



Evaluation of some management options for the tactical use of lucerne phase farming to reduce deep drainage

K. Verburg and W.J. Bond



CSIRO Land and Water Science Report 51/06
October 2006

Copyright and Disclaimer

© 2006 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO Land and Water.

Important Disclaimer:

CSIRO advises that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, CSIRO (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Cover Photographs:

Wheat paddock at Corowa, NSW, lucerne and canola paddocks at Wagga Wagga, NSW, and lupin paddock at Young, NSW

Photographers: Aimee Walker (wheat) and Gordon McLachlan (lucerne, canola, lupin)

Image: Kirsten Verburg

© 2006 CSIRO

ISSN: 1883-4563

Evaluation of some management options for the tactical use of lucerne phase farming to reduce deep drainage.

K. Verburg and W.J. Bond

CSIRO Land and Water / Agricultural Production Systems Research Unit, GPO Box 1666, Canberra, ACT 2601, Australia. kirsten.verburg@csiro.au and warren.bond@csiro.au.

CSIRO Land and Water Science Report 51/06

October 2006

Acknowledgements

The research described here was jointly funded by CSIRO and the Grains Research and Development Corporation. We thank Sri Srikanthan and Andrew Frost for providing the model for stochastic generation of climate data and help with interpretation of the results. We also thank Lisa Brennan and Michael Robertson for discussions on the interpretation of short-term simulations, Zahra Paydar for comments on an earlier draft, and John Hargreaves, Neil Huth, Don Gaydon and Perry Dolling for feedback on APSIM parameterisation issues.

Executive Summary

Lucerne phase farming has been suggested as a way to reduce deep drainage in southern Australia. It is based on the concept that lucerne (*Medicago sativa* L.), a perennial pasture with a deep root system, creates a soil water storage buffer below the root zone of the annual crops, which gradually fills during the subsequent cropping phase and reduces the risk of deep drainage. The rate of refilling is variable because it is affected by the amount and distribution of rainfall as well as management of the crop and the summer fallow. As a result there is uncertainty about the optimum phase lengths that will maximise the impact of lucerne. The use of a soil water measurement below the root zone of annual crops has been proposed as a means to indicate when it is time to change phase. If the soil water measurement suggests that a phase change from wheat to lucerne would be warranted, it may, however, not always suit the overall farm management to put the paddock under lucerne in the coming year. In this report we analyse the consequences for deep drainage of not switching phase when indicated by the measurement. For the soil and climate combination used here, delaying the introduction of lucerne by a year resulted in a 50% probability of increasing deep drainage by less than 5 mm/year for the two years following the decision to delay, including a 7% probability of reducing the amount of drainage. However, there was a 20% probability of an increase in deep drainage of 40 mm/year or more.

The report also explores the benefits and penalties of establishing lucerne by sowing it under wheat in the first year of the lucerne phase. This practice, which is becoming increasingly common in NSW and Victoria, has the potential to increase the number of crops in the lucerne phase farming system, and was expected to reduce the relatively high risk of deep drainage during the first year of lucerne. We found, however, that undersowing lucerne was not as successful in reducing deep drainage as expected, and in some cases led to increased deep drainage, due to lower water use during the first summer after the wheat harvest. The success of undersown lucerne in reducing deep drainage depended on lucerne vigour and management of the wheat residues. Further experimental research is required to determine wheat and lucerne densities, and grazing practices that result in optimum water use during the first summer.

Table of Contents

| | |
|--|-----------|
| 1. Introduction | 1 |
| 2. Materials and Methods | 3 |
| 2.1. APSIM model..... | 3 |
| 2.2. Short term simulated dryland agriculture scenarios..... | 3 |
| 2.3. Climate input..... | 4 |
| 2.4. Stochastic climate generation..... | 4 |
| 2.5. Soil parameterisation..... | 5 |
| 3. Results and Discussion | 6 |
| 3.1. Delaying the change to the lucerne phase..... | 6 |
| 3.2. Undersowing lucerne..... | 8 |
| 4. Conclusions | 10 |
| References | 11 |

1. Introduction

Lucerne phase farming has been suggested as a way to reduce deep drainage in southern Australia (Dunin *et al.* 1999; Stirzaker *et al.* 2000). It is based on the concept that lucerne (*Medicago sativa* L.), a perennial pasture with a deep root system, creates a soil water storage buffer below the root zone of the annual crops, which will gradually fill during the subsequent cropping phase and temporarily reduce the risk of deep drainage. The rate of refilling is variable because it is affected by the amount and distribution of rainfall as well as management of the crop and the summer fallow. As a result there is uncertainty about the optimum phase lengths that will maximise the impact of lucerne on deep drainage reduction.

A measurement from a soil water sensor below the root zone of the annual crops (Figure 1) can provide information as to whether the subsoil has dried sufficiently under the lucerne phase, or has started to rewet under cropping (Bond 2006). Verburg *et al.* (2006) used long term biophysical and economic simulations to evaluate the use of such a soil water measurement below the root zone of annual crops to schedule the phase changes, compared with the usual fixed duration phases. This tactical use of lucerne phase farming was more efficient in reducing deep drainage and provided slightly more optimal trade-offs between average annual deep drainage and average annual gross margin (for example, gross margin was slightly greater for the same deep drainage).

A land manager making a decision about changing phase must also weigh up a number of other considerations, including pasture requirements, commodity prices and weather conditions. Here we analyse what the effect on deep drainage would be if a phase change was delayed for a year. In particular, if the soil water status suggests that a phase change from wheat to lucerne would be warranted from a deep drainage perspective, but it does not suit the overall farm management to put the paddock under lucerne in the coming year, what are the likely consequences of not switching phase for deep drainage in that paddock?

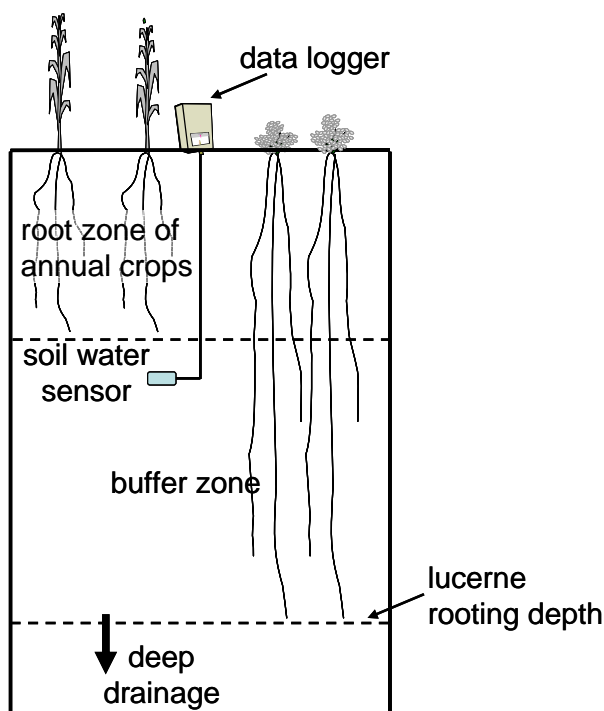


Figure 1: Schematic diagram of the principle of lucerne phase farming and taking a soil water measurement below the root zone of annual crops for tactical scheduling of phase changes

We evaluated (with simulations) the impacts over a two-year period after the soil water status indicated that it was time to change from the cropping phase to lucerne. We compared the deep drainage when the system was switched straight to lucerne (i.e. two years of lucerne), with that when it first had another year of wheat followed by a switch to lucerne in the second year. The analyses focussed on the rainfall conditions experienced in the south west slopes of NSW, where rainfall is on average uniformly distributed throughout the year, although reference is made to the effects of a more winter dominant rainfall regime.

The same simulation set-up was also used to explore the benefits and penalties of undersowing wheat with lucerne. It has been previously suggested (Verburg *et al.* 2001, Verburg and Bond 2003) that sowing lucerne under another year of annual crop rather than alone may be a way to increase the number of crops in the tactical phase systems while maintaining the benefit of lucerne in reducing deep drainage. It would not only allow one more crop before switching to lucerne pasture, but would have the potential benefit that the lucerne had germinated and was ready to start drying the soil water buffer as soon as the crop was harvested in November or December. With annual crops using water earlier during the growing season than lucerne, it could potentially also reduce the relatively high risk of deep drainage during the first year of lucerne, a problem identified by Verburg and Bond (2003), Dolling *et al.* (2005) and Verburg *et al.* (2006). Establishing lucerne by sowing it under annual crops is a practice that is becoming increasingly common in NSW and Victoria. The income from the cover or nurse crop off-sets part or all of the establishment costs of lucerne (Stanley *et al.* 1999; Scott 1995, Naji 2004, Heritage seeds 2005) and development of winter-active varieties have made undersowing more reliable (Angus *et al.* 2000, Heritage Seeds 2005, PIRSA 2004).

We analysed the undersowing option with two-year simulations as outlined above for delayed phase changes. We compared a system with and without undersowing over two years; in one system we switched to lucerne sown alone, whereas in the other lucerne was sown under wheat. Management aspects and model uncertainties that influence the outcomes of these systems are discussed.

2. Materials and Methods

2.1. APSIM model

The simulations were performed with the Agricultural Production Systems Simulator (APSIM; Keating *et al.* 2003; <http://www.apsim.info>), which has flexible structure in which crops and major soil processes are dealt with in separate modules. The model is well-suited to perform analyses of alternative management options due to its manager module which can control actions like sowing and harvesting crops, tillage and fertilising using conditional logic based on states or events within the different modules. Here we used a point-scale configuration with a wheat module (Wang *et al.* 2003), a lucerne module (Robertson *et al.* 2002), a water balance module (APSWIM), a surface residue module (RESIDUE2, Probert *et al.* 1998), and a soil nitrogen module (SOILN2, Probert *et al.* 1998). The APSWIM module is derived from the Soil Water Infiltration and Movement model (SWIM, Verburg *et al.* 1996). It is based on the Richards' equation for water flow and the advection-dispersion equation for solute transport, which are solved numerically using sub-daily time steps. All other APSIM modules have a daily time step. We used APSIM version 2.1 patch 2, except for beta release (patch 3) versions of the crop modules. This version was satisfactorily tested against four detailed data sets by Verburg and Bond (2003).

2.2. Short term simulated dryland agriculture scenarios

Three scenarios for 8 year long simulations were set up (Table 1). The first 6 years of each simulation were used to stabilise the system and to achieve a second year of wheat at the end of the stabilisation period. The analyses focused on the next two years. During the first year of the analysis period (see Table 1) the system either continued with another year of wheat (W), lucerne sown under wheat (W/L), or switched to lucerne alone (L). During the subsequent year (second year of analysis period) lucerne pasture continued where lucerne was sown during the previous year, or was sown if the phase change to lucerne was not made during the previous year.

For the analysis of the delay in changing to the lucerne phase, the soil water potential at a depth of 1.7 m was evaluated on 31 March of the first year of the analysis period. Simulations in which it was wetter than -800 kPa, taken as an indication that a phase change was warranted, were analysed separately from those in which the subsoil was still dry enough. For the Red Kandosol used here (see Section 2.5) a soil water potential of -800 kPa corresponded to a soil water content that was $0.006 \text{ m}^3/\text{m}^3$ wetter than the -1500 kPa "lower limit" or "wilting point". When used as a trigger for change at a depth of 1.7 m, 0.5 m below the root zone of the annual crops, it achieved a 25% reduction in deep drainage compared with a system having lucerne and cropping phases fixed at 3 years each (Verburg *et al.* 2006).

Table 1: Short term simulated dryland agriculture scenarios

| | Stabilisation period | | | | | Analysis period | | |
|----------------------|----------------------|---|---|---|---|-----------------|-------------|---|
| | | | | | | first year | second year | |
| Phase change | W | L | L | L | W | W | L | L |
| Delayed phase change | W | L | L | L | W | W | W | L |
| Undersown Lucerne | W | L | L | L | W | W | W/L | L |

Sowing of wheat (cv. Janz) and lucerne was conditional on sufficient rainfall (at least 30 mm over the previous 10 days) within a sowing window between 1 May and 15 June, or sown "dry" on 15 June. Wheat was fertilised with 140 kg N/ha/season (20 kg N/ha applied at

sowing, the balance 60 days later) and, if sown alone without lucerne, 70% of crop residues were burned on 31 March with the remainder incorporated by tillage on 15 April. When lucerne was sown under wheat, wheat residues were reduced by 50% after harvest to mimic grazing impacts. During the summer fallow (between wheat crops and between wheat and lucerne phases) weeds were allowed to germinate, according to the scheme of Fischer *et al.* (1990), on the first rain event after harvest that exceeded a total of 25 mm (Dec – Feb) or 20 mm (Mar – Apr) over two consecutive days. They were represented as early winter grass at a density of 15 plants/m². If not already senesced, weeds were removed on 15 April. Lucerne was sown at a density of 70 stems/m² and harvested to a height of 50 mm at each flowering. After the first harvest the stem density was increased to 150 stems/m² and this density was maintained throughout the remainder of the simulation. During the stabilisation period the final harvest of lucerne was on 15 December of its third year (year 4) and it was assumed that this harvest coincided with 100% successful removal.

Wheat was allowed to root to 1.2 m, whereas lucerne roots explored the soil to 3 m depth. While there is evidence that lucerne can extract water from deeper depths in some soils (6 m, Verburg and Bond 2003; 3.6 m, Ridley *et al.* 2001), there is also evidence of shallower rooting depths (2 m, McCallum *et al.* 2001). A 3 m rooting depth is a reasonable expectation and provides a conservative analysis of the effect of lucerne. Wheat roots may root deeper or shallower than 1.2 m, depending on soil properties. The 1.2 m depth chosen for the simulations reflects observations over a number of seasons at our experimental site at Charles Sturt University, Wagga Wagga, and other sites in the south west slopes of NSW.

2.3. Climate input

The simulations were carried out for the climate of Wagga Wagga. Daily historical climate data (1957-2004) were obtained for the Australian Bureau of Meteorology station 73127 (Wagga Wagga Agricultural Institute, NSW). To capture the effects of climate variability, each scenario was run for 40 staggered 8-year periods within the 48-year historical climate record (1957-1964, 1958-1965, etc.) and another five stochastically generated climate records based on statistical properties of this data set (see section 2.4 for more details). The station was located close to the experimental site at Charles Sturt University from which the soil properties were obtained (section 2.5). The climate is temperate with a mean annual rainfall of 558 mm for the period 1957-2004. On average, 56% of this falls between May and October. The data (rainfall, solar radiation, maximum and minimum temperatures) were extracted from the SILO Patched Point Dataset (Jeffrey *et al.* 2001; <http://www.bom.gov.au/silo/>).

2.4. Stochastic climate generation

A modified version of the daily climate model from the Stochastic Climate Library (SCL) (Srikanthan and Zhou, 2003; <http://www.toolkit.net.au/scl>) was used to obtain 100 stochastically generated records (each for 1957-2004). In this model a daily model is nested in a monthly model which in turn is nested in an annual model. It focuses on daily characteristics and generates these first. It uses a multivariate AR(1) model to preserve the auto and cross correlations of the climate data. Monthly and annual totals are formed from the daily generated data, and an adjustment procedure is used to ensure that monthly and annual characteristics are preserved. The daily climate model has been successfully evaluated using climate data (rainfall, evaporation and maximum temperature) from 10 sites located in various parts of Australia (Srikanthan and Zhou 2003). The modified version used here also generated solar radiation and minimum temperature.

The climate data generated from the Wagga Wagga climate record was assessed in detail by Verburg *et al.* (2005) and found to be satisfactory with the model preserving 29 of 35 annual statistics, 279 of 360 monthly statistics, and 272 of 312 daily statistics (including mean, standard deviation, coefficient of skewness, lag-one correlation, minimum, maximum, length

of wet and dry spells and the various cross correlations; Srikanthan and Chiew 2003) of the four input variables required by APSIM.

Only five of the 100 stochastically generated climate records were used in the simulations presented here, together with the historical record. It was found that by using 40 simulations started at yearly intervals in each climate records, sufficient climate variability was captured; use of additional stochastically generated records did not change the conclusions probability density functions generated from the simulation outputs.

2.5. Soil parameterisation

The analyses presented here focussed on the conditions (soil and climate) experienced at an experimental site at Charles Sturt University, Wagga Wagga Campus (35.05°S, 147.33°E, alt. 220 m). The soil at the site is a Mesotrophic Red Kandosol (Isbell 1996). The soil profile has a weak textural contrast and the B-horizon is weakly structured. Clay content increases with depth from 23% in the surface 0.05 m to a maximum of 57% at 0.5–0.7 m. An extensive data set from this site was used by Verburg and Bond (2003) to evaluate the use of APSIM to simulate water balances of dryland farming systems on the Riverine plain. The same soil properties were used for the analyses in this paper.

Standard values were chosen for the model constants in SoilN2 and Residue2 (Probert *et al.* 1998), with the following exceptions. Like Asseng *et al.* (1998) and Snow *et al.* (1999), we found it necessary to increase the magnitude of parameters controlling potential mineralisation. We chose to use the value of 0.00025 day⁻¹ of Snow *et al.* (1999) for the potential decomposition rate for the humus pool (rdhum) and increase the daily potential decomposition rate for the soil biomass pool (rdbiom) in proportion to 0.0135 day⁻¹. The reduced effect of dry soil water conditions on mineralisation and nitrification that were proposed by Asseng *et al.* (1998) were also adopted. The potential decomposition rate of wheat surface residue (pot_decomp_rate) was decreased to 0.02 day⁻¹, from the 0.1 day⁻¹ proposed by Probert *et al.* (1998) based on a study at Warra, Queensland. The value of 0.1 day⁻¹ was used for lucerne and weed residues. The need for a smaller value for wheat residues was qualitatively confirmed by surface residue measurements made in an experiment in Wagga Wagga, NSW (Verburg *et al.* 2001, unpublished data). Smaller values were also used by Asseng *et al.* (1998: 0.05 day⁻¹ for wheat residues vs. 0.1 day⁻¹ for lupin residues) and Snow *et al.* (1999; 0.025 day⁻¹ for Eucalypt litter).

3. Results and Discussion

3.1. Delaying the change to the lucerne phase

The impact on deep drainage (over two years) of a delayed phase change to lucerne is shown in Figure 2. When the value of soil water at 1.7 m suggested a phase change was warranted after two years of wheat (83% of simulations, Figure 2a), delaying the introduction of lucerne by one year increased deep drainage by more than 10 mm over the two years (5 mm/year) in 50% of the simulations and in 20% of simulations the increase was more than 80 mm over two years (40 mm/yr). On the other hand, in 7% of the simulations, the delayed introduction of lucerne decreased the amount of drainage over the two years.

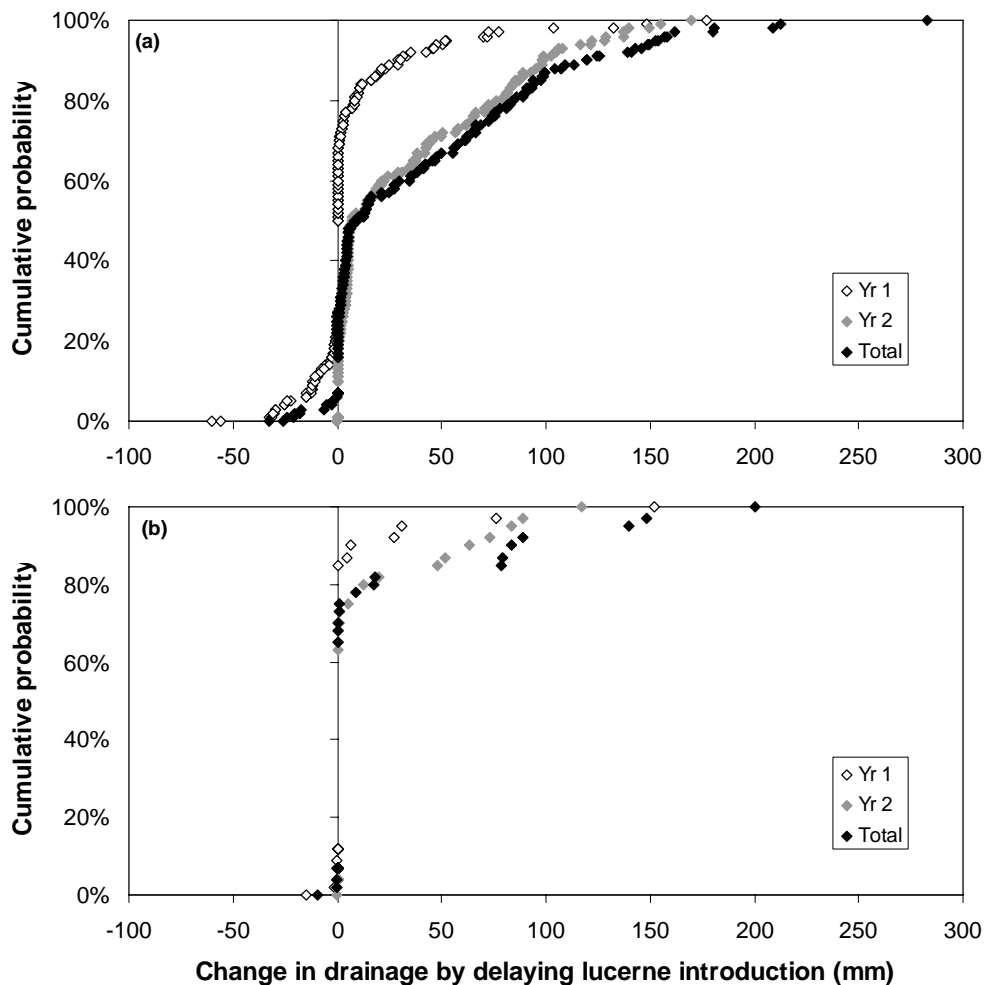


Figure 2: Cumulative probability density functions for the change in drainage caused by delaying lucerne introduction by one year when (a) the soil water triggers at 1.7 m depth suggested a change to lucerne was warranted and (b) a change was not warranted; open symbols represent effect for first year, grey symbols for second year and black symbols are the totals for the combined two years.

When the value of soil water at 1.7 m indicated the soil below the root zone of the crops was still dry enough (less than -800 kPa), the change in drainage over the two years was negligible in 80% of simulations (Figure 2b). This suggests that measuring soil water status below the annual crop root zone allows a differentiation of risk, but for management purposes it would still be more useful if the 50% of cases in which the deep drainage was increased by more than 10 mm could be identified in advance. Long term weather forecasts

could potentially play a role here. Closer analysis of the changes in drainage during the first year showed that the largest increases in drainage due to delaying the introduction of lucerne were experienced in years when rainfall during the November to April period was > 300 mm (Figure 3a), compared with long term (1963-2002) average of 245 mm. A reduction in drainage during the first year occurred in 22% of simulations and tended to be associated with rainfall patterns in the first year that were characterised by relatively high falls in the September to October period (Figure 3b) while rainfall between November and April was average (Figure 3a). While there are exceptions to these observations, delaying lucerne introduction in a year with high November to April rainfall has a high chance of increasing deep drainage, and similarly in a year with high September to October rainfall but, has a chance of reducing deep drainage when November to April rainfall is average. In order to utilise these correlations, weather forecasts would have to be available at least a year in advance, given that the decision to change phase is made no later than March or April and the forecast required to April the next year. Current capability tends to be limited to within-season predictions, although research into longer term predictions is ongoing.

The effect of delaying the introduction of lucerne by a year depends on the soil properties and the climate. For example, for a strongly winter-dominated rainfall and a soil with a small available water holding capacity, which results in a small subsoil water storage buffer, delaying the switch to lucerne almost always resulted in increased deep drainage (results not shown here).

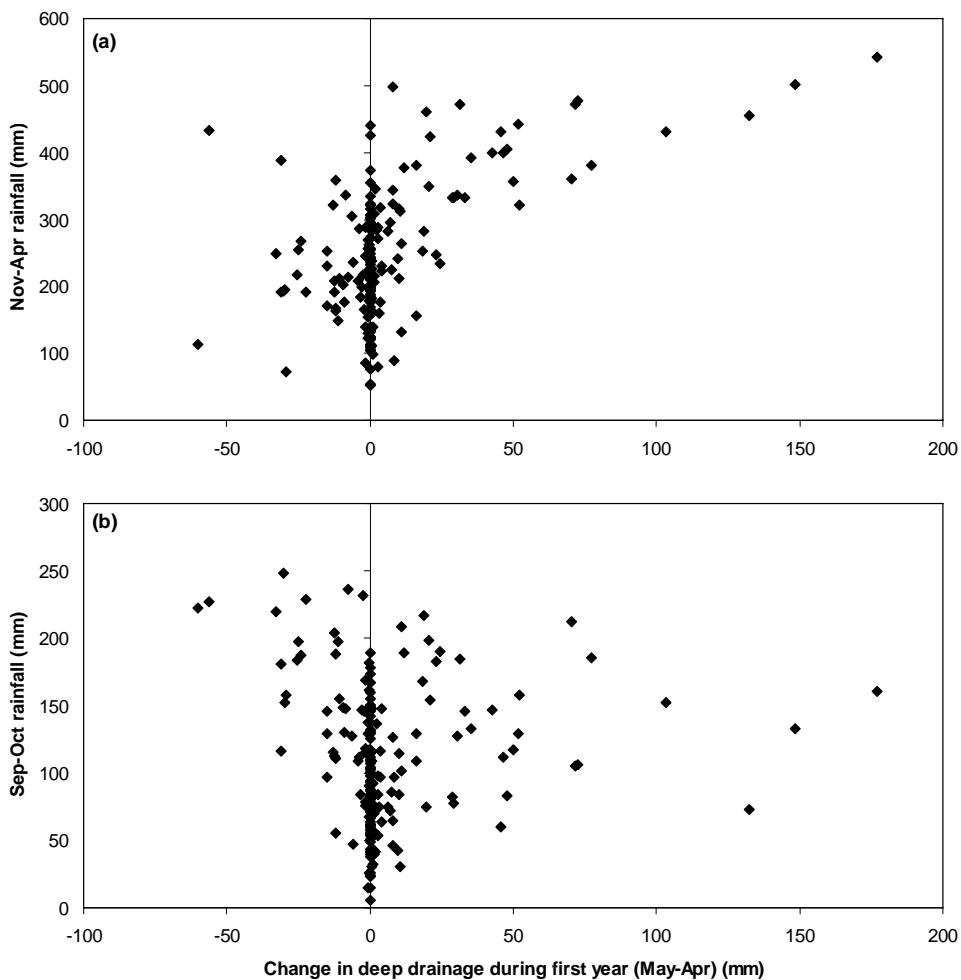


Figure 3: Association of positive or negative change in deep drainage during the first year (Figure 2a) with rainfall in the periods (a) November to April, and (b) September to October.

3.2. Undersowing lucerne

Sowing lucerne under wheat in the first year of the lucerne phase was expected to result in lower drainage during the first year, with little difference in drainage during the subsequent year when lucerne would be in its second year. The results in Figure 4 show that while undersowing reduced deep drainage in the first year in 30% of the simulations, it could also lead to increased deep drainage during both the first and second years. The average differences in soil water storage (0 - 3 m) during the two years of the simulations (Figure 5) confirmed that the undersown case used more soil water during the first months of the growing season with a peak in October of the first year. After that, however, the system without wheat used significantly more water than the undersown case. Growth of the undersown lucerne was apparently so affected by wheat that even after the wheat harvest it could not extract the same amount of water as lucerne sown by itself, resulting in soil water storage remaining higher.

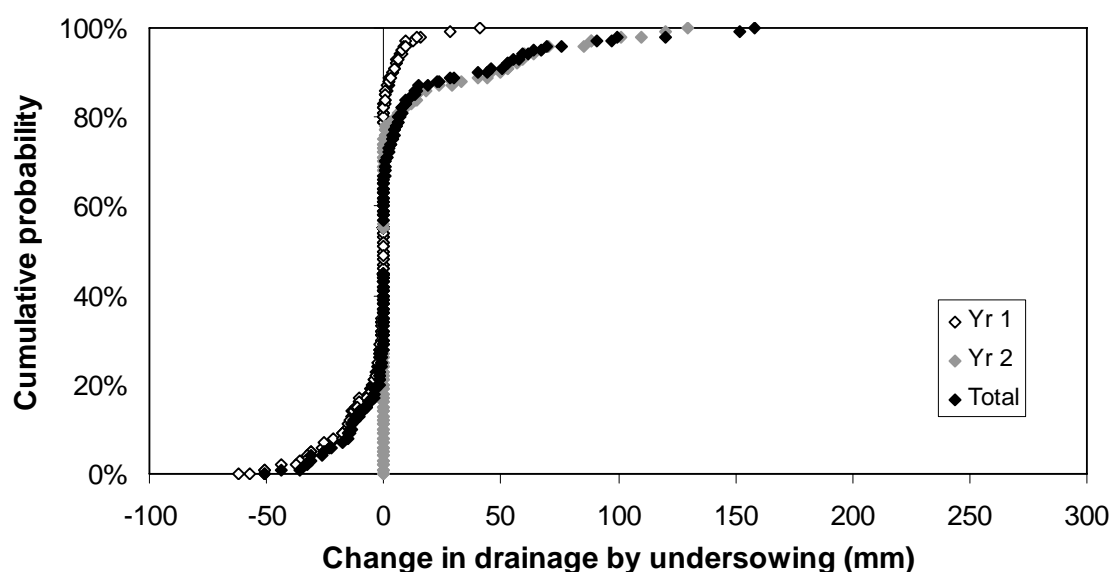


Figure 4: Cumulative probability density function for the change in drainage (over two years) by sowing lucerne under wheat in its first year compared with sowing lucerne alone. Black symbols give the cumulative probability density function for the total change over 2 years, open symbols the cumulative probability density function for the first year and grey symbols the cumulative probability density function for the second year.

Surface cover from wheat residues in the undersown case further reduced evapotranspiration by reducing evaporative losses from the soil surface relative to the lucerne sown alone. As even small differences in soil water can carry over for a long time this, on average, increased the risk of deep drainage. The simulated soil water storage and deep drainage were therefore sensitive to assumptions made about the reduction of wheat residues due to grazing and decomposition. The simulations presented in Figure 4 and Figure 5 assumed a reduction of wheat residues by 50% due to grazing and used a potential decomposition rate of 0.02/day (under ideal moisture, temperature and nitrogen conditions; see Materials and Methods, section 2.5). If this decomposition rate was increased on the grounds that trampled residue has better soil contact, or if it was assumed that grazing reduced the wheat residue load further, the chance of increased deep drainage in the undersown case was reduced, limited to 20% of simulations and at most 20 mm over two years. The percentage of simulations in which drainage was reduced increased slightly to 40%, although the maximum reduction in deep drainage did not change.

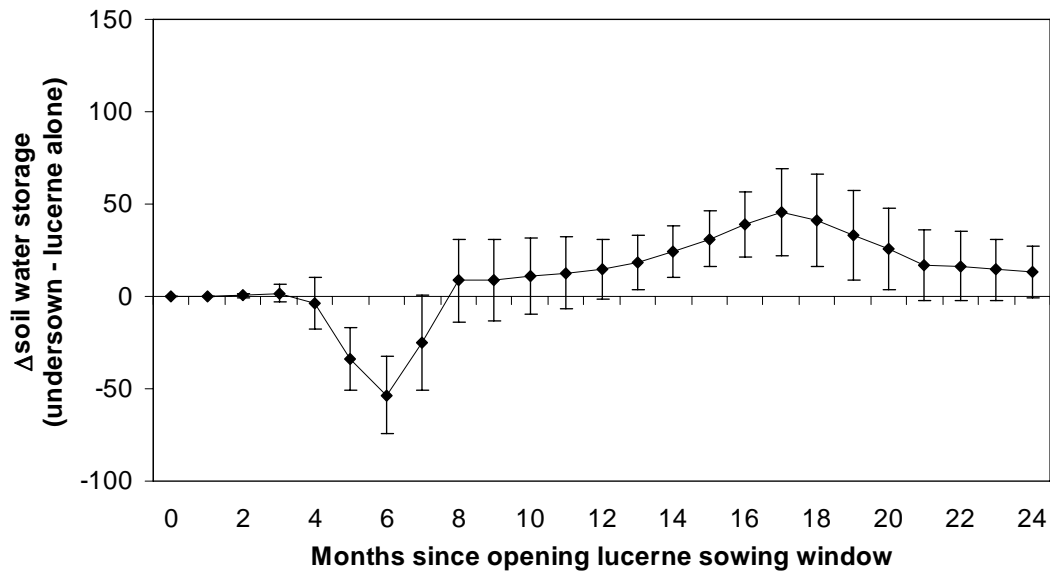


Figure 5: Average difference in total soil water storage (in mm, 0-3 m), during the two year analysis period of the simulations, between a system with lucerne sown under wheat and one with lucerne sown alone. Bars indicate standard deviations.

The results were also strongly impacted by the simulated lucerne vigour and its ability to compete with the wheat crop for light and water. Robertson *et al.* (2004) have tested APSIM's ability to simulate lucerne-crop intercropping at the end of the lucerne phase, but the model's predictions of lucerne establishment, vigour and biomass production as well as its competition with wheat and effects of grazing pressure during establishment have not been well tested. This adds to the uncertainty in predictions of deep drainage and the percentage of cases in which undersowing resulted in no more deep drainage than when lucerne was sown alone.

Experimentally this still is an uncertain area as well. For example, it is generally assumed that the sowing rate of cover crop needs to be reduced (Stanley *et al.* 1999, Lloyd 2003, Naji 2004), but LWA (2001) reports on findings that on a farm in SA a higher rate of lupin (as the cover crop) encouraged lucerne establishment and biomass growth, so that this may be crop specific. Cocks (2001) pointed out that little published information was available and information is needed on 'the relative sowing rates of lucerne and cover crop, row spacing, time of sowing (autumn v. spring), and the relationship of these variables with climate.' Indeed evidence on the influence of climate on establishment is confusing. Studies by Lloyd *et al.* (1998) have suggested that undersowing works better in drier environments, whereas others (e.g. Thompson 2005) have suggested that mild and wet springs are required for success.

4. Conclusions

For the soil and climate studied here, delaying the introduction of lucerne by a year resulted in a 50% probability that deep drainage would be increased by less than 5 mm/year or decreased, compared with only a 20% chance if the phase change was not indicated. On the other hand, in 20% of the simulations, the delayed introduction of lucerne increased the amount of drainage over the two years by > 80 mm. These different responses were found to be associated with different rainfall patterns that could potentially be used to identify years in which the delay of lucerne would not seriously increase the risk of deep drainage if longer term weather forecasts of at least a year in advance were available.

Sowing lucerne under wheat in the first year of the lucerne phase was not predicted to be as successful in reducing deep drainage as expected. It was found that it could also lead to increased deep drainage. The balance between positive (reduced deep drainage) and negative (increased deep drainage) impacts depended on how much water the system could use from November of the first year onwards, which was affected by lucerne vigour and wheat residue cover. Due to the increased popularity of establishing lucerne by undersowing, the development of better management strategies to maximise summer water use (e.g. optimum wheat and lucerne densities, optimum grazing practices) warrants further research. This will require experimental research into the effects of lucerne establishment, lucerne-wheat competition and grazing impacts on lucerne vigour and soil water dynamics. Current model capability is still too uncertain about these effects.

References

- Angus JF, Gault RR, Good AJ, Hart AB, Jones TD, Peoples MB (2000) Lucerne removal before a cropping phase. *Australian Journal of Agricultural Research* 51, 877–890.
- Asseng S, Fillery IRP, Anderson GC, Dolling PJ, Dunin FX, Keating BA (1998) Use of the APSIM wheat model to predict yield, drainage and NO₃– leaching in a deep sand. *Australian Journal of Agricultural Research* 49, 363–377.
- Cocks PS (2001) Ecology of herbaceous perennial legumes: a review of characteristics that may provide management options for the control of salinity and waterlogging in dryland cropping systems. *Australian Journal of Agricultural Research* 52, 137–151.
- Dolling PJ, Robertson MJ, Asseng S, Ward PR, Latta RA (2005) Simulating lucerne growth and water on diverse soil types in a Mediterranean-type environment. *Australian Journal of Agricultural Research* 56, 503–515.
- Dunin FX, Williams J, Verburg K, Keating B (1999) Can agricultural management emulate natural ecosystems in recharge control in south-eastern Australia. *Agroforestry Systems* 45, 343–364.
- Fischer RA, Armstrong JS, Stapper M (1990) Simulation of soil water storage and sowing day probabilities with fallow and no-fallow in southern New South Wales: I. Model and long term mean effects. *Agricultural Systems* 33, 215–240.
- Heritage Seeds (2005) Lucerne establishment & management. (<http://www.heritage-seeds.com.au/lucerne/info/lucerne-establishment.htm>)
- Isbell RA (1996) 'The Australian soil classification.' *Australian soil and land survey handbook*. (CSIRO Publishing: Melbourne, Vic.)
- Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software* 16, 309–330.
- Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18, 267–288.
- Lloyd DL, Johnson B, Teasdale KC, O'Brien SM (1998) Establishing ley legumes in the northern grain belt - Undersow or sow alone. *Proceedings 9th Australian Agronomy Conference, Wagga Wagga NSW, Australia, 20-23 July 1998*. (<http://www.regional.org.au/au/asa/1998/3/019lloyd.htm>)
- Lloyd D, Johnson B, Bullen K, Lowe K, Mackie J, Irwin J (2003) Lucerne in dryland farming systems: cultivar and management suggestions 2003. Queensland DPI & F note. (<http://www2.dpi.qld.gov.au/pastures/4295.html>)
- LWA (2001) Lupins and lucerne. A winning combination for groundwater management. *Salt*, October 2001, 20–21.
- McCallum MH, Connor DJ, O'Leary DJ (2001) Water use by lucerne and effects on crops in the Victorian Wimmera. *Australian Journal of Agricultural Research* 52, 193–201.
- Naji R (2004) Establishing Dryland Lucerne (Recommended Practices). Chapter 4, In: *Managing Dryland Lucerne - Grower's Handbook*. DPI Horsham, Vic (<http://www.dse.vic.gov.au/dpi/nrenfa.nsf>).
- PIRSA (2004) High winter active lucernes undersow SARDI initiative. p. 5 in *Open Gate July 2004*, Government of South Australia.

- Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* 56, 1 28.
- Ridley AM, Christy B, Dunin FX, Haines PJ, Wilson KF, the late A Ellington (2001) Lucerne in crop rotations on the Riverine Plains. 1. The soil water balance. *Australian Journal of Agricultural Research* 52, 263 277.
- Robertson MJ, Carberry PS, Huth NI, Turpin JE, Probert ME, Poulton PL, Bell M, Wright GC, Yeates SJ, Brinsmead RB (2002) Simulation of growth and development of diverse legume species in APSIM. *Australian Journal of Agricultural Research* 53, 429–446.
- Robertson M, Gaydon D, Latta R, Peoples M, Swan A (2004) Simulating lucerne/crop companion farming systems in Australia. *4th International Crop Science Congress (4ICSC)*, 26 Sep – 1 Oct 2004, Brisbane, Australia (http://www.cropscience.org.au/icsc2004/symposia/6/1/926_robertson.htm).
- Scott J (Ed.) (1995) Establishment of pastures on Kirby. Chapter 6, In: *The Pastures of 'Kirby' Farm – 1995*. University of New England, Armidale, NSW (<http://www.une.edu.au/agronomy/pastures/teaching/units/agro321/kirbypastassess/6.htm>).
- Snow VO, Smith CJ, Polglase PJ, Probert ME (1999) Nitrogen dynamics in a eucalypt plantation irrigated with sewage effluent or bore water. *Australian Journal of Soil Research* 37, 527 544.
- Srikanthan R, Zhou SL (2003), Stochastic generation of climate data, *CRC for Catchment Hydrology Technical Report* 03/12 (<http://www.toolkit.net.au/scl>).
- Srikanthan R, Chiew FHS (2003), Stochastic models for generating annual, monthly and daily rainfall and climate data at a site, *CRC for Catchment Hydrology Technical Report* 03/16 (<http://www.toolkit.net.au/scl>).
- Stanley M, Ridley A, Angus J, McCallum M (1999) New life for an old plant. GRDC Advice Sheet August 1999 (<http://www.grdc.com.au/growers/as/lucerne.htm>)
- Stirzaker R, Lefroy T, Keating B, Williams J (2000) A revolution in land use: Emerging land use systems for managing dryland salinity. (CSIRO Land and Water: Canberra)
- Thompson B (2005) Economics of lucerne establishment for the western wheat belt. NSW DPI PrimeFact 119.
- Verburg K, Ross PJ, Bristow KL (1996), SWIMv2.1 User Manual, Divisional Report 130, CSIRO Division of Soils, Australia.
- Verburg K, Bond WJ, Keating BA, Smith CJ, Robertson MJ, Hutchinson P (2001). Simulation of tactical use of phase farming to reduce deep drainage. *Proceedings 10th Australian Agronomy Conference*, Hobart TA, Australia, 29 January – 1 February 2001. (<http://www.regional.org.au/au/asa/2001/p/1/verburg.htm>)
- Verburg K, Bond WJ (2003) Use of APSIM to simulate water balances of dryland farming systems in south eastern Australia. Technical Report 50/03, CSIRO Land and Water, Canberra, Australia.
- Verburg K, Bond WJ, Srikanthan R, Frost AJ (2005) Predicting the impact of climatic variability on deep drainage under dryland agriculture. p. 1716-1722. Zerger, A. and Argent, R.M. (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005.
- Verburg K, Bond WJ, Brennan LE, Robertson MJ (2006) An evaluation of the tactical use of lucerne phase farming to reduce deep drainage. *Australian Journal of Agricultural Research* (submitted)

Wang E, van Oosterom E, Meinke H, Asseng S, Robertson MJ, Huth IN, Keating B, Probert M (2003) The new APSIM-Wheat Model - performance and future improvements. *Proceedings of the 11th Australian Agronomy Conference*, 26 February 2003, Geelong, Victoria.