New challenges for lucerne in southern Australian farming systems – Identifying and breeding diverse lucerne germplasm to match these requirements

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Thesis submitted to the University of Adelaide for the degree of Doctor of Philosophy

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Introduction to this thesis

This is a thesis by publication submitted to the University of Adelaide for the degree of Doctor of Philosophy. The thesis consists of an introduction and literature review followed by four journal publications that form a series of research chapters. The final chapter of general discussion draws the research chapters together and provides links to recent advances in the use of lucerne in southern Australian farming systems.

The first chapter is an introduction and literature review with 2 sections; (i) an introduction to the role of lucerne in southern Australian agriculture, and (ii) a published journal paper that identifies constraints to lucerne production and possible breeding strategies that may be employed to overcome these limitations. The research chapters include the characterisation of new germplasm (chapter 2), evaluation of this material across a broad range of environments (chapter 3), and the suitability of the germplasm in two farming systems (i) a pasture monoculture under persistent grazing (chapter 4), and (ii) a mixture of lucerne and wheat for grain and fodder production (chapter 5). The most suitable ideotpyes of lucerne (identified by winter activity and other characteristics) are discussed in relation to recommending lucerne for these new farming systems, and for the development of new lucerne cultivars.

Abstract

Lucerne is a deep-rooted perennial pasture that is promoted to land managers in southern Australia to mitigate the effects of dryland salinity, a problem of national significance caused by the replacement of native trees and shrubs with annual crops and pastures. In recent years, the acceptance of climate change has provided further rationale for increasing the use of perennial legumes in our farming systems. Perennial legumes have a role in offsetting $C0_2$ emissions by sequestering C and N in soil, and provide new, resilient options for future farming in a warmer and more variable climate. This research has focused on evaluating the diverse range of germplasm found in lucerne (*Medicago sativa spp.*) for a range of attributes in order to determine its compatibility with existing and future farming systems in southern Australia.

Regional field evaluation at 8 sites in southern Australia showed that lucerne is a broadly adapted and robust plant. After 3 years, plant density ranged from 2-55 plants / m^2 with differences in persistence attributed to tolerance to a combination of stresses including soil acidity, saline and sodic subsoils, drought conditions and persistent heavy grazing. Highly winter-active lucerne (class 9-10) was confirmed to be the most suitable group for short phase rotations in southern Australia, providing grazing is well managed. This germplasm was less persistent than other winter activity groups, but produces more total herbage yield in environments with winter dominant rainfall patterns. Highly winter-active lucerne has poor persistence under continuous grazing, but this may aid in its removal when used in rotation with crops. Winter-active germplasm (class 6-8) was more grazing tolerant and persistent, making it the

most suitable group for longer phase rotations (>4 years), or where more flexible grazing management practices are required (i.e. 35 days grazing followed by 35 days recovery). Individual grazing tolerant plants from this group were selected and randomly inter-mated to form new breeder's lines in the development of a grazing tolerant cultivar.

For the first time, the high water-use of a farming system involving wheat over-cropped into lucerne is presented. Lucerne over-cropped with wheat used an additional 43-88 mm of water in comparison to continuous wheat at Roseworthy and Katanning respectively. Over-cropping reduced wheat yield by 13-63%, but it can be more efficient in terms of land area to grow lucerne and wheat as a mixture than on separate parcels of land. Very winter-dormant lucerne (class 1-2) appears to be less competitive with winter cereal crops during wheat establishment. It may also be possible to reduce lucerne's competition with wheat at the critical stage of anthesis, with low spring yielding lucerne varieties identified in this research (SA37908). This group of plants provides excellent potential for the development of high water-use farming systems because they are grazing tolerant and persistent, and have summer forage production and sub-soil water extraction rates that are equivalent to winter-active lucerne.

The research has been used to identify the perfect ideotype for lucerne in phase farming and over-cropping systems, which can be used to set targets in future breeding programs. The research also highlights current opportunities for the integration of lucerne into southern Australian farming systems to help curb the spread of dryland salinity and reduce the impact of climate change.

Declaration

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

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Alan Humphries

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- Finally, and most importantly, I would like to thank my wife Julia for her love and patience throughout this study and beyond!

Chapter 1. Introduction and Literature Review

1.1 Introduction

Australian agriculture is entering one its greatest periods of change, with current farming systems under threat from dryland salinity (Pannell and Ewing 2006), rising fertiliser and fuel prices (ABARE 2008), and the promise of an increasingly warm and more variable climate (Gunasekera *et al.* 2008). New, resilient and robust farming systems require development if farmers are to respond successfully to these challenges. The widespread introduction of herbaceous perennial legumes like lucerne have the potential to provide solutions to these problems because they are drought tolerant, water efficient and able to store atmospheric N and C in soil (Chan *et al.* 2001). Importantly they can be readily adopted into a farming system that maintains grain production.

In the year 2000, the National Land and Water Resources Audit (2000) predicted that the current area of 5.7 million hectares of land at risk or affected by dryland salinity would triple by 2050. Dryland salinity is caused by the replacement of native vegetation with annual crops and pastures, which typically use only 40-60% of annual rainfall (Latta *et al.* 2001:2002). The resulting increase in deep drainage and ground-water recharge causes water tables to rise and bring immobilised salt to the soil sur ,face. Lucerne has been shown to mimic the natural water balance processes of endemic vegetation, using 90-99% of annual rainfall (Cocks 2001; Ward *et al.* 2003) and in doing so is able to curb the spread of dryland salinity.

A spike in the world oil price has seen the cost of N fertiliser soar due to the high-energy demands of its production. Legumes are likely to be increasingly used in cropping rotations to provide biologically fixed atmospheric N to following cereal crops. With lucerne typically able to fix 100 kg/ha of N, the future expansion of this pasture can reduce the 1 M t of industrial N fertiliser used in Australia each year (ABARE 2008) by as much as 30% (based on 25 kg shoot N per tonne dry matter produced, Peoples *et al.* 2001). This reduction in fertiliser use would have a positive influence on climate change by reducing $C0_2$ emissions associated with its production (estimated to be 2 Mt/year) and N_20 emissions that occur from fertiliser application (from Jensen and Hauggaard-Nielson 2003).

The principal method for tackling climate change under consideration is to increase soil organic C (Lal 2004) and N (Gregorich *et al.* 2005) as a way of sequestering greenhouse gases from the atmosphere. In particular, an increased use of perennials in farming systems are being suggested (Giuffre *et al.* 2003; Newton *et al.* 2006; Paustian *et al.* 2000; Su 2007; Zhou *et al.* 2007)). Crop rotation studies in Australia have shown that lucerne produces greater increases in soil C compared to annual medic pastures (Chan *et al.* 2001; Whitbread *et al.* 2000), and that these increases have been shown to last at least 3 to 5 years when grown in rotation with annual crops (Chan *et al.* 2001; Holford 1990). Lucerne is the most drought tolerant and productive (Li *et al.* 2008; Lolicato and Rogers 1997) perennial pasture used in Australia, and therefore delivers the greatest potential to sequester C during the on-set of climate change.

1.2 Lucerne in Australian Farming Systems

Lucerne is currently grown across 3.5 million hectares in Australia, across a wide range of environments from the sub-tropics in Queensland, to Mediterranean environments in southern Australia and the cool temperate climate of southern Victoria and Tasmania. Lucerne is grown as a dryland or irrigated pasture for sheep and cattle grazing, and also for fodder conservation (hay and silage production). Dryland lucerne is used in a variety of farming systems; as permanent pasture, or in shorter phases in rotation with cereal crops. A new farming system involves over-sowing lucerne with cereals for grain or fodder production (over-cropping or inter-cropping). A range of varieties are available differing in their level of winter activity (winter production) for use in these farming systems.

Winter activity

Winter activity is a rating system used to class lucerne into groups based on their level of winter production. It is the single most definable and distinguishing feature of a lucerne population. The scale is expressed in a range from 1 to 11, with 1 referring to low winter production and 11 high (Figure 1). Winter activity is measured by comparing the heights of different varieties 4-6 weeks after defoliation in the period of autumn through winter. The height in cm can then be converted to a winter activity class using the previously defined values for control varieties. The method has been modified from the North American system of fall dormancy, where class refers to the height of the plant in inches after 4-5 weeks of growth in autumn (Teuber *et al.* 1998).

In southern Australia, dry soil conditions generally restrict this measurement to late winter, when moisture is not limiting growth.

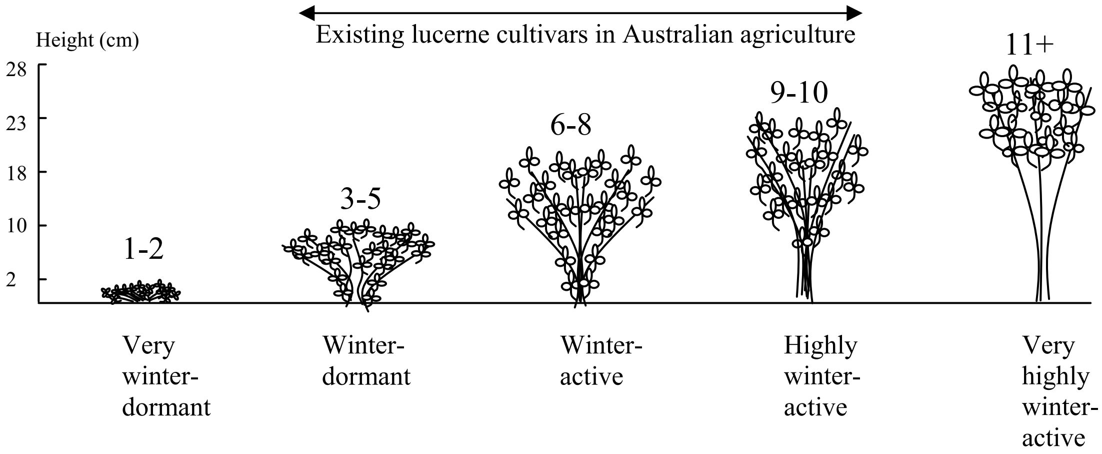

Figure 1. The measurement of winter activity in lucerne, using the height of the plant and expressed on a scale of 1-11. The diagram also indicates changes in habit, and a generalised view of the leaf size and position of leaves in different winter activity classes.

The range of winter activity in current Australian cultivars is between 3 and 10, with winter-active (class 6-8) and highly winter-active (class 9-10) classes most commonly used in the low-medium rainfall zone. There is a large amount of genetic diversity in very winter-dormant lucerne (class 1-2), and this germplasm may be a source of variation for improving lucernes' persistence, or tolerance to grazing, soil acidity and salinity.

Very winter-dormant germplasm may be less competitive in mixtures than winter-active lucerne, potentially making it more suitable for mixtures with winter crops or forages. The value of the very winter-dormant lucerne in a mixture will depend on its contribution to summer production, water-use and nitrogen fixation.

At the other end of the scale, very highly winter-active lucernes (class 11) may increase forage production in low rainfall environments with winter dominant rainfall. Hence, this research project is interested in a diverse range of lucerne germplasm representing the complete spectrum of winter activity to determine the most suitable classes for new and existing farming systems.

Phase Farming: the benefits of lucerne to cropping rotations

Phase farming refers to a rotation where lucerne is grown for 3-5 years followed by a sequence of cereal crops for mixed grain and livestock production enterprise. Lucerne is grown as a high value pasture with greater production than a self-regenerating annual pasture resulting in improved livestock weight gains, increased N fixation, and enhanced weed management.

Lucerne has a long growing season due to its deep taproot, which can access water beyond the root-zone of an annual plant. It also responds quickly to summer rainfall, producing valuable out-of-season forage. Total forage production from lucerne is equal or greater than annual pasture, ranging from 1-2t per 100 mm of rainfall depending on the seasonal distribution of rain (Boschma *et al.* 2008; Latta *et al.* 2002; Ward *et al.* 2003). The availability of a high quality feed over summer is responsible for increases in livestock production in comparison to sub-clover (Egan and Ransom 1996). Production increases are between 10-30% for live-weight gains in cattle (Christian and Shaw 1952; Wolfe 1980) and live-weight and wool production in sheep ((Fitzgerald 1979; Reed *et al.* 1972; Reeve and Sharkey 1980); (Crawford and Macfarlane 1995). The greatest increases in production from lucerne have been realised following increases in stocking rate (Crawford and Macfarlane 1995; Egan and Ransom 1996), or in years with winter drought followed by high summer rainfall (Wolfe 1980). Seasons with high summer rainfall are also responsible for groundwater recharge under annual crops and pastures.

Field experiments investigating the incorporation of lucerne into cereal rotations have demonstrated that lucerne provides a viable high water-use alternative to rotations with annual pastures. Lucerne uses an additional 40-200 mm of soil water (10-200cm) compared to annual pasture (Angus *et al.* 2001; Cocks 2001; Dunin *et al.* 2001; Holford and Doyle 1978; Latta *et al.* 2001, 2002; McCallum *et al.* 2001a; Ridley *et al.* 2001; Wang *et al.* 2008; Ward *et al.* 2001; Whitfield *et al.* 1992) , and at least 2 cereal crops can be grown after a 3 year phase of lucerne before the soil water deficit is removed (Latta *et al. 2001*; McCallum *et al.* 2001; Ridley *et al.* 2001).

Benefits of lucerne to the rotation include breaks in cereal diseases and improved options for weed control. Broad spectrum knockdown herbicides can be used on established lucerne stands to change herbicide groups and control important crop weeds like annual ryegrass (*Lolium rigidum* Gaud.)(Doole and Pannell 2008). This can have important implications for control of diseases such as cereal cyst nematode (CCN), hosted on annual grasses. Competition for soil moisture can dramatically reduce establishment and growth of weeds (Bee and Laslett 2002; Latta *et al.* 2001), reducing the requirement for herbicide control.

In comparison to rotations with sub-clover, wheat yield responses following lucerne have been variable, with yield reductions reported by McCallum *et al.* (2001a) but equivalent or higher yields reported by Latta *et al.* (2001, 2002, 2006). McCallum *et* *al.* (2001a) simulated a range of environmental conditions using computer models, and found that whilst average grain yield penalties were 0.4 t/ha or 15%, large yield penalties were very uncommon.

The timing of lucerne removal (spring versus autumn) has been shown to impact on both the likelihood and extent of yield reductions (Angus *et al.* 2000), and the length of hydrological control (Verburg *et al.* 2007). Each additional month between lucerne removal and wheat sowing lead to an increase in wheat yield of 8% and a grain protein increase of 0.3 percentage units (Angus *et al.* 2000). Most farmers use herbicides to remove lucerne, usually in conjunction with grazing (Davies and Peoples 2003). The success of lucerne removal has been greatly improved following recommendations to apply herbicide when storage reserves in the crown were being replenished; usually 3-4 weeks after defoliation (Davies and Peoples 2003). The timing of lucerne removal (autumn versus spring) also impacts on summer livestock feed, weed management, and the availability of N to following crops.

Lucerne is capable of fixing large amounts of biological N (Chan 2001; Chan *et al.* 1998; Dear *et al.* 1999; Holford 1990; Whitbread *et al.* 2000). Nitrogen is made available to following cereal crops through decomposition and mineralisation of the taproot and crown when the stand is removed. The long C:N ratio of lucerne means that the N is mineralised slowly in comparison to fine rooted annual species (Angus *et al.* 2006; Bolger *et al.* 2003), with a benefit to following cereal crops for up to 5 years (Entz *et al.* 2002). The growth, death and decay of a perennial legume's large underground root mass has a large positive impact on soil fertility by adding C and N.

The sequestration of C and N in soil is also important in reducing atmospheric greenhouse gases, and may eventually be used for C trading.

Over-cropping or intercropping: a new farming system?

Over-cropping or intercropping is a farming system where two species are grown in mixture, with the aim of maximising complimentary interactions so that they outweigh any negative impacts associated with inter-species competition (for light, water and nutrients). Lucerne has been evaluated in mixtures for grain yield improvements in a range of crops including maize (Sankaran and Sankaran 1986), finger millet (Shankaralingappa and Rajashekara 1992) and sunflower (Kandel *et al.* 1997). Over-cropping wheat into established lucerne has been by assessed by Angus *et al.* (2000), Egan and Ransom (1996), Magid *et al.* (1991), McCallum *et al.* (2001b), Prasad and Singh (1991) and White (1989) with a wide range of success.

Over-cropping wheat, barley and oats into established lucerne pasture reduced grain yields by 0-62% in north-central Victoria (Egan and Ransom 1996). Dry matter yields between overcropped and monoculture wheat at anthesis were equal, identifying the post-anthesis period as the most critical for competition. In a study of irrigated lucerne and wheat, Magid *et al.* (1991) identified competition for N as a limiting factor for grain yield production, and they were able to eliminate the yield penalty by applying N fertiliser.

Further support to the importance of N nutrition in over-cropping wheat into lucerne comes from Angus *et al.* (2000), who reported a reduction in grain protein in the absence of a grain yield penalty. This result was achieved following an unsuccessful attempt to remove lucerne with herbicides in autumn, leaving a lucerne density of 5-10 plants/ m^2. Results from Egan and Ransom (1996) also suggest that reducing lucerne plant density may act as a useful means to decrease competition. In the study by Angus *et al.* (2000), competition for light and nutrients was reduced whilst the lucerne plants recovered from a sub-lethal dose of herbicide. Whilst the opportunity to over-crop lucerne arose following poor success with lucerne removal, the decision to use herbicides to suppress competition from lucerne in an overcropping strategy was later supported by Davies and Peoples (2003). The positive result by Angus *et al.* (2000) was also benefited from a season with high rainfall, leading to the recommendation that over-cropping may be more successful in high rainfall environments.

Lucerne has been shown to reduce winter waterlogging to the benefit of oversown wheat in trials with heavy clay or duplex soils in the 5-600 mm rainfall zone of southern New South Wales (McCallum *et al.* 2001b). Standing surface water, observed only in the continuous cropping treatment, resulted in a reduction in grain yield from continuous cropping (3.6 t/ha) compared to wheat oversown into lucerne (3.9 t/ha). The lucerne / wheat over-cropping system reduced soil moisture in comparison to separate phases of lucerne and wheat, because of the level of recharge that occurred outside of the lucerne phase (McCallum *et al.* 2001b).

In southern Australia, over-cropping lucerne with a cereal is anticipated to be used where a high percentage of perennials are desired in the farming system. From a hydrological perspective, this farming system has the advantage of maintaining lucerne 100% of the time, reducing the risk of groundwater recharge that may otherwise occur in a phase farming system during the sequence of annual crops (McCallum *et al.* 2001b; Ridley *et al.* 2001). A permanent lucerne pasture is also likely to increase the benefits of C sequestration and improve soil physical properties.

There are other reasons why lucerne may be grown in mixtures with plants for food or fodder production. Lucerne is commonly overcropped with forage grasses for improved total biomass production, as found in examples of lucerne with forage sorghum (Buxton *et al.* 1998; Hallam *et al.* 2001), oats (Lanini *et al.* 1999) and maize (Jellum and Kuo 1996). Oversowing grasses into lucerne for hay has been shown to reduce weed invasion in China (Li *et al.* 2001), and extend the life of lucerne stands heavily infested with weevils (*Hypera* spp.) in California (Putnam *et al.* 2001). Growing lucerne in strips in cotton fields has been used to increase the density of predatory insects (beetles and laceweings) of *Helicoverpa* spp. (Mensah 1999) and to trap *Lygus* (Godfrey and Leigh 1994) and green mirids (*Creontiades dilutus*)(Mensah and Khan 1997), thereby reducing the severity of these pests in surrounding cotton .

Conclusion

This review provides compelling evidence that lucerne will play a major role in future southern Australian farming systems. Perennials such as lucerne provide a much closer match to the endemic vegetation than annual crops and pastures, therefore offering a greater chance of producing food and forage in a sustainable manner. An opportunity exists to identify the ideotypes for lucerne in phase farming and over-cropping farming systems, and to identify germplasm that matches these requirements.

The second part of this literature review (Humphries and Auricht 2001) looks at the potential for improving lucerne by plant breeding to overcome the principal challenges restricting its production in the cropping zones of Australia. Following this chapter, a list of research questions is formulated to narrow the range of topics and direct the research in this PhD.

CHAPTER 1.4

Breeding lucerne for Australia's southern dryland cropping environments

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Breeding lucerne for Australia's southern dryland cropping environments

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Abstract. Lucerne is a deep-rooted perennial forage legume with an important role in preventing dryland salinity in southern Australian cropping regions. Annual cereal production has created a water-use imbalance, which is placing the industry under threat through rising saline watertables and resultant dryland salinity. Lucerne is being incorporated into cropping systems to reduce groundwater recharge and improve the sustainability of grain production.

Existing lucerne varieties have been developed for the animal industries, primarily for the areas with high rainfall or irrigation. The new challenge is to develop lucernes specifically for southern Australian cropping systems. This paper provides a background literature review of the breeding challenges that are anticipated in the development of these new types of lucerne. Lucerne is intolerant of acidic soils, waterlogging, saline soils, and intensive grazing. Other important attributes covered include the ability of the plant to fix nitrogen with existing rhizobia and be resistant to diseases that affect lucerne and other crops in the rotation. Finally, this paper addresses some of the breeding strategies that will be used to screen lucerne germplasm for tolerances to these soil conditions and diseases.

Additional keywords: acidity, grazing, waterlogging, salinity, nitrogen fixation, insect and disease resistance, seedling vigour.

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1.4 Research Questions

The 2-part literature review identified many opportunities for further research. In this thesis, the potential for improving the suitability of lucerne for phase farming and over-cropping will be explored by evaluating a diverse range of lucerne germplasm in these farming systems. The following list of questions has been formulated to direct the research presented in this thesis.

Aim: To define an ideotype of lucerne that specifically matches the requirements of a phase farming system, and identify germplasm that matches this ideotype.

1. What is the most suitable winter activity for lucerne in phase rotations (3-5 years lucerne followed by 3-5 years cropping) in southern Australia?
2. What is the tolerance of a broad range of lucerne germplasm to grazing by sheep? Is the level of tolerance high enough to support persistence in large paddocks in the absence of strict rotational grazing?
3. What is the adaptation of a diverse group of germplasm to a range of acidic and alkaline soils in SA and WA?

Aim: To define an ideotype of lucerne that specifically matches the requirements of an over-cropping system, and identify germplasm that matches this ideotype.

1. What is the influence of winter activity on the seasonal distribution of herbage yield in diverse lucerne germplasm?
2. How useful is the measurement of 'winter activity' in describing very winter-dormant germplasm?

3. Can competition for light, water and nutrients between lucerne and over-cropped wheat be reduced by using very winter-dormant lucerne?
4. Can germplasm be selected with specific seasonal growth patterns to match requirements for lucerne grown in mixtures with wheat?
5. What is the effect of winter activity on water use? Are very winter-dormant lucernes able to use equivalent amounts of water as winter-active lucerne?

CHAPTER 2

Preliminary evaluation of diverse lucerne (*Medicago sativa* sspp.) germplasm to identify new material for livestock and cropping based farming systems in Australia

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Preliminary evaluation of diverse lucerne (*Medicago sativa* sspp.) germplasm to identify new material for livestock and cropping based farming systems in Australia

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Abstract. A preliminary evaluation protocol is described of *Medicago sativa* that enables a diverse range of germplasm from different winter-activity groups to be evaluated in the same experiment. The protocol was used to compare the seasonal growth patterns of very winter-dormant *M. sativa* sspp. *falcata* and *caerulea* accessions with highly winter-active *M. sativa* ssp. *sativa* accessions. Herbage production was strongly related to winter activity in the cumulative first year of growth and in second-year winter months, but completely unrelated in 3 cuts in the following spring. The vertical measurement of plant height was confirmed to be a good indicator of herbage production in winter, but neither stem height nor length were good indicators of spring production.

The preliminary evaluation protocol identified highly winter-active class 10–11 germplasm with high winter production and excellent recovery after cutting, and accessions of *M. sativa* sspp. *caerulea* and *falcata* (winter activity class 1) with excellent spring and summer production. These wild relatives of lucerne have great potential to increase the area of cultivated *M. sativa* in Australia, largely as a component in pasture mixtures. They also offer improved quality traits over winter-active Lucerne, including a higher leaf to stem ratio, and a lower stem thickness and internode length.

Additional keywords: alfalfa, genetic resources, lucerne in pasture mixtures, rotations, dryland salinity.

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CHAPTER 3

Persistence of diverse lucerne (*Medicago sativa* sspp.) germplasm under farmer management across a range of soil types in southern Australia

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Persistence of diverse lucerne (*Medicago sativa* sspp.) germplasm under farmer management across a range of soil types in southern Australia

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Abstract. The persistence of a diverse group of lucerne (*Medicago sativa* sspp.) germplasm was evaluated under farmer management across a range of acidic and neutral-alkaline soils at 8 sites in South and Western Australia. Dryland field trials were sown in parallel with commercial lucerne paddocks being grown in rotation with cereal crops, remaining unfenced and under management by the farmer for the life of the stand. The combined differences in soil type, grazing management, and low rainfall contributed to large differences in average lucerne persistence between sites in South Australia and Western Australia. After 3 years, plant frequency (a measure of plant density used to monitor persistence) averaged 17% (at least 17 plants/m^2) on the strongly acidic soils in Western Australia and 30% on the neutral-alkaline soils in South Australia (at least 30 plants/m^2). Differences in persistence were attributed to the combined stresses of soil pH, drought conditions, and grazing management. Genetic correlation analyses between sites failed to show any clear patterns in the performance of entries at each site, except for a high correlation between 2 South Australian sites in close proximity. Highly winter-active germplasm was less persistent than other winter activity groups, but was higher yielding when assessed in an additional trial at Katanning, WA. Highly winter-active lucerne (class 9–10) should continue to be recommended for short (2–4 year) phases in rotation with cereals, and winter-active groups (6–8) should be recommend for longer (4–7 year) phases in rotations. The results of this evaluation are also being used to identify broadly adapted, elite genotypes in the breeding of new lucerne cultivars for the southern Australian cropping districts.

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CHAPTER 4

Tolerance of Australian lucerne (*Medicago sativa*) germplasm to grazing by sheep

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Tolerance of Australian lucerne (*Medicago sativa*) germplasm to grazing by sheep

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Abstract. The sheep grazing tolerance of a diverse range of lucerne germplasm (*Medicago sativa* subspp. *sativa*, *falcata* and *caerulea*) was investigated at Roseworthy in South Australia. Lucerne entries were established on a sandy loam soil in 1998 and managed with rotational grazing management for the first 12 months. Continuous grazing by sheep in the following year reduced the plant density of each entry as measured by plant frequency estimates by 2–98%. Lucerne was allowed to recover, then grazed continuously for another 12 months. There was great diversity in tolerance to sheep grazing among the entries tested, with final plant frequency ranging from 0–13% for highly winter-active entries, 7–23% (at least 7–23 plants/m^2) for winter-active entries and 11–40% for winter dormant entries. A grazing tolerance index of commercial cultivars was determined by comparing their plant frequency decline under continuous grazing to that under rotational grazing in an adjacent experiment. Australian-bred highly winter-active cultivars displayed a greater level of tolerance than those developed overseas. The superior performance of several breeders' lines in the continuously grazed trial indicates there is further scope for improvement with selection and breeding.

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CHAPTER 5

Over-cropping lucerne with wheat: effect of lucerne winter activity on total plant production and water use of the mixture, and wheat yield and quality

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Over-cropping lucerne with wheat: effect of lucerne winter activity on total plant production and water use of the mixture, and wheat yield and quality

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Abstract. Two field experiments in southern Australia investigated a farming system of over-cropping wheat (*Triticum aestivum* L.) into established lucerne (*Medicago sativa* subsp. L.) varieties of different winter activity ratings. The study was completed at Roseworthy, South Australia, and Katanning, Western Australia, between August 2000 and May 2003 in seasons receiving below average and average rainfall. Comparative lucerne persistence and biomass, wheat biomass, grain yield and protein contents, and soil water contents were measured. Wheat grain yield was reduced by 13–63% by over-cropping lucerne compared with wheat monoculture. Winter-dormant lucerne (winter activity Classes 0.5 and 2) reduced the yield penalty compared with winter-active varieties (Classes 6 and 10) in 2 of the 4 evaluations. The positive response to applying N at sowing in the second year of over-cropping wheat at Katanning was greatest in the most winter-dormant lucerne treatment (winter activity 0.5). Soil water contents were similar under the lucerne/wheat over-cropping and lucerne monoculture treatments irrespective of lucerne winter activity. Deficits of up to 43 mm at Roseworthy and 88 mm at Katanning were measured in the 0–200-cm soil profile at the start of the third summer of the study. The study shows that it can be more efficient in terms of land area to over-crop wheat into lucerne than to grow monocultures on separate parcels of land akin to phase farming. The improved productivity of over-cropping is associated with the separation of growth patterns of winter wheat and summer-active lucerne. This farming system offers great potential for improving sustainability and productivity in southern Australian cropping rotations.

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Chapter 6. General Discussion

The recent string of drought-affected seasons in southern Australia have provided chilling examples of the conditions predicted to become more common with the onset of climate change. Changing climate and increasing levels of dryland salinity will heighten the risk of cropping if our farming systems remain unchanged. By 2050 mean temperature will be on average at least 2 degrees warmer (Gunasekera *et al.* 2008), and there will be an additional 12 million hectares of land affected by dryland salinity (National Land and Water Resources Audit 2000). These forecasted conditions are drivers for change, making it imperative to evaluate new, resilient and sustainable options for future Australian agriculture.

Dryland salinity management

For the first time, the high water-use of a companion farming system involving wheat over-cropped into lucerne has been presented (Chapter 5). Lucerne over-cropped with wheat used an equivalent amount of water to a lucerne monoculture, extracting an additional 43-88 mm of soil water in comparison to continuous wheat at Roseworthy and Katanning. There was no difference in water-use between very winter-dormant and the winter-active lucerne germplasms. This information adds to the knowledge of the impact of different farming practices on salinity management.

A major refocus of salinity control has recently been proposed by Barrett-Lennard *et al.* (2005) and Wang *et al.* (2008), shifting attention to valley floors, and the use of perennial plants to intercept drainage or use water directly from shallow watertables. Where valley floor top-soils are non saline they represent our most fertile and productive soils for cropping, providing the most attractive position in the landscape for an over-cropping farming system.

Recent results have shown that lucerne also has the ability to lower groundwater levels under unfavourable conditions, including very saline groundwater, high sodium chloride chemistry and high groundwater levels (Dolling *et al.* 2005; Ferdowsian *et al.* 2002). These observations are supported by the research reported here, where soil water extraction at Roseworthy and Katanning (Chapter 5) occurred on soils with sodic and saline sub-soils.

In large catchments with negligible flow between land units, perennials should continue to be recommended throughout the landscape. Fillery and Poulter (2006) have shown that on a deep sand lucerne will extract an additional 163 mm of water to a depth of at least 5 m compared to annual pasture. This depth of depletion of soil water in a loamy sand is similar to that reported by Ward *et al.* (2003) but much deeper than noted in other Australian studies (Angus *et al.* 2001; Dunin *et al.* 2001; Latta *et al.* 2001, 2002; McCallum *et al.* 2001a; Ridley *et al.* 2001; Ward *et al.* 2001).

The high water-use of lucerne in studies reported by Fillery and Poulter (2006) and Latta *et al.* (2001, 2002) occurred on soils that were acidic to strongly acidic (pH 4.3-4.8 $CaCl_2$), which is similar to the soil pH at Katanning, Dumbleyung and Wittenoom Hills (Chapters 3 and 5). The results provide further support that lucerne can successfully reduce recharge on acidic soils previously thought to be unsuitable for lucerne.

Lucerne in phase rotations with annual crops

The transition from lucerne in permanent pastures to a role that is more closely integrated into cropping rotations has provided the impetus to expand the range of cultivars that are available. This research aimed to identify an ideotype of lucerne that is specifically tailored to meet the requirements of a cereal farming system.

The phase rotation farming lucerne ideotype is a plant with high winter activity for quick response to an autumn break and high biomass through winter when rainfall is dominant. Grazing tolerance is important because many farmers do not rotationally graze, and because sheep do not graze large paddocks evenly. Hence there is a role for very grazing tolerant lucerne in continuously grazed pastures and longer rotations (or permanent lucerne). There is possibly also a role for a low level of grazing tolerance to aid in lucerne removal by heavy grazing in short phase rotations rather than by cultivation and herbicide application (Davies *et al.* 2005). The inherent problem with grazing intolerant lucerne for easy removal is that it is un-likely to have sufficient persistence to survive through the length of the phase. Existing cultivars Rapide and Rippa are grazing intolerant, and their persistence under grazing is so poor that they do not persist for 3-5 years even under rotational grazing (Chapters 4 and 5).

This project aimed to identify genetic resources to match the requirements of this phase rotation ideotype. A broad range of germplasm was grown and a characterisation protocol developed to measure differences in winter production, regrowth vigour and herbage quality (Chapter 2). The protocol also has standard control varieties and statistical analysis, which have helped to improve comparisons between this germplasm cohort and others evaluated more recently. The characterisation identified several very highly winter-active accessions (SA32064, SA32070 and SA32073) for extensive field evaluation in the low-medium rainfall cereal zone of southern Australia.

The regional evaluation trials confirmed that winter-active and highly winter-active lucerne varieties are the most productive classes for lucerne monocultures in phase rotations. While on average highly winter-active lucerne was less persistent than winter-active lucerne across the 8 regional evaluation sites, there was large genotypic variation within these winter activity classes. A highly winter-active lucerne cultivar, 'SARDI Ten', had the greatest herbage yields in the cutting trial at Katanning, WA and should continue to be recommended for short rotations with cereal crops where grazing is well managed. There were also large differences between the average persistence of lucerne in SA and WA, however some entries appeared to be broadly adapted across these environments. The best performing entries were SARDI breeding lines A8, L233, L234 and L286 (Chapter 3). Differences in persistence between genotypes and environments were attributed to the combined affects of soil acidity, drought conditions and grazing management.

In experiments related to this research, a complex of fungal diseases caused by *Rhizoctonia*, *Pythium* and *Fusarium* spp. have been identified as major constraints to lucerne establishment in SA in association with root lesion nematode (*Pratylenchus* spp., Ballard pers. comm. 2007). Whilst variation for tolerance to these diseases is currently unknown, the ability of germplasm to tolerate disease infection at establishment is likely to have contributed to the results.

The level of grazing tolerance of the populations evaluated in regional field trials was measured directly in a continuous grazing trial at Roseworthy, SA. Australian cultivars were shown to have a much higher level of tolerance compared to varieties developed for hay and silage overseas. Individual plants from the winter-active group with excellent levels of grazing tolerance were selected from the trial and randomly inter-mated to produce new breeders lines. These lines have since had further cycles of selection for grazing tolerance and insect and disease resistance, in the development of a grazing tolerant cultivar. Shifts in winter activity associated with selection for grazing tolerance, reported by Sledge *et al.* (2003), have also occurred in this germplasm. A grazing tolerant cultivar 'SARDI Grazer' is expected to be released to farmers in 2012 following reselection for higher winter activity in 2008 and commercial seed multiplication.

Further research is recommended to determine if the improved grazing tolerance of this new cultivar will allow a 2-paddock rotational system (approximately 35 days grazing followed by 35 days recovery) to be used without adverse effect on plant survival, pasture and animal production. This management could replace the strict rotational grazing management of 7-14 days grazing followed around 35 days recovery, which is recommended for current varieties. Greater adoption of lucerne in phase rotations with cereal crops could then be expected due given no requirements for additional fencing or intensive sheep management.

Companion farming: over-cropping lucerne with wheat

An over-cropping system with wheat oversown into lucerne has the advantage of maintaining grain production in comparison to a rotation with separate phases of lucerne and wheat monocultures. As the worlds population increases and places higher demands on food production, the importance of this system being adopted successfully increases. The over-cropping system increases the percentage of perennials in the landscape and as a consequence improves recharge control, and C and N sequestration in comparison to a phase farming system.

The ideotype for lucerne suitable for over-cropping with a winter cereal is a persistent and very winter-dormant plant that does not compete strongly for water, light and nutrients during the lifecycle of the crop. The critical periods of competition are at establishment (Angus *et al.* 2000) and anthesis (Egan and Ransom 1996). Establishment of seedlings of lucerne under a crop is essential, but this does not necessarily translate to needing a high level of seedling vigour, as indicated by the successful establishment of very winter-dormant lucernes with poor seedling vigour at Dumbleyung and Moorlands (Chapter 3). A lucerne for over-cropping must also be very grazing tolerant, as lucerne and wheat stubbles are likely to be continuously grazed for several months. Improvements in N fixation or disease resistance are likely to be beneficial to the companion cereal.

The preliminary evaluation experiment (Chapter 2) identified very winter-dormant accessions of *M. sativa* ssp. *falcata* and *caerulea* for further research with either low (SA37908) or high (SA35188, SA37610) spring-summer yield potential. The low spring yielding lucerne may be less competitive with wheat at anthesis, but would also be less productive for grazing over summer. These sub-species of *M. sativa* are known to be drought and grazing tolerant, but were previously thought to be too low yielding for use in southern Australia due to its Mediterranean climate.

In regional field evaluation trials, the very winter-dormant accessions of M. sativa ssp. *falcata* and *caerulea* (SA6493, SA19015, and SA10125) showed persistence equal to winter-active lucerne. The continuous grazing trial at Roseworthy (Chapter 4), showed that this germplasm group is very grazing tolerant, potentially enabling a farmer to graze the lucerne and wheat stubble continuously throughout the summer with few recovery periods. This ensures that these lines are good candidates for a companion farming system where the lucerne is maintained permanently and needs to be long-lived and grazing tolerant.

Over-cropping experiments at Roseworthy and Katanning evaluated the potential of this farming system. A lower grain yield penalty in 2 out of 4 combined seasons was achieved from over-cropping very winter-dormant lucerne compared to over-cropping more winter-active varieties. Competition for N between lucerne and wheat plants appeared to be equally as important as soil water content, and a result from one season showed that very winter-dormant lucerne was less competitive in taking up applied N in comparison to winter-active lucerne.

Recent experiments in the southern Australian wheat-belt have confirmed the yield penalty of 0-63% for wheat oversown into lucerne in this study. Reductions in yield ranged from 17 (Harris *et al.* 2007) to 25 (Harris *et al.* 2008) and 0-53% (Latta and Lyons 2006). In these investigations, reductions in wheat yield were attributed to competition for soil moisture and N. In Western Australia, Latta and Lyons (2006) demonstrated that lower than typical lucerne densities of 4 plants/m^2 reduced wheat yield only when rainfall was low. Attempts at reducing competition were also made by Harris *et al.* (2008), with applications of additional N, water and these combined, increasing cereal grain yield by 13-40%, 35% and 49% respectively. Suppression of lucerne with herbicide caused a significant reduction in lucerne persistence (Harris *et al.* 2008), resulting in the authors suggesting further research into less detrimental strategies for in-crop lucerne suppression. One such option is a very winter-dormant lucerne variety as reported here, and suggested by Pecetti *et al.* (2006).

The very winter-dormant lucerne could also be managed in a mixture for forage production with species such as volunteer annual *Medicago* pasture in cropping rotations, or perennial Mediterranean grasses for permanent pasture production in higher rainfall zones (Sandral *et al.* 2006) where traditional winter-active lucerne varieties fail to persist (Lodge *et al.* 2003). Pecetti *et al.* (2008) have been developing germplasm for this purpose in Italy with a focus on prostrate or semi-erect germplasm selected from crosses between *M.sativa* ssp. *falcata* and *sativa*. In Canada, Katepa-Mupondwa *et al.* (2002) have been selecting very winter-dormant, winter-hardy germplasm for mixtures with bromegrass (*Bromus* spp.).

Conclusion

The results show that winter-active and highly winter-active lucernes are suitable for phase rotations with annual crops, as they are persistent, productive, and tolerant to grazing and drought. This farming system offers a solution to managing salinity, and increases C and N in soils to restore soil fertility and mitigate the effects of climate change.

A new farming system involving wheat oversown into lucerne is not yet available for widespread adoption, but offers substantial advantages over a phase farming system if it can be made successful. This research has identified an ideotype for this system that is very winter-dormant and grazing tolerant. Companion farming systems increase the area of perennials in the landscape whilst maintaining crop production, providing further benefits to the environment and bridging the gap to achieving truly sustainable food production.

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