An evaluation of the tactical use of lucerne phase farming to reduce deep drainage.

K. Verburg, W.J. Bond, L.E. Brennan and M.J. Robertson

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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)
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K. Verburg\textsuperscript{AD}, W.J. Bond\textsuperscript{A}, L.E. Brennan\textsuperscript{B} and M.J. Robertson\textsuperscript{C}

\textsuperscript{A}CSIRO Land and Water / Agricultural Production Systems Research Unit, GPO Box 1666, Canberra, ACT 2601, Australia.

\textsuperscript{B} CSIRO Sustainable Ecosystems / Agricultural Production Systems Research Unit, Queensland Bioscience Precinct, 306 Carmody Rd, St Lucia 4067, Australia.

\textsuperscript{C} CSIRO Sustainable Ecosystems / Agricultural Production Systems Research Unit, Private Bag 5, PO Wembley WA 6014, Australia.

\textsuperscript{D} Corresponding author; e-mail: kirsten.verburg@csiro.au

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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 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. There is, therefore, uncertainty about the optimum phase durations that will maximise the impact of the lucerne phase.

Computer simulations were applied to evaluate the use of a soil water measurement below the root zone of annual crops to schedule the phase changes, referred to as tactical phase farming. The results confirmed the concept behind phase farming. In general, phase farming showed clear benefits by reducing average annual deep drainage significantly, but at the cost of lower average annual gross margin. Tactical phase farming improved the trade-off between deep drainage and gross margin relative to fixed duration phases; for a given amount of average annual deep drainage the average annual gross margin was larger, and for a given gross margin the drainage was smaller. These benefits were small, however.

The average gross margins for the tactical systems were lower than those of fixed phase systems with the same percentage of time under cropping. This was especially the case when the tactical solutions resulted in short lucerne phases and contributed to the small benefits from tactical phase farming. Enforcing a minimum duration for the lucerne phase afforded improved benefits.

Climate and soil type influenced the results in that the benefits of tactical phase systems were largest compared with fixed phase systems in soils with a large available water holding capacity (resulting in a larger buffer) and when the variability of the refilling rate was high.

For soils with a small available water capacity, resulting in a small soil storage buffer, and with a climate that caused rapid refilling, the reduction in drainage as a result of incorporating a lucerne phase (fixed duration or tactical) was offset by the increased deep drainage that occurred during the first year of the lucerne phase. In these cases the deep drainage outcome of a phase system was a function primarily of the percentage of time under cropping and lucerne, and soil water measurements (tactical phase farming) did not result in any benefits over fixed duration phases.
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1. Introduction

Salinisation of farm land and increasing river salt concentrations are a source of great concern in parts of Australia. They are attributed to the mobilisation of stored salt by increased groundwater recharge resulting from the replacement of perennial native vegetation by annual crops and pastures (Black et al. 1981; Peck and Williamson 1987; Halvorson et al. 1988; Dunin et al. 1999). The source of the additional recharge is water passing below the (usually) shallower root zone of the introduced vegetation. In this report we will refer to water lost below the plant root zone as deep drainage.

Considerable effort has gone into finding management systems that reduce deep drainage. A promising option in the 300-600 mm rainfall zone is phase farming, in which lucerne (Medicago sativa L.), a perennial pasture with a deep root system, is grown in phase with annual crops (Stirzaker et al. 2000). It is based on the concept that because lucerne can extract water from the soil below the root zone of annual crops, it has the ability to "capture" water that has not been used by those crops before it is lost to the groundwater. By doing this it also creates a buffer which refills again under a subsequent phase of annual cropping (Figure 1).

The effectiveness of lucerne phase farming has been tested in a number of experimental field studies (e.g. Ridley et al. 2001; McCallum et al. 2001; Ward et al. 2002) and computer simulations of the system suggest large reductions in deep drainage are possible (Dunin et al. 1999; Keating et al. 2002). Uncertainty remains, however, about when to switch from one phase to the other to maximise the impact of lucerne. This is because refilling of the buffer depends on the amount and timing of rainfall (Ridley et al. 2001; McCallum et al. 2001; Verburg et al. 2006), both of which are highly variable (Verburg et al. 2005), as well as crop and summer fallow management (Verburg et al. 2004). The rate at which the buffer refills also depends on how much rainfall the system loses through runoff and evaporation from the soil surface as well as the water use of the annual crops, which determine how much water escapes past the bottom of the root zone of the annual crops each year. With the buffer zone wetting from the top it has been suggested that a soil water measurement just below the root zone of the crops might often give a timely warning of deep drainage occurring at deeper depth (below the root zone of lucerne, see Figure 1) and could therefore be used as a trigger for changing phases (Verburg et al. 2001; Verburg and Bond 2003).

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.
In this report we use computer simulations to test the idea that a soil water measurement made below the root zone of annual crops can improve the effectiveness of phase farming with lucerne for reducing deep drainage. We refer to this as the “tactical” use of lucerne phase farming and evaluate its impacts on predicted deep drainage and economic returns, the latter represented using gross margins for wheat and lucerne. We compare the tactical systems with systems having phases with fixed durations and study the effect of different soil water sensor placement depths, different sensor sensitivities, and the impact of climate and soil type. Elsewhere we explore the interaction of tactical phase farming with management options like delaying the introduction of lucerne and sowing lucerne under wheat in the first year of the lucerne phase.

To simplify the analyses wheat is used as the only annual crop, although in reality the cropping phase would most likely consist of a rotation of cereals and canola to minimise disease carry-over problems that one might normally experience in wheat-on-wheat systems. The model ignores any possible disease carry-over.

Deep drainage under dryland agriculture, and phase farming in particular, is extremely variable. Verburg et al. (2005) have shown that this is due to the fact that the ordering of wet periods in a climate record affects year-to-year soil water carry-over effects and also due to the timing of wet periods relative to the beginning and end of each phase. They suggested that the use of stochastically generated climate input into multiple simulations provided a better representation of the variability of the climate-soil-vegetation system than use of the historical climate record alone. This also had the advantage of allowing a better understanding of the potential outcomes and their probability of occurrence, while preserving the inherent nature of the historical record. In this report, therefore, most analyses were performed using, for each climate considered, 1 historical record and 100 stochastically generated records.
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 a 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. Long term simulated dryland agriculture scenarios

Four types of dryland agriculture systems were analysed (Table 1). The first was a continuous wheat system. Sowing of wheat (cv. Janz) 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 70% of crop residues were burned on 31 March with the remainder incorporated by tillage on 15 April. During the summer fallow 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/m$^{-2}$. If not already senesced, weeds were removed on 15 April.

The second system was continuous lucerne (cv. Sceptre), in which lucerne was resown every six years within the same sowing window between 1 May and 15 June and using the same rainfall rule. It was sown at a density of 70 stems/m$^2$ and harvested to a height of 50 mm at each flowering. After the first harvest the stem density was increased to 150 stems/m$^2$ and this density was maintained throughout the rest of the 6 year cycle. Final harvest of each cycle was on 15 December.

The other two systems used phases of lucerne and wheat. The systems are referred to as either "fixed", in which the wheat and lucerne phases were of set duration (1 to 4 years, see Table 1), or "tactical", in which the duration of each wheat and lucerne phase varied and the change from one phase to the next was prompted by soil water status below the root zone (at depths of 1.3 m, 1.7 m or 2.1 m). Sowing windows and conditions, fertilisation and management of residues and weeds in the summer fallow periods were identical to those of the continuous wheat and lucerne simulations. To simplify the analysis, all wheat crops in the phase systems were fertilised with the same amounts as in the continuous wheat system. This ensured that the system contained a well managed cropping phase, but prevented it from being used to analyse the effect of lucerne on nitrogen supply to subsequent wheat crops. 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 to 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.
In the tactical simulations we explored the effects of using different values of soil water status to trigger the decision to change phases and of evaluating the soil water status against these values at different depths. In each case the soil water status was defined in terms of a soil water potential. The driest soil condition used to trigger the phase change decision corresponded to a soil water potential of \(-800\) kPa; as soon as the soil at the trigger depth became wetter than \(-800\) kPa the decision was made in the model to switch to lucerne, and when it later became drier than \(-800\) kPa the model invoked the decision to return to a cropping phase. Other soil water potentials used were less negative (i.e. wetter) up to \(-10\) kPa (see Table 1). The depths at which soil water status was evaluated against the trigger values were 0.1, 0.5 and 0.9 m below the annual crop root zone, at depths of 1.3, 1.7 and 2.1 m. Soil water status was evaluated on 15 December for a change out of lucerne, with removal of the lucerne that same day if the change criterion was met. For a change into lucerne, the soil water status was evaluated on 1 March to allow for sufficient preparation time prior to opening of the sowing window on 1 May.

The simulations were run for a 48 year period (1957-2004). The first five years of the simulation period were used to allow the simulation to stabilise. These years were not included in the analyses, which focused on the period May 1962 – April 2004 (42 years, each running from 1 May until 30 April). In the case of the fixed phase systems this allowed a fixed number of complete cycles. The exceptions to this were the 2×2, 4×4, 2×3 and 3×2 fixed phase systems where the analysis period was reduced to 40 years (May 1962 – April 2002) to ensure inclusion of only full phase cycles. For both fixed and tactical phase systems, the simulations started with first year wheat in 1962, unless otherwise indicated. Tactical management started in 1962 for the tactical simulations, with a fixed 3×3 phase system run between 1957 and 1961.

**Table 1: Simulated dryland agriculture scenarios**

<table>
<thead>
<tr>
<th>Continuous wheat (CW)</th>
<th>Continuous lucerne (CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed phases (W×L)</strong></td>
<td>4×2 (4 years wheat, 2 years lucerne; 7 cycles)</td>
</tr>
<tr>
<td></td>
<td>4×3 (4 years wheat, 3 years lucerne; 6 cycles)</td>
</tr>
<tr>
<td></td>
<td>4×4 (4 years wheat, 4 years lucerne; 5 cycles)</td>
</tr>
<tr>
<td></td>
<td>3×2 (3 years wheat, 2 years lucerne; 8 cycles)</td>
</tr>
<tr>
<td></td>
<td>3×3 (3 years wheat, 3 years lucerne; 7 cycles)</td>
</tr>
<tr>
<td></td>
<td>2×2 (2 years wheat, 2 years lucerne; 10 cycles)</td>
</tr>
<tr>
<td></td>
<td>2×3 (2 years wheat, 3 years lucerne; 8 cycles)</td>
</tr>
<tr>
<td></td>
<td>2×4 (2 years wheat, 4 years lucerne; 7 cycles)</td>
</tr>
<tr>
<td></td>
<td>1×2 (1 year wheat, 2 years lucerne; 14 cycles)</td>
</tr>
</tbody>
</table>

| **Tactical phases** | Phase changes in response to soil water trigger at 1.3 m depth: out of lucerne when soil water potential \(\leq -800\) kPa, into lucerne when soil water potential \(>\) threshold potential values ranging from \(-800\) to \(-10\) kPa |
|                     | Phase changes in response to soil water trigger at 1.7 m depth: out of lucerne when soil water potential \(\leq -800\) kPa, into lucerne when soil water potential \(>\) threshold potential values ranging from \(-800\) to \(-10\) kPa* |
|                     | Phase changes in response to soil water trigger at 2.1 m depth: out of lucerne when soil water potential \(\leq -800\) kPa, into lucerne when soil water potential \(>\) threshold potential values ranging from \(-800\) to \(-10\) kPa |

* Additional variations: one scenario in which the phases were changed when the soil water potential was \(-200\) kPa, and one set of scenarios in which the lucerne phase was forced to be at least 3 years duration.
2.3. Historical climate input

Most of the analyses were carried out for the climate of Wagga Wagga, NSW based on the daily historical climate data (1957-2004) from the Australian Bureau of Meteorology station 73127 (Wagga Wagga Agricultural Institute, NSW), which was located close to the experimental site at Charles Sturt University. 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. To explore the effects of different rainfall conditions with higher average annual rainfall or a more Mediterranean distribution other historical climate records were used. They were from Harden (NSW), Maryborough (Victoria), and Moora (WA). Details of these climate records, average annual rainfall and seasonality of rainfall are included in Table 2. 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/).

Table 2: Location and rainfall statistics (1957-2004) of historical climate records used in the simulations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Bureau of Meteorology Station</th>
<th>Average annual rainfall (mm)</th>
<th>Seasonality of rainfall (% of rain May-Oct)</th>
<th>Australian rainfall zone¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wagga Wagga, NSW</td>
<td>73127, Wagga Agricultural Institute</td>
<td>553</td>
<td>56</td>
<td>Uniform</td>
</tr>
<tr>
<td>(35.05°S, 147.35°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maryborough, Vic.</td>
<td>88043, Maryborough Town</td>
<td>549</td>
<td>61</td>
<td>Mostly winter</td>
</tr>
<tr>
<td>(37.06°S, 143.73°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harden, NSW</td>
<td>73016, Harden Bundarbo Street</td>
<td>604</td>
<td>53</td>
<td>Uniform</td>
</tr>
<tr>
<td>(34.56°S, 148.38°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moora, WA</td>
<td>08091, Moora town</td>
<td>447</td>
<td>78</td>
<td>Dominant winter</td>
</tr>
<tr>
<td>(30.64°S, 116.01°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Definitions from Australian Bureau of Meteorology

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. Results for the other four climate records were similar. This provides confidence for using these additional climate records in the simulations to represent together the climates at the four different locations considered in this report.

2.5. Soil parameterisation

In our evaluation of tactical phase farming, we initially 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 report.

To explore the impacts of soil type, selected simulations were also performed using the soil hydraulic properties of an Orthic Tenosol (Isbell, 1996) from an experimental site near Moora, WA. This soil is best described as a deep sand. The soil and experimental site have been described in detail by Anderson et al. (1998). A detailed evaluation of APSIM against data from the experimental site was carried out by Asseng et al. (1998) and the soil properties have since been used in various simulation analyses (e.g. Asseng et al. 2001, Farre et al. 2004, Dolling et al. 2006), although mostly with an alternative water balance module in APSIM, the tipping bucket model SoilWat2 (Probert et al. 1998). Soil hydraulic parameterisation of this soil for the APSWIM module was obtained from Oliver and Smettem (2005; their field based parameterisation). The same parameterisation was also used by Ward (2006).

Only soil hydraulic properties were varied; soil fertility properties (parameterisation of the SOILN2 module) were kept the same as for the Red Kandosol. Therefore the simulations of deep drainage were not fully reflective of the conditions experienced at the Moora experimental site. In particular, deep drainage predictions would be underestimated due to the higher fertility of the Red Kandosol. Verification of the simulations was made by changing the fertility parameters, fertiliser additions, and weed management (no summer weeds) to match those of Asseng et al. (1998). This suggested that similar quantities of median annual deep drainage were predicted (99 vs. 109 mm/yr) for the same historical period (1910-1990). Using the same period was important as average rainfall for 1910-1990 was 460 mm, whereas for the period used in the analyses here (1957-2004) it was 447 mm.

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).

### 2.6. Biophysical model outputs

For each simulation scenario we determined the annual deep drainage, which was evaluated below the deepest roots at 3 m depth and averaged over the 42 year simulation. Unless otherwise noted, further statistical analysis, including a global mean, was performed using the average drainage values obtained for each of the 101 climate records (1 historical and 100 stochastic climate records).
In analysing the soil water dynamics under lucerne-wheat phase farming we also calculated the soil water deficit in the buffer zone (1.2 – 3 m) for selected scenarios. This deficit was calculated by subtracting the water storage at a given time from the soil water stored at the “drained upper limit” of the soil. This limit, also referred to as “field capacity”, represents the amount of water remaining in the soil after internal drainage has become negligible following a major wetting event. When the soil water deficit value is negative (i.e. the soil is wetter than drained upper limit), the risk of deep drainage therefore increases markedly.

While useful, the concept of field capacity or drained upper limit unfortunately does not have a firm theoretical basis (Koorevaar et al. 1983; Hillel 1982). Unless the groundwater table is shallow, gravity will ensure that internal drainage continues indefinitely. A precise definition of drained upper limit is therefore impossible because it depends on what is considered negligible flow. An operational definition often used by agronomists is the soil water stored after a soil has been fully saturated and then allowed to drain for two to three days. Strictly speaking the drainage time allowed should be varied according to the soil hydraulic properties, e.g. by using a neutron moisture meter to monitor the drainage process (Dalgliesh and Foale, 1998). Another common method for estimating the field capacity or drained upper limit is through association with given soil water potentials; values of between −10 and −33 kPa have been suggested in the literature (e.g. Marshall and Holmes, 1979; Cassell and Nielsen, 1986)). The APSIM-SWIM model assumes −10 kPa suction for this purpose, as also suggested by Marshall and Holmes (1979). As shown in Figure 2a, this soil water potential indeed appeared to be a good cut off for deep drainage for the Red Kandosol from the experimental site at Charles Sturt University. There was a marked increase in the risk of monthly deep drainage for negative soil water deficit values when the deficit was calculated relative to −10 kPa. For the Orthic Tenosol or deep sand from Moora, WA, however, −10 kPa was not a sensible limit for calculation of soil water deficits, as this resulted in deep drainage occurring well before the calculated deficits reached 0 mm (Figure 2b). In order to allow for comparisons between the different soils to be made, we calculated the soil water deficit for the Orthic Tenosol (Moora, WA) relative to the soil water storage at which the soil water deficit corresponded to a maximum monthly deep drainage of 5.5 mm. For the Orthic Tenosol this resulted in a correction of 75 mm to the soil water deficit that was previously calculated relative to −10 kPa (Figure 2a,b). It is equivalent to calculation of the soil water deficit relative to −28.4 kPa, a value that is compatible with the lower end of the range commonly associated with field capacity (−33 kPa) referred to above.

Figure 2: Relationship between simulated monthly deep drainage past 3 m and soil water deficit in the buffer zone (1.2-3m) at the end of the month; results from the cropping phase of the 3×3 fixed phase system; (a) Red Kandosol and Wagga Wagga climate, and (b) Orthic Tenosol and Moora climate. The dashed lines indicate the point at which deep drainage exceeds 5.5 mm/month and determines the correction to be applied to buffer zone deficit of the Orthic Tenosol.
2.7. Economic analysis

Gross margins were used as an appropriate measure of economic performance for comparisons of the ‘point’ or paddock-scale biophysical analyses considered in this report. Annual gross margins ($/ha) were calculated for the period 1 May – 30 April to match the analysis period for deep drainage. For a given year of the simulation, the annual gross margin was calculated for either wheat or lucerne, as determined by the phase. An average annual gross margin was obtained for each long-term scenario described above in the same way as for deep drainage by averaging over 101 simulations, each consisting of 42 years of various combinations of wheat and lucerne.

Wheat gross margins were calculated from simulated grain yield (adjusted to commercial moisture content, 12%) and simulated grain protein:

Wheat gross margin ($/ha) = 
\[ \text{grain price ($/t) \times wheat yield (t/ha)} - \text{wheat variable production costs ($/ha)} \]

The wheat variable costs were assumed to be $300/ha, consistent with variable costs reported in NSW Department of Primary Industries (2005) Farm Enterprise Budgets for the Southern Zone (East) region for 2004. Wheat prices used accounted for different quality grades, depending on the grain protein concentration (Table 3). They were based on the 2004/2005 AWB Estimated National Pool 1 Return ($/t FOB) (AWB 2006).

Pasture (rather than hay production) is the dominant use of dryland lucerne production in the study area (NSW Department of Primary Industries, pers. comm.). To calculate a gross margin to value the lucerne phase on an annual basis, it was assumed that lucerne pasture supported a sheep agistment activity. The rationale for this approach receives consideration in section 4, Scale of analysis. For the lucerne phase a lucerne establishment cost of $130/ha was used, derived from NSW Agriculture Farm Enterprise Budget for lucerne and subclover pasture for the Southern Zone (East) (NSW Department of Primary Industries 2005). This compares with $91/ha from Hirth et al. (2001) and $135/ha from O’Connell (2003). Based on Hirth et al. (2001), other variable costs included a superphosphate topdressing every second year (e.g. year 3 in the fixed 3×3 phase system) of $30/ha and $36 for grass seed and lucerne removal in the final year. Income from lucerne pasture was valued using an agistment fee of $0.07/sheep/day. The simulated biomass was converted to a usable dry matter production based on 65% utilisation efficiency. The number of sheep grazing days were based on a consumption of 1.5 kg/day of dry matter (NSW Department of Primary Industries 2006). In summary:

Lucerne gross margin ($/ha) = 
\[ \text{income from sheep agistment ($/ha)} - \text{variable production costs ($/ha)} \]

where, income from sheep agistment = sheep grazing days \times agistment fee ($/sheep/day)
and, sheep grazing days = usable dry matter (kg/ha) / consumption (kg/sheep/day)

As annual gross margins were calculated for the period 1 May – 30 April, this meant that the year of lucerne establishment and all subsequent years except the final year of the lucerne phase each reflected 12 months of growth (e.g. first and second year of fixed 3×3 phase systems). Lucerne production varied during the final year (e.g. third year of the fixed 3×3 phase system) in response to removal date (15 December or 15 February) resulting in 8.5 or 10.5 months of production, respectively.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Protein</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>APH&lt;sup&gt;1&lt;/sup&gt;</td>
<td>&gt;13</td>
<td>$214</td>
</tr>
<tr>
<td>AH&lt;sup&gt;2&lt;/sup&gt;</td>
<td>&gt;11.5</td>
<td>$204</td>
</tr>
<tr>
<td>APW&lt;sup&gt;3&lt;/sup&gt;</td>
<td>&gt;10</td>
<td>$197</td>
</tr>
<tr>
<td>FEED</td>
<td>&gt;0</td>
<td>$155</td>
</tr>
</tbody>
</table>

<sup>1</sup>APH=Australian Prime Hard,  <sup>2</sup>AH=Australian Hard,  <sup>3</sup>APW=Australian Premium White
3. Results and Discussion

3.1. Soil water dynamics under lucerne-wheat phase farming

To study the soil water dynamics under lucerne-wheat phase farming we first consider the fixed 3×3 phase system that was also simulated by Dunin et al. (1999) and Keating et al. (2001, 2002). The depletion by lucerne of soil water in the buffer zone and the gradual refilling of this buffer during the cropping phase was confirmed by the simulations of this system for the soil and climate of our experimental site at Wagga Wagga (Figure 3). Note that the values in Figure 3 are the deficit on 30 April in each year of the 6 year cycle. The variability in buffer zone deficit was determined using the combined results of 101 simulations (using 1 historical and 100 stochastically generated climate records), each containing seven 6 year cycles. The extent of refilling of the buffer zone, a process which reflects the balance between rainfall, runoff and evapotranspiration, was found to be already highly variable after just one year of cropping (Figure 3). This is due to the variability of both the amount and distribution of annual rainfall. The rainfall record has a coefficient of variation of 26% for annual rainfall in the period 1957-2004 (mean annual rainfall of 553 mm) and that of individual months ranges from 48% to 100% (average 75%).

The probability of deep drainage occurring in the subsequent 12 months under cropping increased with decreasing buffer zone deficit as determined on 30 April (Figure 4). For a deficit larger than 80 mm there was only a 5% probability of deep drainage in the next year exceeding 45 mm. For a deficit of between 10 and 30 mm this probability was increased to 25% and for a deficit of less than 0 mm it was increased to 68%. In the latter case drainage in the next/subsequent year always exceeded 14 mm.
Due to the variability shown in Figure 3 and Figure 4 the soil water deficit of the buffer zone created by lucerne sometimes prevented deep drainage for less than a year while in other cases there could be several years of cropping before deep drainage occurred. Simulations of the fixed 3×3 phase system showed that there was a 19% probability that deep drainage of more than 5 mm occurred within the first year of cropping (down from 70% for continuous wheat), while in 45% of the simulated 3×3 cycles there was still no deep drainage by the end of the third year (Table 4).

Table 4: Probability of annual (1 May – 30 Apr) deep drainage greater than 5 mm for continuous wheat, continuous lucerne, and cumulative by the end of the different years of the wheat phase in the fixed 3×3 phase system (3 years wheat, 3 years lucerne).

<table>
<thead>
<tr>
<th>Continuous wheat</th>
<th>Continuous lucerne</th>
<th>First year wheat</th>
<th>Second year wheat</th>
<th>Third year wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>5%</td>
<td>19%</td>
<td>39%</td>
<td>55%</td>
</tr>
</tbody>
</table>

The drying process under lucerne was less variable, with the maximum buffer zone deficit generally achieved after 2 years, or 2 summers in the simulated scenario (Figure 3). The buffer zone deficit was lower on average at lucerne removal on 15 December in the third year (86 mm) than on 30 April in the second year (90 mm) because winter rains sometimes wetted the soil in the buffer zone (Figure 5b). Later removal of the lucerne resulted in the buffer zone deficit being closer to the seasonal maximum (average 90 mm for lucerne removal on 15 February). The later removal of lucerne also increased the deficit at the start of the cropping phase (87 mm on average compared with 81 mm for December removal), because it resulted in a shorter fallow period and a decreased chance of soil water storage prior to cropping.
Figure 5: The simulated soil water deficit in the buffer zone (1.2 – 3 m depth) at the end of each month into (a) the cropping phase or (b) the lucerne phase of the fixed 3×3 phase system (3 years wheat, 3 years lucerne; Red Kandosol, Wagga Wagga climate). The two phases are defined to start on 1 May, so that 30 April (as presented in Figure 3) corresponds to months 12, 24 and 36. Box represents 25 and 75 percentiles, whiskers the 10 and 90 percentiles, and symbols the 5 and 95 percentiles, line and dots inside box indicate the median and mean, respectively. The period July to September is given by months 3-5, 15-17, and 27-29.
To optimise the timing of phase changes, in order to switch to lucerne before the buffer zone gets too wet and back to cropping as soon as it has dried out sufficiently, one needs a measure of the leakage of water past the root zone of the crops. Rather than determining the soil water deficit for the whole buffer zone, it can be seen in the historical simulation of the fixed 3×3 phase system in Figure 6a-c that the soil water status just below the root zone of the annual crop is a suitable and more practical alternative. It usually provided a timely warning of deep drainage occurring at 3 m depth. The soil water below the root zone is effectively an integrated measure of rainfall input and evaporative losses. It therefore appears promising for scheduling phase changes from the view point of reducing deep drainage risk. Of the two soil water measurements (Figure 6b,c) the soil water potential is more sensitive to change than the soil water content in the range between “lower limit” or “wilting point” (~1500 kPa) and the “drained upper limit” or “field capacity” (~10 kPa). Soil water potential based sensors would, therefore, be more suitable as triggers for changing phase than sensors measuring soil water content.

Figure 6: (a-c) Simulated deep drainage and soil water dynamics under a fixed 3×3 phase system and (d) deep drainage predicted for a tactical simulation using soil water potential (~800 kPa) at 1.7 m as a trigger for phase changes. The horizontal axis shows the phase in each year from 1962 to 2003 (W = wheat, L = lucerne). Historical climate record was used for these simulations.
3.2. Impacts on deep drainage of tactical management of phase changes

We tested the tactical approach of timing the phase changes according to changes in soil water status at a point below the root zone of annual crops by first using a soil water potential of \(-800\) kPa at 1.7 m depth to trigger the phase change decision. For the Red Kandosol of our experimental site at Wagga Wagga this corresponds to a soil water content that is 0.006 m\(^3\)/m\(^3\) wetter than the \(-1500\) kPa "lower limit" or "wilting point". If the soil at the trigger depth (1.7 m) was wetter than \(-800\) kPa on 1 March, the decision was made in the model to switch to lucerne in the subsequent sowing window; it did not switch back to wheat until the soil at that depth was dried to \(-800\) kPa again.

Compared with the fixed 3×3 phase system this approach reduced deep drainage in some years, as shown in Figure 6a,d. In other years, however, deep drainage increased depending on the timing of large rainfall events relative to the phase cycle. Over the 42 year analysis period and using 101 simulations (with 1 historical and 100 stochastically generated climate records) the average annual deep drainage was reduced from 16 to 12 mm (Table 5). Comparing the value of soil water potential against the trigger value at a shallower depth (e.g. 1.3 m) resulted, on average, in earlier phase changes and reduced the risk of deep drainage, whereas taking the measurements at deeper depth (e.g. 2.1 m) resulted, on average, in later phase changes and increased the risk of deep drainage (Table 5).

It is also clear from Table 5 that the largest reduction in deep drainage was achieved simply by the introduction of lucerne into the cropping system (a 24 mm/yr reduction on average in the fixed 3×3 phase system compared with continuous wheat). Tactical management of phase changes further reduced deep drainage, but on average its effect was much smaller (another 3 - 6 mm/yr). This effect was highly variable, however, as shown in Figure 7. Depending on the stochastically generated climate, the change in average annual deep drainage over 42 years due to introduction of tactical management could be anywhere between a 12 mm reduction and a 5 mm increase in average annual deep drainage for a trigger at 1.3 m and between a 15 mm reduction and a 10 mm increase for a trigger at 2.1 m. The extremely variable response is due to the large variability in rainfall (between and within years) and its timing relative to the position in the phase cycle (Verburg et al. 2005).

<table>
<thead>
<tr>
<th>System</th>
<th>Average annual deep drainage (mm)</th>
<th>% years under cropping</th>
<th>Average annual gross margin ($/ha)</th>
<th>Average annual wheat gross margin ($/ha wheat)</th>
<th>Average annual lucerne gross margin ($/ha lucerne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous wheat</td>
<td>40</td>
<td>100</td>
<td>566</td>
<td>566</td>
<td>-</td>
</tr>
<tr>
<td>Fixed 3×3 phases</td>
<td>16</td>
<td>50</td>
<td>368</td>
<td>545</td>
<td>190</td>
</tr>
<tr>
<td>Tactical, soil water trigger at 1.3 m</td>
<td>10</td>
<td>41</td>
<td>302</td>
<td>493</td>
<td>167</td>
</tr>
<tr>
<td>Tactical, soil water trigger at 1.7 m</td>
<td>12</td>
<td>48</td>
<td>333</td>
<td>509</td>
<td>173</td>
</tr>
<tr>
<td>Tactical, soil water trigger at 2.1 m</td>
<td>13</td>
<td>53</td>
<td>356</td>
<td>516</td>
<td>179</td>
</tr>
</tbody>
</table>
The rainfall variability and timing issues that caused the simulations with climate records sampled from the same population to behave so differently were also responsible for the apparent outlying behaviour of the simulation that used the historical climate record (black symbol in Figure 7). The historical record, while used to define the stochastically generated climate (see Materials and Methods, section 2.4), is only one realisation of the climate. Using only the historical record would have resulted in a different evaluation of the options than the more complete description of the potential climate variability using stochastically generated records. For example, on the basis of the historical record alone using the soil water potential at 2.1 m as the trigger would not have been considered favourable as it would have increased deep drainage, whereas the simulations with stochastic climate records suggest it is the trigger depth with the most win-win outcomes (outcomes with both a decrease in deep drainage and an increase in gross margin). The simulations using the stochastically generated climate sets also provide an understanding of the probability of different outcomes, which is not possible using the historical record alone (Verburg et al. 2005).
Figure 7: Simulated effect of the introduction of tactical decision making in phase farming (based on comparing soil water potential values at depths of 1.3, 1.7, and 2.1 m with the trigger value of -800 kPa) on average annual deep drainage and average annual gross margin ($/ha) in the 42 year analysis period using the historical climate record (black) and 100 SCL generated climate records (grey); 90 percent confidence intervals of mean (small ellipse) and overall population (large ellipse) are shown as well. The effects are shown as changes relative to the results for the fixed 3×3 phase system for each climate record used.
3.3. Gross margins of tactical systems compared with the fixed 3×3 phase system

Production impacts of tactical management depended on the depth of the soil water trigger. The shallow trigger at 1.3 m, which achieved the greatest reduction in deep drainage, reduced the proportion of years under cropping from 50% to 41% (Table 5). The average cropping phase duration for this system was reduced to 1.6 years, whereas the lucerne phase was on average 2.4 years (Table 6). As the lucerne pasture was calculated to be a lower value enterprise than wheat cropping, this shift towards more time under lucerne contributed to a reduced overall annual gross margin (Table 5).

Other factors in the reduced overall annual gross margin were the lower average gross margins for the wheat and lucerne years in the tactical systems (see Table 5). They were a consequence of the fact that because both cropping and lucerne phases were on average shorter there were also more phase changes (Table 6). In the case of lucerne the more frequent phase changes meant that the first year variable costs (due to establishment) were spread over a shorter phase, lowering the average annual lucerne gross margin. In the case of wheat, the simulations showed that yield was on average lower in the first and second years after lucerne in the tactical systems. Combined with the shorter cropping phases this resulted in lower average wheat gross margins. The lower yields were caused by the soil water storage at sowing being on average lower in the tactical systems, because when the soil was wet the system would have switched to lucerne. Any beneficial nitrogen impacts of the lucerne phase on wheat yield were not reflected in the results because the simulations were for well fertilised systems (see Materials and Methods, section 2.2).

With deeper soil water values used as the trigger, the proportion of years in cropping increased (Table 5) and the phase durations increased as well (Table 6). This contributed to higher average wheat and lucerne gross margins (Table 5), and an increase in average annual gross margin. The system based on a soil water value at 2.1 m achieved more cropping opportunities than the fixed phase system, but average gross margins were lower than for the fixed phases due to the lower wheat and lucerne gross margins, which were a consequence of the shorter phases.

As with deep drainage, the gross margin response over 42 years varied widely (Figure 7). The percentage of 42 year sequences that resulted in an improvement of average annual gross margin increased with increasing depth at which soil water was evaluated, but this was to some extent at the expense of the reduction in deep drainage. The percentage of years with both a positive effect on gross margin and a reduction in deep drainage relative to the fixed 3x3 phase system (win-win) increased from 10% with soil water evaluated at 1.3 m to 29% at 2.1 m.

Table 6: Average and maximum phase durations and number of phase changes for the tactical systems in comparison with the fixed 3×3 phase system. The simulations used the soil characteristics of the Red Kandosol and the climate data of Wagga Wagga.

<table>
<thead>
<tr>
<th>System</th>
<th>Average (Maximum) phase duration (yr)</th>
<th>Average number of phase changes*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wheat cropping</td>
<td>Lucerne pasture</td>
</tr>
<tr>
<td>Fixed 3×3 phases</td>
<td>3.0 (3.0)</td>
<td>3.0 (3.0)</td>
</tr>
<tr>
<td>Tactical, soil water trigger at 1.3m</td>
<td>1.6 (7.0)</td>
<td>2.4 (8.0)</td>
</tr>
<tr>
<td>Tactical, soil water trigger at 1.7m</td>
<td>2.0 (8.0)</td>
<td>2.4 (6.0)</td>
</tr>
<tr>
<td>Tactical, soil water trigger at 2.1 m</td>
<td>2.5 (18.0)†</td>
<td>2.4 (8.0)</td>
</tr>
</tbody>
</table>

* The number of lucerne to wheat phase changes is higher than wheat to lucerne phase changes in tactical systems because the simulations all start with first year wheat, i.e. they start with a lucerne to wheat phase change.
† The sequence of 18 wheat crops was for an exceptionally dry period, in which the average annual rainfall was only 404 mm/yr. The next longest sequence of wheat crops lasted 11 years.
3.4. Benefits of tactical management compared with other fixed phases

The preceding analyses have focussed on how the tactical phases compare with fixed 3×3 phase systems, which is only one option for a fixed phase system. Others, with longer or shorter phases and different proportions of wheat and lucerne could also have been chosen. Figure 8 shows the average benefits of the three tactical management options relative to those of a number of different fixed duration phase systems and the systems with continuous wheat or continuous lucerne. Benefits of a system relate to the trade-off between a reduction in average annual deep drainage and the average annual gross margin achieved by the system. From Figure 8 it is clear that any introduction of lucerne into the continuous annual cropping system (represented by continuous wheat) reduced deep drainage significantly, but always at an economic cost, as represented by gross margins. For this paddock scale analysis, there was no win-win situation relative to continuous wheat for the modelled wheat-lucerne systems, although it should be noted that the economic returns depend on market prices and opportunities, which could be explored further through sensitivity testing. The extent to which the trade-offs were significant for whole-farm economic performance is not assessed here, but the issue receives further consideration later in this report (section 4).

Figure 8: Predicted trade-off between average annual deep drainage and average annual gross margin for different fixed and tactical (~800 kPa trigger value evaluated at 1.3, 1.7 or 2.1 m depth) phase systems, continuous wheat (CW) and continuous lucerne (CL). Fixed phases are designated as number of years wheat × number of years lucerne. Average outcomes are represented by the 90 percent confidence intervals around the mean. The dotted line connecting CL and CW is added to assist visualisation. The Pareto front is tentatively drawn as an envelope. (Simulation results for the Red Kandosol and Wagga Wagga climate)

While gross margins of the phase systems did not exceed those of continuous wheat, based on the assumptions used in the analysis, there are some system changes that were on average win-win, e.g. a switch from 2×2 fixed phases to tactical phases with a soil water trigger at 2.1 m (Figure 8). The inherent systems dynamics are such that there is a limit to how far win-win changes can be pushed. In the x-y space of Figure 8 there is a set of optimal compromise solutions known as the "Pareto" optimal solution front, after the Italian Vilfredo Pareto (1848-1923) who first applied this concept in the context of economics. The Pareto optimal front represents the set of optimal solutions across deep drainage and economic criteria; no other solutions closer to the bottom right hand corner of the parameter space are possible. Choice between members of the Pareto optimal set is a trade-off – a reward in one dimension against a penalty in the other. It is not possible to come closer to the win-win situation (maximum yield for minimum deep drainage) than this front. For a given average annual deep drainage, the Pareto optimal solution would have the highest achievable gross
An evaluation of the tactical use of lucerne phase farming to reduce deep drainage

Margin and for a given average annual gross margin, it would have the lowest achievable average annual deep drainage. Along this front there are optimal solutions that focus more on deep drainage reduction and those that focus more on increasing gross margin. The objectives of the land manager determine the choice of solution. We have not attempted to determine the exact location of the Pareto optimal front, but it is tentatively drawn as an envelope around the scenarios considered in this report. It is clear, however, that, whatever its exact location, the tactical phases are closer to the Pareto optimal front than the fixed phases. The three tactical options chosen favour reduction in deep drainage rather than optimising economic returns.

The dotted line joining continuous lucerne (CL) and continuous wheat (CW) is a theoretical line of simple mixing of phases of different durations. Simple mixing of phases represents the situation when one considers multiple paddocks with similar hydrological positions in the landscape some of which are under permanent lucerne pasture while others are always used for annual cropping. The average trade-offs between deep drainage and gross margin would then be given by a point on the dotted line, depending on the proportion of the two types of paddocks. Both fixed and tactical phase systems fell below this line in Figure 8, indicating that for a given average annual drainage they achieved a higher average annual gross margin relative to simple mixing, or for a given average annual gross margin they resulted in less deep drainage. This is due to carry-over effects from one phase to the next, as will be explained in more detail later in the report (section 3.6). The results in Figure 8 suggest that for the combination of Red Kandosol and Wagga Wagga climate, using phase farming in all paddocks would result in more optimal solutions than a mosaic of dedicated lucerne pasture and cropping paddocks could achieve. Of course, whole farm issues such as flexibility and whole farm economics as well as catchment connectivity issues may override these benefits. They are discussed in more detail in the Scale of analysis section (section 4).

Comparison of the different duration fixed phase systems, shows that a higher percentage of lucerne in the system reduced both average annual deep drainage and average annual gross margin. The duration of phase also impacted on the balance between deep drainage and gross margin. The short 2x2 phase was sub-optimal compared with the 3x3 or 4x4 phases, despite having the same percentage of lucerne in the system. The main cause for this was that the gross margins of the shorter 2 year phases were not as favourable as those of longer duration, as discussed in the previous section for the tactical phase systems. In addition, the short 2 year lucerne phases increased the proportion of first year lucerne with higher deep drainage risk and the 2 year lucerne phase did not always allow for sufficient time to dry out the soil to reduce deep drainage during the subsequent cropping phase. For fixed phases a minimum of three years of lucerne therefore seems to provide a better probability of deep drainage control. The average lucerne phase durations of 2.3 – 2.4 years achieved by the tactical phases suggests, however, that in many cases (around 70%) 3 years is longer than required.

In Figure 8 the average trade-offs between deep drainage and gross margin for the different systems were given by the 90 percent confidence intervals around the mean, rather than just the means themselves, to acknowledge the variability of the outcomes. Variability was highest for continuous wheat and lowest for continuous lucerne. Variability of outcomes in the tactical phase systems was lower than that of fixed phase systems. This suggests that tactical phase systems may also have an advantage over fixed phase systems in having more predictable outcomes. The average trade-offs of the tactical phase systems were clearly different from the fixed phase systems. To simplify the presentation of further analyses later in this report, the average trade-offs will be presented by symbols reflecting only the global mean.
3.5. Effect of soil water trigger value

The value used to evaluate soil water potential and trigger a phase change in the tactical simulations presented so far was relatively stringent (−800 kPa). Very little wetting at the depth of the sensor was required to trigger a phase change into lucerne, while the soil had to be almost at wilting point before a change back to the cropping phase was triggered. For the Red Kandosol this corresponded to a volumetric water content of only 0.006 m³/m³ more than wilting point.

We also explored the effect of using less stringent triggers. In the first case, the trigger value at 1.7 m was replaced for both phase changes by −200 kPa; i.e. a phase change into lucerne occurred when the soil water potential was > −200 kPa and out of lucerne as soon as the soil water potential was ≤ −200 kPa. This corresponded to a volumetric water content of 0.02 m³/m³ more than the wilting point of the Red Kandosol. The predicted average trade-off between annual deep drainage and annual gross margin for this system is shown by the open symbol in Figure 9b. Compared with the original trigger value (−800 kPa) this relaxation caused an increase in both deep drainage and gross margin (Table 7, open symbol Figure 9b) and brought the result closer to those for the fixed phases. If the trigger value was only relaxed (to −200 kPa) for a phase change into lucerne, the increase in gross margin was similar, but deep drainage increased less (Table 7, Figure 9b). Relaxing the trigger value only for a phase change out of lucerne is not a practical option as it would often result in the system going straight back into lucerne due to the stricter trigger applied for the latter decision.

Figure 10 illustrates why there was more deep drainage when the trigger value was set to −200 kPa (at 1.7 m in this example) for a change of phase from lucerne to cropping. The whole profile was much wetter than if it was set to −800 kPa, increasing the risk of deep drainage significantly. It is therefore important that the soil water buffer be dried sufficiently for the tactical system to be a better option and be closer to the Pareto line of optimal solutions.

As the trigger value for changing into lucerne was relaxed further (to −10 kPa), while keeping the trigger value for changing out of lucerne at −800 kPa, the trade-off outcomes followed a line not unlike the Pareto line sketched in Figure 8. They all represent solutions that are slightly more optimal than the fixed duration phases (Figure 9a,b,c).

Table 7: Predicted percentage of years under cropping, average annual deep drainage, average annual gross margin, and average durations of wheat and lucerne phases for different soil water trigger values measured at 1.7 m depth (Red Kandosol, Wagga Wagga climate).

<table>
<thead>
<tr>
<th>Trigger phase change out of lucerne (kPa)</th>
<th>Trigger phase change into lucerne (kPa)</th>
<th>% cropping</th>
<th>Average annual deep drainage (mm)</th>
<th>Average annual gross margin ($/ha)</th>
<th>Average duration wheat phase</th>
<th>Average duration lucerne phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>−200</td>
<td>−200</td>
<td>52</td>
<td>14</td>
<td>343</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>−800</td>
<td>−800</td>
<td>48</td>
<td>12</td>
<td>333</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>−800</td>
<td>−200</td>
<td>50</td>
<td>13</td>
<td>347</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>−800</td>
<td>−50</td>
<td>53</td>
<td>13</td>
<td>357</td>
<td>2.5</td>
<td>2.4</td>
</tr>
<tr>
<td>−800</td>
<td>−20</td>
<td>58</td>
<td>15</td>
<td>378</td>
<td>3.0</td>
<td>2.3</td>
</tr>
<tr>
<td>−800</td>
<td>−17</td>
<td>65</td>
<td>19</td>
<td>409</td>
<td>4.0</td>
<td>2.3</td>
</tr>
<tr>
<td>−800</td>
<td>−15</td>
<td>71</td>
<td>23</td>
<td>433</td>
<td>5.1</td>
<td>2.3</td>
</tr>
<tr>
<td>−800</td>
<td>−10</td>
<td>76</td>
<td>25</td>
<td>454</td>
<td>6.2</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Figure 9: Predicted trade-off between average annual deep drainage and average annual gross margin for tactical phase farming (solid black circles) for a range of values of the trigger for switching into lucerne (−800 kPa to −10 kPa) when placed at (a) 1.3, (b) 1.7, and (c) 2.1 m depth. The systems were all switched out of lucerne when soil water potential dried to −800 kPa at the given depth. The open circle in (b) shows the result of using a −200 kPa trigger value for switching both into and out of lucerne. Black squares represent the continuous wheat and continuous lucerne systems, and grey symbols represent the fixed duration phases as in Figure 8. Dotted line connecting CL and CW added for reference. (Red Kandosol, Wagga Wagga climate record).
3.6. Impact of climate and soil type

It is interesting to examine how the deep drainage and gross margin outcomes for different phase farming scenarios change relative to each other in response to different climates and soil types. The climate at Maryborough has a similar long-term average annual rainfall to Wagga Wagga, but its monthly distribution is slightly more winter-dominant (Table 2). This increased the average annual deep drainage, but also increased average annual gross margins, especially that of the cropping phase, in all scenarios (cf. Figure 9 and Figure 11a). Introduction of lucerne phase farming reduced deep drainage quite effectively relative to continuous cropping, although the opportunity cost ($ loss in gross margin per mm reduction in deep drainage) was slightly higher than for the same soil with the Wagga Wagga climate. Tactical management for the Maryborough climate was more effective in reducing this opportunity cost than for the Wagga Wagga climate. This is shown by the larger gap between the fixed and tactical systems (cf. Figure 9 an Figure 11a). Using the slightly wetter climate of Harden, lowered the opportunity cost of reducing deep drainage by the introduction of lucerne (cf. Figure 9 and Figure 11b). The effectiveness of tactical management relative to fixed phases was similar to that for the same soil with the Wagga Wagga climate.

For all three climates used, tactical phase systems produced solutions that were more optimal, ie. they had lower average annual deep drainage than fixed phase systems for the same average annual gross margins. Using the winter dominant rainfall regime of Moora, WA and the local Orthic Tenosol (deep sand) produced a different result. In this case the tactical solutions were less optimal than the fixed phase systems (Figure 11c). This apparently surprising result is best explained by first considering only the effect that the different phase systems have on deep drainage. This can be achieved by removing the economic component and considering instead the percentage of time under cropping. The resulting graphs for three soil/climate combinations (Red Kandosol for Wagga Wagga and Maryborough climates, and Orthic Tenosol for Moora climate) are shown in Figure 12. They show that for a given percentage of time under cropping the tactical phase systems always reduced deep drainage compared with the fixed phase systems, although the difference was minimal for the Moora combination (Figure 12c). Tactical phase systems were most effective in reducing deep drainage for the Maryborough case (Figure 12b). Other features of Figure 11 and Figure 12 that warrant attention are the positions of the different fixed phase systems.
relative to the theoretical simple mixing line between continuous lucerne (CL) and continuous wheat (CW), and the fact in Figure 11c (Moora) no scenario provides a more optimal outcome relative to simple mixing.

Figure 11: Predicted trade-off between average annual deep drainage and average annual gross margin in different phase farming systems for three additional combinations of climate and soil type (a-c, as indicated). Tactical phase farming (closed black circles) used a range of soil water potential values at 1.7 m to trigger the switch into lucerne (-800 kPa to -10 kPa). The systems were all switched out of lucerne at -800 kPa. The black squares represent continuous wheat (CW) and continuous lucerne (CL) systems, and grey symbols represent the fixed phases. Dotted line connecting CL and CW added for reference.
Figure 12: Predicted average annual deep drainage as a function of percentage time under cropping for the Red Kandosol at (a) Wagga Wagga and (b) Maryborough, and (c) the Orthic Tenosol at Moora. Tactical phase farming (closed black circles) used a range of soil water potential values at 1.7 m to trigger the switch into lucerne (-800 kPa to -10 kPa). The systems were all switched out of lucerne at -800 kPa. The black squares represent continuous wheat (CW) and continuous lucerne (CL) systems, and grey symbols represent the fixed phase systems. Dotted line connecting CL and CW added for reference. For the continuous and fixed phase systems the percentages of time under cropping were set (see Table 1), whereas in the tactical systems the percentages of time under cropping were a result of the simulations and represent the average over 101 simulations of 42 years.
As discussed earlier (section 3.4), the dotted line joining continuous lucerne and continuous wheat is a theoretical line of simple mixing of phases of different durations. In reality the phase systems are characterised by carry-over effects, which reduce drainage during the first years of the wheat phase (consistent with the intent of lucerne phase farming) and cause increased drainage during the first year of lucerne (an unfortunate side-effect). These carry-over effects are illustrated for the 3×3 fixed phase system in Figure 13 for the Red Kandosol with Wagga Wagga climate. Average annual drainage in all three years of the wheat phase stayed well below that of continuous wheat, indicating that for this system the buffer deficit created during the lucerne phase had a relatively long lasting effect. The overall reduction in drainage (for the combined wheat and lucerne phases) was more than 50%, causing the average annual drainage to be below the simple mixing line in Figure 12a.

For the same soil type but the more winter-dominant rainfall distribution at Maryborough, the relative reduction in deep drainage was almost as effective during the wheat phase, but drainage increased quite dramatically during the first year of lucerne, causing the overall average to be just below 50%. The longevity of the buffer deficit at Moora, on the other hand, was significantly shorter, with drainage during the 3rd year of the cropping phase similar to that of continuous wheat. Again drainage during the first year of lucerne was high.

![Figure 13: Long-term average drainage during each year of the 3x3 fixed phase system scaled between long-term average annual drainage under continuous lucerne (CL, 0%) and continuous wheat (CW, 100%); Red Kandosol with Wagga Wagga climate in black symbols, with Maryborough climate in grey symbols, and Orthic Tenosol for Moora climate in open symbols.](image-url)

The limited carry-over effect in the first year of wheat after lucerne for the Orthic Tenosol at Moora are a function of the rapid refilling of a comparatively small soil water buffer between the bottom of the annual crop root zone and that for lucerne (average maximum deficit of 75 mm versus 94 mm for the Red Kandosol, see Figure 14a and Figure 3). At Moora the average annual drainage during the first years of the wheat phase and the first year of lucerne were unaffected by the duration of the preceding phase, provided that phase had lasted at least 2 years. Extending the phase durations beyond 2 years, therefore, made the overall average annual deep drainage a function of the proportion of time under these phases. As a consequence the different fixed systems collapsed onto a straight line in Figure 12c. For the Red Kandosol with Wagga Wagga or Maryborough climates the buffer deficits lasted longer on average and caused the 2×2 fixed phase system to have slightly higher drainage than the 3×3 or 4×4 fixed phase systems.
The rapid creation and refilling of the small buffer deficit in the Orthic Tenosol with the Moora climate determine that for this climate and soil combination, the reduction in drainage achieved by lucerne-cropping phase systems compared with continuous cropping is not so much a benefit of the creation of a buffer deficit, but more a function of the percentage of time spent as lucerne pasture. As a consequence and also because the annual variation in the rate of creation and refilling of the buffer deficit was small (Figure 14a), tactical phase systems did not provide much further reduction in drainage (Figure 12c).

Figure 14: Soil water deficit in the buffer zone (1.2 – 3 m depth) on 30 April (unless otherwise indicated) at different stages of the fixed 3×3 phase system (3 years wheat, 3 years lucerne, with December removal of lucerne); (a) Orthic Tenosol, Moora climate, and (b) Red Kandosol, Maryborough climate. The box represents 25 and 75-percentiles, the whiskers the 10 and 90 percentiles, the symbols the 5 and 95 percentiles, the solid line inside the box the median, and the dashed line inside box the mean. Data from seven 6 year cycles in 101 simulations.
When the buffer deficit is larger and the rate of refilling more variable, drainage reductions are achieved with tactical phase systems through optimising the timing of the phases on the basis of the soil water store. This is illustrated by comparing average drainage under first year wheat for the three soil/climate combinations (Orthic Tenosol with Moora climate, Red Kandosol with Maryborough and Wagga Wagga climates). For the Moora combination the cropping phase started with a maximum buffer deficit having little variability (Figure 14a) and as a consequence the average drainage for the first year of wheat was always the same (19 mm), regardless of the duration of the preceding lucerne phase (provided it was 2 years or more). Variability in buffer deficit at end of the 3 year fixed lucerne phase was highest for the Maryborough combination, allowing tactical phase farming based on subsoil water to make relatively large reductions in the following year by extending the lucerne phase when needed (Table 8). Later removal of lucerne at the end of the lucerne phase (15 February instead of 15 December) increased the average buffer deficit at the start of the cropping phase and reduced its variability. This reduced average drainage for the first wheat year, reducing the benefits of tactical phase systems (Table 8).

Unfortunately the tendency for phase changes to occur more often in the tactical phase systems results in lower gross margins, because there are more first year wheat crops with lower yield, more first year lucerne with lower productivity, and the lucerne establishment cost is spread over fewer years. For the Moora soil/climate combination, the lucerne phase duration resulting from using a trigger value of −800 kPa to switch back to cropping was on average 2.1 years (standard deviation 0.4). The tactical phase systems in Figure 11c, therefore, had similar results to those fixed phase systems with a 2 year lucerne phase (1×2, 2×2, 3×2, 4×2) and a similar percentage of time under cropping. For example a trigger value of −800 kPa for going into lucerne resulted in an average cropping phase duration of 1.1 years (standard deviation 0.2) and combined with an average lucerne phase duration of 2.1 years its trade-off between deep drainage and gross margin was similar to the 1×2 fixed phase system. If an additional constraint was used in the simulation scenarios for the Moora soil/climate combination, namely that the lucerne phase must be at least three years long, the gross margin outcomes of the tactical phase systems were improved, and their outcomes matched the fixed phase systems with ≥3 year lucerne phases (Figure 15).

<table>
<thead>
<tr>
<th>Climate / Soil combination</th>
<th>Month of lucerne removal</th>
<th>Average buffer deficit at start of cropping phase (mm), standard deviation shown in parentheses</th>
<th>Average drainage during first year of wheat phase (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed 2×2 phase</td>
<td>Tactical phase†</td>
<td>Fixed 2×2 phase</td>
</tr>
<tr>
<td>Wagga Wagga / Red Kandosol</td>
<td>Dec 78 (21)</td>
<td>87 (11)</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Feb 86 (14)</td>
<td>88 (10)</td>
<td>8</td>
</tr>
<tr>
<td>Maryborough / Red Kandosol</td>
<td>Dec 70 (25)</td>
<td>88 (6)</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Feb 86 (10)</td>
<td>86 (9)</td>
<td>12</td>
</tr>
<tr>
<td>Moora / Orthic Tenosol</td>
<td>Dec 71 (13)</td>
<td>72 (8)</td>
<td>19</td>
</tr>
</tbody>
</table>

† Trigger values used ensured average phase durations close to a 2×2 fixed phase system; −200 kPa for Wagga Wagga December removal (on average W×L = 2.3 ×2.4), −800 kPa for Wagga Wagga February removal (on average 2.1 ×2.0), −30 kPa for Maryborough December removal (on average 2.3 ×2.9), −200 kPa for Maryborough February removal (on average 2.0 ×2.0), and −40 kPa for Moora (on average 2.2 ×2.0).
An evaluation of the tactical use of lucerne phase farming to reduce deep drainage

Figure 15: Predicted trade-offs between average annual deep drainage and average annual gross margin in different phase farming systems for the Orthic Tenosol and Moora climate combination, where the tactical phase systems (black circles) are run with an additional requirement that the lucerne phase lasted at least 3 years. The black squares represent continuous wheat (CW) and continuous lucerne (CL) systems, and grey symbols represent the fixed phases. Dotted line connecting CL and CW added for reference.
4. Scale of analysis

The phase farming systems in this report and the management of phase changes have been simulated at the ‘point’, or paddock, scale. In reality management occurs at the scale of a whole farm, where multiple paddocks and a mix of enterprises are considered simultaneously. While not addressed in this study, the feasibility of implementing the tactical phase systems on a farm should be assessed in terms of whether there is sufficient flexibility at the whole-farm scale to switch different paddocks in and out of the pasture phase when indicated by a soil water measurement, and the impact it has on the total area of pasture on the farm. Tactical phase systems could result in the area of the farm under lucerne changing from year to year, rather than occupying a fixed proportion of the farm. O’Connell (2003) highlighted the sensitivity of whole-farm profitability to the area of lucerne on a farm. In the context of a WA mixed farming system, the profitability of including lucerne in the system was primarily due to savings on supplementary feed costs when the feed gap was experienced and the study identified an economically optimal area of lucerne, beyond which the economic value of lucerne diminished as a larger area was established.

In this report the economic analysis was based on gross margin comparisons, which were appropriate to the scale of the point/paddock scale biophysical simulations. However, the whole-farm considerations highlighted above place limitations on economic evaluation that is confined to the paddock-scale of analysis. Within these constraints, the analysis valued lucerne as a sheep agistment activity as a means of addressing the difficulties of valuing a farm’s livestock enterprise, a ‘whole farm’ activity, at the paddock scale. While agistment is not expected to be the dominant commercial practice for undertaking livestock production, the advantage of considering agistment value was that it only reflects that value contributed by the pasture under investigation, independent of the area, type and timing of other pasture on the farm. A further simplification in our analysis was that the agistment fee for lucerne pasture remained constant for all simulations, regardless of quantity of lucerne production. If, in reality, the variation in simulated lucerne pasture production mirrored a regional situation, agistment fees would be expected to reflect pasture supply and demand.

Another consideration in evaluating lucerne phase farming in a whole farm context is whether the time that it is necessary to keep paddocks under lucerne in order to reduce deep drainage results in an unprofitably large area of lucerne in wetter periods (Kingwell et al. 2003). In that context it is also important to realise that the different paddocks on a farm may be hydrologically connected and that not all parts of a farm contribute equally to groundwater recharge. Topography within the farm or within the wider catchment may determine locations where lucerne is more or less effective in reducing recharge and/or impact on stream salinity. This has been illustrated by Brennan et al. (2004) at the farm scale and Wang et al. (2004) at the catchment scale.

Quantifying the impacts of phase farming in terms of its effect on recharge in the catchment rather than just a reduction in deep drainage below the root zone determines the ultimate trade-off decision between environmental and economic impacts. This requires an understanding of local ground and surface water flows, which is not always available. The approach used in this report to evaluate phase farming at the point/paddock scale in terms of gross margins and deep drainage is therefore a starting point to explore the potential of different management strategies in a way that is independent of local conditions. For application at individual farms the analysis of benefits of tactical phase farming would need to take into account these whole farm profitability issues (in relation to optimal lucerne area and flexibility) and farm/catchment hydrology aspects, as well as considering local climate and soil types.
5. Concluding remarks

The principle behind lucerne phase farming for deep drainage control is the development, during the lucerne pasture phase, of a soil water storage buffer below the root zone of the annual crops that reduces the risk of deep drainage during the subsequent cropping phase. We found that while this principle holds, the reduction in drainage was to greater or lesser extent offset by the increased deep drainage that occurred during the first year of the lucerne phase (over and above drainage under established lucerne). Where the subsoil storage buffer was small and the climate caused rapid refilling, for example for the combination of Moora climate and Orthic Tenosol, increased deep drainage under first year lucerne offset the temporary decrease in deep drainage under cropping completely. In these cases the deep drainage outcome of a phase system was a function primarily of the percentage time under cropping and lucerne.

The small size of the subsoil storage buffer for the Orthic Tenosol analysed here was a consequence of soil hydraulic properties. In other cases, subsoil constraints which limit the depth of rooting of lucerne (Dolling et al. 2005; Ward et al. 2006) may produce a small subsoil storage buffer. The effectiveness of lucerne phase farming is not just determined by the size of the storage buffer alone. It is controlled by the size of the buffer relative to the rate of refilling. The latter is determined by the rainfall regime (amount and distribution) and the soil hydraulic properties in the root zone.

Where longevity of the subsoil storage buffer more than compensated for the increased deep drainage under first year lucerne, phase farming had clear benefits in improving the trade-off between average deep drainage and average gross margin (e.g. Red Kandosol with the Wagga Wagga climate, Figure 8). These benefits were slightly larger when the phase changes were tactically managed, especially where variability in rate of refilling was large (e.g. Red Kandosol with the Maryborough climate and lucerne removal in mid-December, Figure 11a). However, in general the benefits of tactical management were small.

The use of a soil water "measurement" below the root zone of the annual crops as trigger for tactical phase changes proved a useful way to characterise the state of emptying or refilling of the soil storage buffer. By varying the depth of "measurement" different balances between deep drainage and gross margin could be achieved (see e.g. Figure 7, Figure 8). An alternative and more effective way to vary the balance of the trade-offs was by changing the soil water potential at which the system was switched from cropping to lucerne. It is difficult, however, to determine what values of soil water potential to use as the trigger in order to achieve particular trade-offs between deep drainage and gross margin, without knowing more about the soil hydraulic properties. This is an area that would need further research before generalised guidelines relating to target trade-offs could be given.

The average gross margins for the tactical phase systems were lower than those of fixed phase systems with the same percentage of time under cropping. This was especially the case if the tactical solutions resulted in short lucerne phases, as for the combination of the Orthic Tenosol and the Moora climate. As a consequence the tactical phase systems often only provided slightly more optimal trade-offs and in the case of the Orthic Tenosol and the Moora climate they were worse than fixed phase systems with longer lucerne phases. The latter could be avoided by enforcing a minimum duration for the lucerne phase.

In extrapolating to the farm scale and considering multiple paddocks in similar hydrological positions in the landscape, the results presented here suggest that if the predicted trade-offs of phase systems are below the theoretical line of simple mixing of phases (Figure 8, Figure 11a,b), the use of phase farming in all paddocks could result in more optimal solutions than a mosaic of dedicated lucerne pasture and cropping paddocks could achieve. On the other hand, if the trade-offs of phase farming systems were above the line of simple mixing (Figure 11c), it may well be that dedicated paddocks for lucerne pasture and annual cropping would provide a better trade-off between deep drainage and gross margin.

The use of tactical phase farming in multiple paddocks introduces other issues. It may cause the total area under lucerne pasture to vary from year to year, which may compromise farm
management flexibility and impact on whole farm profitability. The agistment approach used here was chosen to allow gross margin comparisons at the paddock scale in isolation from the rest of the farm. Further evaluation of lucerne phases in a mixed-farming system with multiple paddocks should value lucerne pasture as a ‘whole farm’ activity and address the issues of flexibility and the economically optimal area of lucerne on the farm. The local landscape context and catchment connectivity should then be considered as well, to determine what mosaic of dedicated and phase farming paddocks would provide the most optimal solutions.
References


