop yields have been reported here, raising the possibility that seasons characterised by early and large quantities of opening autumn rainfall could recharge depleted soil profiles before sowing and reduce early yield losses under companion cropping. Benchmarking the minimum level of plant available water at sowing to produce acceptable yielding companion crops across a range of soil types through simulation modelling, may provide a useful guide in deciding when to companion crop.

The impact on lucerne, from agronomic intervention aimed at improving companion cereal yield, has not been widely reported. Long-term simulated data presented in our study, suggest that strategies aimed at reducing the competitive advantage of lucerne, particularly pre-crop suppression, will lead to a production trade off. In other words, greater companion cereal yields, at the expense of annual lucerne production. Interestingly, APSIM simulations showed that any improvement in companion cereal yield leading to depressed lucerne yield and therefore less subsoil (<1.1 m) water use during the growing season (April-October), resulted in more ‘spared’ subsoil moisture available for lucerne growth over the subsequent summer.

Harris *et al*. (2007a) showed no significant improvement in companion cereal yield from in-crop lucerne suppression applied in late winter, but did report that in some season’s, grain quality was enhanced by reducing lucerne pod and flower contamination of the grain sample. Furthermore anecdotal information based on interviews of farmers practising companion cropping with lucerne; suggest that the primary reason for undertaking the practice is for improved grain quality (Harris *et al*. 2003). Long-term simulated data presented in our study, provides further evidence that in-crop lucerne suppression is unlikely to produce higher grain yielding cereal crops in the presence of lucerne.

Conclusion

Competition between the companion cereal and lucerne appears largely driven by the availability of stored soil water around sowing of the companion crop. Long-term simulations showed consistently less stored soil water at sowing under companion cropping, compared with cereals grown in monoculture. Therefore the severity of competition between the companion cereal and lucerne appears strongly influenced by the quantity of in-crop rainfall. Thus companion cropping would not be suitable in environments where crop yield relies on stored soil water. The combination of pre-crop lucerne suppression and N fertiliser can improve companion crop performance, but the success of these strategies will largely depend on the amount of in-crop rainfall (decile ≥3 GSR). Our long-term simulations showed that improvements in companion cereal performance resulted in a decline in annual lucerne production, particularly from pre-crop lucerne suppression.

Acknowledgements

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Chapter 7. Overarching Discussion

The replacement of native vegetation with annual crops and pastures has reduced total annual transpiration, resulting in greater leakage of water into the surrounding landscape and associated environmental problems, such as dryland salinity in southern Australia (Dunin *et al*. 2001). The perennial forage legume lucerne (*Medicago sativa*) has shown the most promise for providing greater water use than annual crops or pastures in temperate high rainfall, mixed livestock cropping systems (Crawford and Macfarland 1995; Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001; Ridley *et al*. 2001; Ward *et al.* 2001; McCallum *et al*. 2001; Ward *et al.* 2002).

Despite the many advantages that lucerne can offer to mixed livestock cropping systems, its adoption remains low, accounting for less than 5% of surveyed paddocks across the cropping landscape of north eastern Victoria, in south eastern Australia (Grey 2004). A formula for its successful integration into mixed farming systems needs to be developed to facilitate broader adoption and increased water use. Sowing annual crops into lucerne could provide greater flexibility for the integration of lucerne into mixed livestock cropping systems. But first a broader understanding of the implications of companion cropping on annual crop production is required, before determining the role that companion cropping might play in helping integrate lucerne into mixed farming systems.

Earlier research into lucerne companion cropping has quantified component plant responses to competition, without providing an understanding of the underlying reasons contributing to the observed outcomes. There has been limited attempt to understand what causes yield decline in cereals growing with lucerne; and how agronomic intervention might alter competition for resources, and produce greater annual crop yield in the presence of lucerne; and whether competition from the associated annual crop might compromise lucerne's capacity to dry subsoils and ultimately reduce water leakage below the root zone (Chapter 2).

Answers to these questions will define the role that companion-cropping can play in the integration of lucerne into Australian farming systems.

The North Boorhaman field experiment (Chapter 3) was established to study the effect of resource supply on competition in cereal and lucerne mixtures; and was designed on the findings by Egan and Ransom (1996) who suggested competition for soil water between the companion crop and lucerne at cereal grain filling, was the likely cause of yield reductions in companion crops. However, the data collected from the North Boorhaman experiment clearly showed that competition was apparent early in the growing season when cereal biomass in the presence of lucerne was significantly ($P<0.05$) lower than the biomass production of cereal grown in monoculture. Although there were no differences in cereal establishment compared with cereals grown in monoculture, companion cereals produced significantly ($P<0.05$) less tillers, spikes, biomass, and consequently grain yield. Early competition for water or nitrogen or both appeared likely, but the field based research provided insufficient evidence to rule out either.

The Burraja experiment (Chapter 4) studied the role of agronomic intervention (companion cereal type, in-crop lucerne suppression and N fertiliser) for increasing companion crop yields, but found these strategies had limited effect. Although in 2003 a response to N fertiliser was measured in the cereal biomass, but not in the preceding or subsequent years, highlighting the potential for rainfall and N interactions and a potential value of computerised modelling to explore these interactions further. The Burraja experiment also supported the findings of the North Boorhaman experiment, showing competition adversely impacting on companion cereal production early in the growing season. Early reduction in companion cereal productivity has been found in other parts of Australia; Humphries *et al*. (2004) reported a 50% reduction in companion cereal biomass at the end of winter in Western Australia and South Australia. These observations across a range of environments tend to suggest that the early reduction in companion cereal growth may be quite common. Strategies aimed at mitigating competition between the annual crop and lucerne, are likely to be more effective early in the growing season.

The timing of companion crop yield decline was identical in Chapters 3 and 4, despite the use of a winter dormant lucerne cultivar (cv. Pioneer 54Q53) at North Boorhaman (Chapter 3), and a winter active cultivar (cv. Aquarius) at Burraja (Chapter 4). One would expect that winter active lucerne with greater winter vigour and growth compared with winter dormant lucerne, would provide more competition to a neighbouring cereal crop. However, in reality winter activity in most lucerne varieties appears to have limited effect because irrespective of winter activity, most of the biomass produced by all lucerne types occurs over the spring summer period. Humphries *et al*. (2004) showed no difference in companion crop grain yield in the presence of winter active lucerne compared with winter dormant, with the exception of the highly winter dormant lucerne cultivar Jindera. Unlike the majority of lucerne cultivars, Jindera has been bred for stabilising exposed earth banks and not for grazing purposes, and as a consequence it's dry matter production is typically half that of other commercially available cultivars (Li *et al*. 2010).

The discrepancy between the Egan and Ransom (1996) and the subsequent studies of Humphries *et al*. (2004) and in the journal papers presented in chapters three and four may have been due to the age of the lucerne stands in the respective studies. Egan and Ransom (1996) studied companion crop response from annual crops sown into young (< 1 year old) lucerne stands, compared with the later studies reporting crop productivity largely in the presence of older (2-7 years) stands, with the exception of the first year of the North Boorhaman experiment. Dolling *et al*. (2003) showed lucerne root exploration into the subsoil was much slower in clay soils compared with sandy soils, with roots taking up to two years to reach a depth of 2 m in clay subsoil. Differences in soil types impacting on lucerne root exploration and early growing season rainfall patterns, possibly recharging the profile in the subsequent year of companion cropping, could provide explanations for the different observations of when competition impacts on annual crop productivity in the presence of lucerne.

The literature raised the possibility of allelochemical release from lucerne interfering with the growth and development of neighbouring companion plants (Miller 1983; Chung and Miller 1995). Much of this theory had been drawn from bioassay glasshouse research, where workers were unsure whether the concentrations of allelochemicals were a true representation of field conditions (Waller *et al*. 1993). Given that in this study, there was no compromise in companion crop establishment at both field experimental sites, in any year, allelopathic interactions were not considered a major contributor to the observed decline in cereal productivity prior to cereal stem elongation. Only if future field research can measure lucerne releasing allelochemical concentrations into the soil at levels similar to that studied in the bio-assay work, should further investment be made into exploring this possible mechanism as an inhibitor to companion cereal productivity. Such field research would also need to keep in mind the competition for water, nitrogen and light, all of which could impact on early companion crop establishment and vigour.

Both field experiments were useful in quantifying the temporal consequences of competition between the companion cereal and lucerne components, but difficult to determine what was causing the decline in cereal productivity in the presence of lucerne, compared with cereals growing in monoculture. To investigate these relationships further and under a wider range of seasonal conditions, computerised modelling was considered a logical progression to study competition between the companion cereal and lucerne, in response to resource supply and agronomic intervention, over a longer time frame than the field experiments.

APSIM (Agricultural Production Systems Simulator) has been designed to simulate biophysical processes in farming systems; whilst providing the flexibility to stipulate specific management inputs. To ascertain whether APSIM was sufficiently robust for studying competition, simulated outputs were compared against field observations from the North Boorhaman field experiment (Chapter 5). The validation of APSIM was a prerequisite in determining the suitability of the model, and for identifying any weaknesses in the model, before undertaking any longer-term simulations of lucerne companion cropping. Results from the validation showed that the model could simulate both lucerne and cereal growth, generally in line with field observations provided soil mineral N was constrained within field observations. APSIM was found to exhaust soil mineral N under companion cropping more rapidly than observed in the field data and this may have been due to excessive lucerne N uptake over the summer/autumn period preceding the companion crop planting in the model. The model may benefit from modifications made to the way plant N uptake is calculated, based on changes in leaf area (Lemaire *et al*. 2005) rather than as currently based on potential biomass accumulation. This may improve the accuracy of estimates of lucerne N removal from the soil. The canopy module used in the simulations appeared to sufficiently partition light amongst the component crops to simulate cereal and lucerne production in line with field data, and could be used to simulate other mixed herbaceous plant communities, as more plant modules become available through further development of the APSIM model.

In model simulations using long term climate data (Chapter 6) lucerne used more water over the summer/autumn period, and companion cereals were frequently sown into a drier soil profile, compared with cereals sown after the summer/autumn fallow in monoculture. Furthermore, APSIM predicted cereal photosynthesis stress in response to soil water availability early in the growing season in companion cereals compared with no stress in cereals grown in monoculture for the corresponding period. Therefore a reduction in the supply of soil water early in the growing season appears to be a contributing factor for the reduction in crop productivity prior to cereal stem elongation. Reductions in soil water supply early in the growing season could also reduce crop N uptake.

While competition for soil water was ruled out after the results from the North Boorhaman field experiment reported in chapter three, closer inspection of the soil water data shows a trend toward lower soil water at sowing under companion cropping compared with cereals grown in monoculture. Competition for soil water was possibly overlooked for a number of reasons. Firstly long-term simulations of the cereal monoculture assumed no summer weed invasion, and therefore the only loss of water over the fallow period in the simulations was from soil evaporation. In comparison the cereal monoculture in the corresponding field experiment lost soil water through transpiration from summer weeds and soil evaporation over the fallow period. Therefore the modelling output presented in chapter six probably exaggerates the differences in stored soil water under the respective companion crop and cereal monoculture treatments. In addition the long-term simulations did not consider lucerne stand decline over time, a well documented outcome of aging stands from over grazing (Lodge 1991; Humphries *et al*. 2006) or disease pressure (Irwin 1977). This may have also contributed to the model over-estimating the impact of the associated lucerne growth on the neighbouring companion cereal. Secondly the neutron moisture meter method used in both the Burraja and North Boorhaman field experiments did not measure soil water in the 0-10 cm soil layer. The model outputs presented in chapter six accounts for this soil layer. Future field research investigating competition between the annual crop and lucerne should include changes in topsoil (0-10cm) moisture, after all this is the depth at which the annual crop seed is planted, and where germination, growth and development commences.

Simulation modelling also showed that the productivity of the companion cereal crop, particularly in the presence of pre-crop suppressed lucerne, was largely determined by growing season rainfall. Unlike cereals growing in monoculture, cereals growing with lucerne do not have access to stored soil water at sowing. In the absence of stored soil water, companion crops receiving low in-crop rainfall are likely to have the greatest companion cereal yield reductions.

Indications from the modelling study that companion crop productivity decline is greatest under low growing season rainfall may be supported by other studies. Published declines in companion cereal grain yield from Egan and Ranson (1996), Humphries *et al*. (2004) and the journal papers presented in chapters three and four have been combined to describe the effect of growing season (April – October) rainfall on companion crop performance (Figure 1). These field data, presented in Figure 1, support the findings from the simulation study presented in chapter six. This study can conclude that productivity losses from companion cropping with lucerne are likely to be higher in areas where crop productivity relies on significant proportions of stored soil water; and that companion crop productivity is likely to be higher in winter than summer dominant rainfall environments.

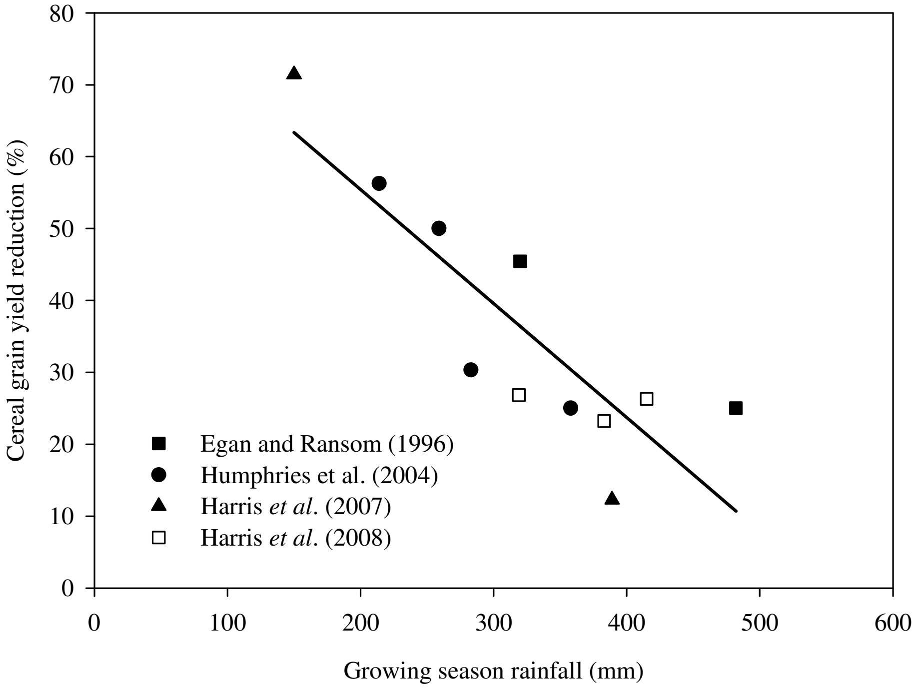

Figure 1. The relationship between cereal grain yield reduction (%) by lucerne and growing season rainfall.

Data from the North Boorhaman field experiment raised the possibility of greater combined demand for soil N from cereal and lucerne growing in mixture, compared with cereal growing in monoculture. However, without measurements of lucerne N fixation it was impossible to ascertain competition for soil N between the cereal and lucerne components. Under the circumstances investigated in both field experiments and within the parameters set for the long-term simulations, both field measured and simulated data largely showed the same relative yield increase from top-dressed N, irrespective of lucerne presence. In addition simulated cereal photosynthesis stress in response to N availability was largely identical in cereals growing with and without lucerne. One might question that there could have been an overall shortage of N causing identical stress in both the monoculture and companion crop systems, but even at the high N input (60N) the N stress remained identical in both the cereal crop growing with and without lucerne (Chapter 6). Therefore in both the field and simulation studies presented in this thesis, competition for N appeared less consequential than competition for soil water in determining the fate of the companion cereal, a consequence of soil drying by lucerne over the preceding summer autumn period. Competition for N can not be entirely ruled out as water stress will also affect companion crop N uptake.

In the absence of specific measurements on lucerne N_2 fixation (Unkovich *et al.* 1994), greater combined (lucerne and cereal) plant demand for N alone is insufficient evidence to conclude that competition for N was impacting on companion crop growth early in the growing season after the completion of the North Boorhaman experiment. One would expect there could be some competition, regardless of N fixation, but the extent could not be determined without N fixation measurements. Experiments specifically designed to quantify lucerne N_2 fixation and soil mineral N uptake by lucerne and the companion crop in comparison with the N uptake of cereals grown in monoculture would be required, to clarify whether competition for soil N is a critical component contributing to competition in cereal and lucerne mixtures. Additional experiments assessing N_2 fixation by lucerne might provide further insight into possible competition for soil N between plant components, but were not possible with the resources available in this study.

Research elsewhere into white clover (*Trifolium repens*) wheat mixes in Denmark concluded that limitations in N supply may have restricted the growth of associated wheat (Thorsted *et al*. 2006). The Thorsted *et al*. (2006) study also speculated that under low N availability white clover could compensate through N_2 fixation, thereafter utilising more resources than its wheat counterpart. While the Denmark work highlights the possibility of competition for N in lucerne wheat mixes, the research was undertaken in a relatively non water limiting environment (mean annual rainfall > 770 mm) and white clover was established only two months prior to seeding wheat. These climatic and agronomic factors limit the parallels that can be drawn, between lucerne companion cropping systems in southern Australia and the white clover wheat mixtures in northern Europe.

Close parallels between lucerne companion cropping systems and other mixed cropping systems in the world are not apparent. Whilst there are many examples of cover cropping with a cereal to establish a pasture, and research studying weed and crop interactions, examples of annual crops growing with established perennials in temperate environments are scant. One example is the ‘Dehesa’ system in Spain and Portugal where scattered evergreen oak (*Quercus*) tree species grow between pastures and annual crops (Joffre *et al*. 1999), proving complementary water use as the oak trees have a higher dependency on deep water reserves throughout the late spring and summer period, largely avoiding competition for water with herbaceous vegetation reliant on winter rainfall (Cubera and Morena, 2007). While lucerne has a similar temporal water use pattern to oak trees, the study reported in this thesis showed less complimentary water use, with extraction of soil water by lucerne having a negative affect within the root zone subsequently occupied by the companion cereal.

Perhaps a contributing factor for the complimentary water use in the "Dehesa" system is the density of oak trees, commonly forty to fifty trees per hectare (Joffre *et al*. 1988), a system of open woodlands that may also contribute to the negligible impact on the neighbouring cereal crop or pasture, and the fact that the trees are quite old might result in net annual tree growth and water use being modest. In comparison, lucerne companion cropping systems expose the companion cereal to greater competition. Lucerne is in much closer proximity to the companion crop and grows vigorously.

Despite companion crop productivity being strongly influenced by the quantity of in-crop rainfall, the long-term simulations demonstrated that agronomic intervention might play an important role in determining the performance of the companion crop. APSIM predicted that pre-crop lucerne suppression might allow the companion cereal time to develop a canopy height advantage over the neighbouring lucerne, facilitating greater light, and subsequent soil water and N capture, and improving companion crop productivity. Field research in the United Kingdom has reported improved cereal production after severe defoliation of white clover, through either heavy gazing, cutting to 2 cm height or chemical suppression before over sowing cereals, in comparison with cereal production after no prior white clover defoliation (Williams and Hayes 1991; Jones 1992; Jones and Clements 1993). Similarly, Eberlein *et al*. (1992) found in field studies in the US, that suppression of lucerne coinciding with the planting of corn (*Zea mays*) significantly increased associated corn production, with their light interception data indicating greater light capture by corn growing with suppressed lucerne compared with unsuppressed lucerne. Interestingly despite corn, a C4 plant, having a significant height advantage over a winter wheat, lucerne suppression still played a critical role in boosting corn production. Although the corn lucerne mix example involves two summer active crops, where lucerne suppression would presumably be of greater benefit compared with a winter crop, the same principles of increased light interception by the annual crop would still apply. Therefore to maximise the competitive advantage of the companion crop, suppression of lucerne at companion crop planting is likely to be an essential management strategy for improving companion crop yield.

Both field data and simulation runs showed no productivity gains in companion cereal from the application of in-crop suppression of lucerne applied at the end of winter. Although grain quality could not be assessed in the APSIM model, in some seasons during the Burraja experiment, in-crop suppression of lucerne delayed lucerne flowering and reduced lucerne pod and flower contamination of the harvested wheat grain. Topsoil moisture also played an important role in increasing the efficacy of the clopyralid herbicide in the field experiment and the effectiveness of this practice to deliver uncontaminated companion cereal grain. However, in-crop suppression applied in 2003 at the Burraja experiment highlighted the potential for killing rather than suppressing some lucerne plants, and the need for developing less detrimental methods of lucerne suppression for improving companion cereal grain quality. Future research could explore other herbicide options such as bromoxynil + diflufenican, which were found to have suppressive effects on lucerne when used at the North Boorhaman field experiment to control broadleaf weeds, without a detrimental impact on lucerne plant density.

In spite of competition for N appearing less consequential than water in this study, both field and simulated data showed that top-dressing fertiliser N under favourable growing season rainfall, could significantly improve the productivity of both cereals growing with and without lucerne. Long-term simulations showed that once growing season rainfall exceeded 242 mm, companion cereal grain yields were likely to respond to top-dressed N. These finding raise the possibility of developing agronomic tools similar to those developed for stand alone cereal crops. For instance, assessment of water use efficiency (French and Schultz 1984) to determine target grain yields and consequent N demand accompanied by estimates of N supply (planting and in-crop N mineralisation) to determine any shortfalls in N availability.

Of course there would be the added complexity of estimating lucerne N demand and how much of that N demand would be supplied through N fixation.

While depressed companion cereal yields are highly probable in companion cropping systems, this study highlighted other potential benefits arising from the practice. For instance, the North Boorhaman experiment reported greater combined (cereal and lucerne) biomass production from companion cropping, compared with cereal and lucerne grown in monocultures. Growing the two plant species together thus resulted in a degree of complementary growth. The companion cereal was more efficient at utilising winter rainfall in comparison with lucerne grown in monoculture; and lucerne growing in the presence of the companion cereal, was more efficient at utilising late spring/summer rainfall compared with cereals grown in monoculture. Whilst increased rainfall utilisation by lucerne over summer, reduced companion cereal productivity, this was potentially balanced by greater quantities of high quality lucerne forage for livestock over some summers. On the whole, companion cropping achieved a more continuous supply of forage, raising the possibility that this practice might be attractive to graziers, especially if a forage companion cereal was planted with lucerne.

Increased total biomass production in lucerne wheat mixes has not been reported elsewhere in the literature, however there are examples of greater biomass production in pea (*Pisum sativum*) barley mixes (Hauggaard-Nielsen 2001) and white clover wheat mixes (Thorsted *et al*. 2006) in comparison to respective cereals grown in monoculture. In white clover wheat mixes, Thorsted *et al*. (2006) suggested that this additional production over the cereal monoculture was achieved through root systems of the respective crops achieving greater combined exploration of the soil, and therefore greater below ground capture of soil resources than wheat sown in monoculture. Perhaps a similar intermingling of lucerne and cereal roots achieving greater soil exploration, may have also contributed to the greater total biomass reported in this study.

Both the Burraja and North Boorhaman field experiments confirmed that lucerne growing in the presence of a companion cereal, could maintain dry subsoils and reduce vertical drainage below the root zone, compared with cereals growing in monoculture. However, unlike at Burraja, companion cropping at North Boorhaman reduced lucernes' capacity to extract deep subsoil water (>1.1 m), compared with lucerne grown in monoculture. The discrepancy between sites may have been due to the age of the lucerne stand when companion cropping was introduced. At Burraja the lucerne stand was four years old and had already dried the subsoil before the introduction of companion cereals. Whilst at North Boorhaman companion cereals were first sown, when the lucerne stand was eight months of age; a time when lucerne roots were still proliferating and the association with the companion cereal appears to have compromised root exploration. Therefore, the timing of the introduction of the companion cereal to the lucerne stand, could impact on the effectiveness of lucerne to dry the subsoil. This finding suggests that to achieve effective drying of the entire soil profile and mitigation of potential salinity threats, companion crops should not be introduced, until lucerne roots have had time to fully develop.

The economic feasibility of companion cropping remains in question given the magnitude of grain yield reductions, particularly under low growing season rainfall. However, focusing solely on reduced grain yields ignores other factors that contribute to the economics of the total companion cropping system; for example, the economic value of grazing lucerne-crop stubbles over the summer. Economic analyses that examines companion cropping at a whole farm level would need to put a value on the quantity and nutritional quality of the summer feed supply, which may vary considerably depending on the summer rainfall, as well as the savings in reduced frequency of lucerne removal and re-establishment costs. The results of the study reported in this thesis could provide a sound platform on which to assess the economic merits of companion cropping systems utilising lucerne and cereals and will be invaluable for establishing the commercial merit of these companion cropping systems in different environments.

Aside from N fertiliser, companion cereal type and lucerne suppression (pre-crop and in-crop) evaluated here, other agronomic strategies for mitigating competition that could be studied include the choice of companion forage species and density, and the spatial arrangement of lucerne and crop. Research into plant density through biophysical and computer crop simulations, could expand on the earlier work of Egan and Ransom (1996) and Latta and Lyons (2006), to explore the relationships between lucerne density, crop yield reductions and profile soil water, to determine if it's possible to utilise low lucerne density stands to minimise grain yield reductions but maintain dry subsoils to combat dryland salinity. Recent technological developments in no-till seeders and global positioning systems create the possibility for innovative combinations of perennial forages and annual crops; including lucerne – crop alleys at a range of scales with potential benefits for both crop and forage production.

Capeweed (*Arctotheca calendula*) and wild radish (*Raphanus raphanistrum L.*) invasion of companion cropping treatments, at both the Burraja and North Boorhaman sites highlighted that herbicide options for broadleaf weed control in cereal/lucerne mixtures are limited. Research aimed at developing herbicides for selective removal of broadleaf weeds from lucerne stands, would be beneficial to the management of companion cropping systems.

This study has demonstrated that pre-crop lucerne suppression and fertiliser inputs have a role in boosting companion crop productivity under favorable growing season conditions. However, grain yield reductions are likely in cereals growing mixtures with lucerne, due to lucerne's extraction of soil water over the preceding summer months creating a drier soil profile at seeding of the companion crop, thus exacerbating competition for soil water.

Conclusion

Integrating lucerne into dryland temperate farming systems does not mean that farmers are locked into growing separate phases of lucerne and annual crops, as this study has shown, there are many benefits arising from sowing annual crops into established lucerne. But the success of grain production from companion cropping will be largely driven by in-crop rainfall, as the availability of stored soil water at sowing appears to play a major role in competition between the companion cereal and lucerne. Data presented from this study suggesting that environments receiving long-term mean growing season (April – October) rainfalls of more than 350 mm, are likely to experience lower grain production penalties (<30%) compared with environments receiving less rainfall. Whilst stored soil moisture is useful in most cropping environments, grain production from companion cropping can be ruled out in environments where winter crops rely largely on stored soil moisture accumulated over the preceding summer months. Under favourable growing season rainfall, agronomic strategies particularly pre-crop lucerne suppression and N fertiliser can play an important role in enhancing the companion cereals capacity to capture resources and fully utilise the available seasonal moisture at the expense of the neighbouring lucerne.

This study has demonstrated the difficulty of maintaining dry subsoils whilst minimising yield reductions in companion cereals grown with lucerne. While the dry subsoils are beneficial for reducing leakage of water below the root zone and the potential associated harmful impacts on the surrounding environment, the dry upper profile (top 1m) can be detrimental to the yield of the companion cereal. The adoption of companion cropping, is likely to be influenced by what landholders consider to be the most important priority; production or minimising the impact of their farming practices on the surrounding environment. When considering production from companion cropping systems, grain yield losses appear inevitable, but one also needs to consider extra summer lucerne production between companion crops. Therefore companion cropping is more likely to appeal to mixed cropping/livestock producers, in winter dominant rainfall regions that receive some significant summer rainfall events, and where landholders are consciences of balancing production with less impact on the surrounding environment.

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