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Summer forage cropping as an effective way to control deep drainage in south-eastern Australia—A simulation study

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Abstract

Excessive drainage of water beyond the root zone of agricultural plants is complicit in causing extensive dryland salinity in southern Australia. Opportunistically sowing summer forage crops within winter cereal rotations could be a flexible means of reducing this deep drainage whilst achieving additional livestock production. A simulation-based feasibility study was conducted to assess the effectiveness of summer forage cropping in altering the water balance and to predict any adverse effects on winter crop yield. At the study location in southern New South Wales an average of 37% of the 557 mm annual rainfall falls outside wheat growing season, i.e., in the summer fallow period. Summer cowpea crops planted in the fallow period were predicted to yield 1.3 t/ha of biomass on average (range of 0–5.7 t/ha) if sown every year. Crops failed to establish in 1 year out of 5, and predicted yield failed to exceed 1.0 t/ha in 52% of years. Compared with a wheat–fallow scenario, the wheat–cowpea systems increased evapotranspiration outside the wheat growing season by up to 40% depending on summer crop frequency. Continuous wheat–cowpea cropping reduced deep drainage by 62% but also reduced yields of following wheat crops by 13%. Opportunistic summer cropping was less effective than continuous summer cropping in terms of total deep drainage reduction but produced more biomass per crop sown, and incurred smaller yield penalties on wheat. The simulation results suggest that opportunistic summer forage cropping is effective in reducing deep drainage and, compared to lucerne phase farming systems, offers greater management flexibility and smaller winter crop yield penalties. Further studies are needed on the practicality and economic benefit of the proposed summer forage cropping.

Keywords: Water balance; Wheat yield; Cowpea; Climate variability; Modelling

1. Introduction

In southern Australia, native tress, shrubs and pasture have been converted into agricultural cropping and grazing systems on a huge scale (Hatton and Nulsen, 1999). Replacement of deep-rooted perennial vegetation with shallow-rooted annual crops and pastures has reduced the plant water use, leading to increased drainage below the plant root zone (deep drainage) and recharge to groundwater aquifers. The Australian landscape is characterised by high salt loads in subsoils, low surface relief for drainage water and low transmissivity of groundwater systems. The changed land use has altered the hydrological cycle, resulting in rising groundwater tables, mobilisation of salt towards surface soil and rivers, and subsequent land and river salinisation. While many farming systems in Australia are strongly water-limited, this salinisation process, caused by increased deep drainage, is threatening the sustainability of Australia's dryland agriculture. Along with engineering solutions like large scale water and salt interception along the rivers, changes in land use and farm management practice have been considered the primary means to mitigate the salinity problem (Stirzaker et al., 2000; Keating et al., 2002).

Unfortunately, management strategies for economic productivity and environmental performance are often in conflict; strategies to improve the long-term sustainability usually imply an economic cost (Keating et al., 2003b;

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Keating and Harle, 2004). This is the case in southern New South Wales (NSW) where rotational cropping with annual winter crops (mainly wheat and canola) in combination with grazed pastures is the dominant dryland cropping system due to favourable economic returns. Under this system, a summer fallow period extends from harvest time (November or December) through to the sowing time (May to end of June dependent on timing of rainfall) of winter crops. Summer cropping is not popular, due in part to unreliable rainfall. Concern for the environmental degradation associated with excess drainage under annual cropping has led to a search for new cropping systems and management strategies that are economically viable and environmentally benign.

A comprehensive modelling study to explore the water balance of different dryland farming systems in the Murray-Darling Basin (Keating et al., 2002) indicated that water excess (runoff plus deep drainage) is strongly episodic, with 60% simulated to occur in 25% of years. Water excess was highest for annual wheat cropping, lowest for continuous lucerne pasture, and intermediate for opportunity cropping (a mixture of summer sorghum and winter wheat cropping), and for systems combining cropping with lucerne. Increased perenniality and more intensive crop rotations including winter and summer crops seem to be the most effective ways to reduce deep drainage. However, most of the available options suggest trade-offs are likely, with perennial based systems being less profitable than annual cropping (Keating et al., 2003b; Verburg et al., 2007).

The inclusion of perennial lucerne in cropping systems has been studied through both field experimentation and modelling. Lucerne phase farming (3 years of lucerne followed by 3–4 annual crops) was found to be economically viable and reduce annual deep drainage by 60% compared to wheat–fallow systems (Hirth et al., 2001; Verburg et al., 2007). Further reduction in drainage could be achieved by tactically introducing lucerne into the cropping rotation when the soil profile was wet (Verburg et al., 2007). Companion cropping (directly drilling an annual crop into an existing perennial lucerne stand) was predicted to use more water than wheat–lucerne phase farming (wheat and lucerne each 3 years) in areas with annual rainfall less than 750 mm, but to suffer a larger reduction in winter wheat yield (Keating et al., 2002). Over-cropping lucerne with wheat was demonstrated experimentally in South and West Australia to achieve a similar water use to lucerne monoculture, but with a wheat yield penalty of 13–63% depending on site and season (Humphries et al., 2004).

Summer cropping, combined with winter annual crops, has the potential to reduce deep drainage, provide quality stock feed and weed control (e.g., Postlethwaite and Coventry, 2003), and to reduce winter crop waterlogging. However, it is likely to reduce yield of the following winter crop in some years due to reductions in stored soil water. In the Mediterranean-type climate in Western Australia, Robertson et al. (2005) predicted that wheat and summer sorghum cropping could reduce deep drainage by 3–25 mm/year, compared to annual wheat cropping alone, but subsequent wheat yields were decreased by an average of 10% at wetter and 30% at drier locations. Sorghum grain and biomass yields were not very reliable and so there did not appear to be a strong justification for summer cropping in that environment.

Climatic conditions in southeast Australia may be more conducive for summer cropping due to a more uniform distribution of rainfall, but there is lack of research on this issue. Increased evapotranspiration due to summer weed growth has been shown to reduce deep drainage (Verburg and Bond, 2003; Verburg et al., 2007).

In assessing the feasibility of summer cropping, analyses need to incorporate long-term climate variability, temporal patterns in cropping cycles and residue management, and interactions with local soil conditions as they combine to influence crop yield and the water balance. This suggests that insights into system performance from pre-experimentation modelling analysis would usefully inform the design of subsequent field experimentation. This paper presents such a simulation analysis. Summer crop (cowpea) production and associated impacts on winter crop (wheat) yield and water balance are modelled using the APSIM farming systems model (Keating et al., 2003a) and long-term historical data for Simmons Creek in southern NSW. Alternative sowing strategies for the summer forage crops are evaluated in an effort to improve the trade-offs.

2. Materials and methods

2.1. Site specification

The study site is on the middle slopes of the Simmons Creek catchment near Walbundrie in southern New South Wales (35.68°S, 146.71°E). Historical climate data from 1889 to 2005 were obtained from the SILO patched point database (www.bom.gov.au/SILO) for the Walbundrie station (Station No 074115, 35.69°S, 146.72°E). Annual rainfall ranges from 200 mm to 1030 mm with a mean of 560 mm (1889–2005). Rainfall is highly variable both inter- and intra-annually. On average, spring, summer, autumn and winter rainfall accounts for 27%, 20%, 23% and 30% of the annual rainfall, respectively.

The hydraulic properties of the soil used in the simulation are shown in Fig. 1. The Mesotrophic Red Kandosol (Isbell, 2002) is derived from Aeolian ‘parna’. It is widely used for cropping in surrounding areas and is the most extensive soil mapping unit in the Simmons Creek catchment. The soil has a sandy clay loam texture in the A-horizon, with light clay in the upper B-horizon grading to medium clay by 80 cm depth. Maximum soil depth exceeds 5 m. The soil has a capacity to store 139 mm of plant available soil water (PAWC, water held between −10 and −1500 kPa matric potential) in the profile to 1.5 m depth.

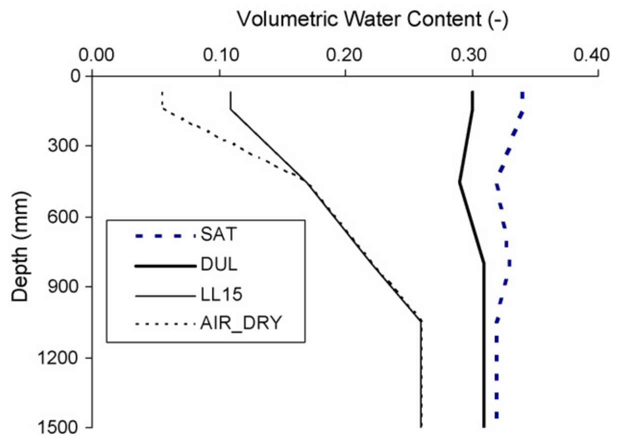

Fig. 1. Soil hydraulic properties of the study site in Simmons Creek, NSW, Australia. SAT, DUL, LL15 and AIR_DRY are the soil water content at saturation, drained upper limit, lower limit (−1500 kPa matric potential), and air dry water content, respectively (all laboratory-determined).

Wheat (*Triticum* spp.) and cowpea (*Vigna unguiculata*) were selected as representative winter and summer crops and their maximum rooting depth in this soil was assumed to be 1.5 m.

Soil water content profiles were initialised at the drained upper limit (DUL) on 1 January 1889. Simulations were run from 1 January 1889 to 31 December 2005. The first two years of simulation output were discarded to minimise impact of arbitrary initialisation assumptions on conclusions made from the modelling.

2.2. APSIM model and its validation

The agricultural production systems simulator APSIM 5.1 (Keating et al., 2003a) was used to simulate the performance of wheat–fallow and wheat–cowpea cropping systems. APSIM modules used included Wheat, Cowpea (Robertson et al., 2002); Soilwat2, Soiln2, and SurfaceOM (Probert et al., 1998); and a Manager module that allows conditional application of management rules. The APSIM-Wheat module in APSIM5.1 combines elements of earlier versions of wheat modules used in APSIM (Meinke et al., 1998; Keating et al., 2001; Wang et al., 2003).

APSIM is well tested, widely used in Australia (Keating et al., 2003a), and applied in different crop growing zones worldwide (Asseng et al., 2000). Earlier validation results of the APSIM-Wheat module are given in Wang et al. (2003). Performance of APSIM to simulate wheat systems in terms of crop yield, field water and nitrogen balance in areas close to the study site can be found in Verburg and Bond (2003), Lilley et al. (2003) and Lilley et al. (2004). Combined, these studies assessed model predictions against detailed field monitoring in long-term (6+ years) trials. A range of data was used including soil moisture data from soil coring and neutron moisture meter measurements, evaporation from weighing lysimeters, mineral nitrogen data from soil coring, and crop yield and biomass data. They concluded that in general the APSIM model is able to simulate wheat growth and yield, closely reproduce water balance measurements, reasonably simulate nitrogen balance, and reflect observed sensitivity in crop production and water balance due to management changes. APSIM has also been tested extensively in other locations and found to be robust, for example in terms of wheat growth and yield, soil water balance and summer soil water dynamics in the Western Australia wheat belt (Asseng et al., 1997, 1998; Dolling et al., 2006; Robertson et al., 2005).

The generic APSIM legume model has been tested on an independent set of experiments, predominantly from the tropics and subtropics of Australia, varying in cultivar, sowing date, water regime (irrigated or dryland), row spacing, and plant population density (Robertson et al., 2002). Simulation accuracy was found to be similar to that achieved by single-crop models suggesting that diverse legume species can be modelled without loss of accuracy or physiological rigour. APSIM-Cowpea, which is based on the generic legume model, has also received separate testing including cultivars, sowing date, irrigation, soil type, and row spacing (http://www.apsim.info/apsim/Publish/apsim/cowpea/docs/cowpea_science.htm).

As this study is a feasibility study, no specific model testing was conducted. Instead, we rely on the various verifications mentioned above. Model coefficients dictating the phenological development of the crops were selected based on typical local crop flowering and maturity dates. Agronomic variables such as dates of sowing windows, plant populations established, and rates of nitrogen fertiliser applied were chosen to reflect local practice as ascertained from local farmers and agronomists. No attempt was made to simulate the growth and impact of weeds.

2.3. Simulation scenarios

Wheat–summer fallow system ('WFS' – wheat–fallow with stubble): In this scenario, the wheat cultivar 'Janz' was sown every year at a sowing depth of 40 mm, if more than 20 mm of rainfall (cumulative) was received in a 10-day period, with the sowing window between 20th April and 30th June, or when the end of the sowing window was reached. At maturity, wheat grain was harvested and 30% of the stubble was removed to mimic light grazing. It was assumed that the remaining 70% of stubble become flattened and subsequently available for decomposition. Stubble remaining at the end of March was removed to simulate burning.

At sowing 50 kgN/ha was applied as fertiliser, and an extra 80 kgN/ha was applied during crop growth. This 130 kgN/ha applied is consistent with the practice of leading local farmers. Soil nitrogen was reset to 50 kgN/ha mineral N at sowing each year. Soil organic nitrogen and carbon were also reset every year to levels measured in the catchment in 2003 and 2004. Soil water was not reset at any time so that soil water carry-over effects from previous seasons were represented.

Wheat–summer fallow with early stubble removal (‘WFB’ – wheat–fallow with bare ground): In this scenario, 90% of wheat stubble was removed 4 days after wheat harvest, consistent with the stubble management in the wheat–cowpea scenarios described later. Everything else remained the same as in the WFS option above. Comparing this scenario with the WFS scenario will show the impact of early stubble removal. Comparison with wheat–cowpea scenarios will reveal the impact of summer forage cropping, independent of stubble management, on wheat yield and water balance (deep drainage).

Wheat–cowpea double cropping system: As in the WFB option, 90% of wheat stubble was removed 4 days after wheat harvest to simulate baling of straw. An early maturity cowpea cultivar ‘Banjo’ was chosen as a summer forage crop. The cowpea crop was sown at a depth of 40 mm with a plant density of 25 plants/m^2 (assuming direct drill into undisturbed soil). 25 kg N/ha was applied at sowing to assist crop establishment. The cowpea crop was harvested once it reached maturity or at the end of March, whichever occurred first. One day after cowpea harvest, 90% of the above ground residues were removed.

Four different sowing decision strategies were simulated and compared:

- WC4DS: A cowpea crop was sown every summer 4 days after wheat harvest.
- WCR20: A cowpea crop was sown only if more than 20 mm of rainfall (cumulative) was received in a 10-day period, with the sowing window extending from 4 days after wheat harvest to the end of January.
- WCS50: A cowpea crop was sown if more than 20 mm of rainfall (cumulative) was received in a 10-day period, with the sowing window extending from 4 days after wheat harvest to the end of January, and if the soil profile was at 50% or more of its plant available water capacity (PAWC).
- WCS75: A cowpea crop was sown if more than 20 mm of rainfall (cumulative) was received in a 10-day period, with the sowing window extending from 4 days after wheat harvest to the end of January, and if the soil profile was at 75% or more of its PAWC.

The cumulative rainfall was calculated each day for the last consecutive 10 days. Soil moisture was simulated each day and was checked whether it reached 50% or 75% of plant available water capacity.

The rationale for comparing the four alternative sowing strategies was that deep drainage events are highly episodic occurring in wet years, and that summer forage crops are likely to confer the largest wheat yield penalty in dry years when reliance on stored soil water is greatest. The trade-off between reduction in deep drainage and the yield penalty in the subsequent wheat crop can be manipulated through choice of summer forage sowing strategies. Evaluation of alternative sowing strategies should help understand how to achieve more reduction in deep drainage for less reduction in winter wheat yield.

2.4. Simulation analysis

Analyses focused on the opportunity of incorporating summer forage cropping into the current winter crop–summer fallow system, and comparing performance of the cropping systems in terms of their long-term average production and water balance. The following aspects were analysed:

- Summer forage sowing strategies as they affect the number of summer crops sown, winter wheat yield, and deep drainage.
- Impact of summer forage cropping on crop transpiration, evaporation and deep drainage as compared to a summer fallow.
- Impact of summer forage cropping on wheat grain yield.
- Amount of stored soil moisture at sowing and harvest of the wheat crops in the wheat–fallow and wheat–cowpea systems.
- Contribution of stored soil moisture to winter and summer crop growth.
- Likely trade-offs between reduced deep drainage with summer forage cropping and grain yield penalties in winter wheat.

In this paper, deep drainage refers to the drainage of water past 1.5 m depth in the soil profile (i.e., past the crop root zone). Water storage dynamics in the regolith beneath 1.5 m depth were not simulated and nor were lateral water fluxes.

3. Results

3.1. Impact of growing season rainfall and stored soil moisture on wheat yield and drainage

Fig. 2 shows the simulated wheat grain yield and drainage (in the wheat growing season) of the wheat–summer fallow system as affected by growing season rainfall and the stored plant available soil moisture at wheat sowing time (SSMS). Inter-annual variation of growing season rainfall could explain 73% of the variation in wheat grain yield (Fig. 2a). SSMS also affected wheat grain yield which tended to increase with greater SSMS (Fig. 2b). With increasing SSMS, the yield difference between wet and dry years became smaller with the minimum grain yield increasing with SSMS (Fig. 2b). The inter-annual variation of the sum of growing season rainfall and SSMS explained 77% of variation in wheat grain yield (Fig. 3a).

Deep drainage in the wheat growing season was also strongly correlated with growing season rainfall ($R^2 = 0.60$) (Fig. 2c). For years with growing season rainfall less than

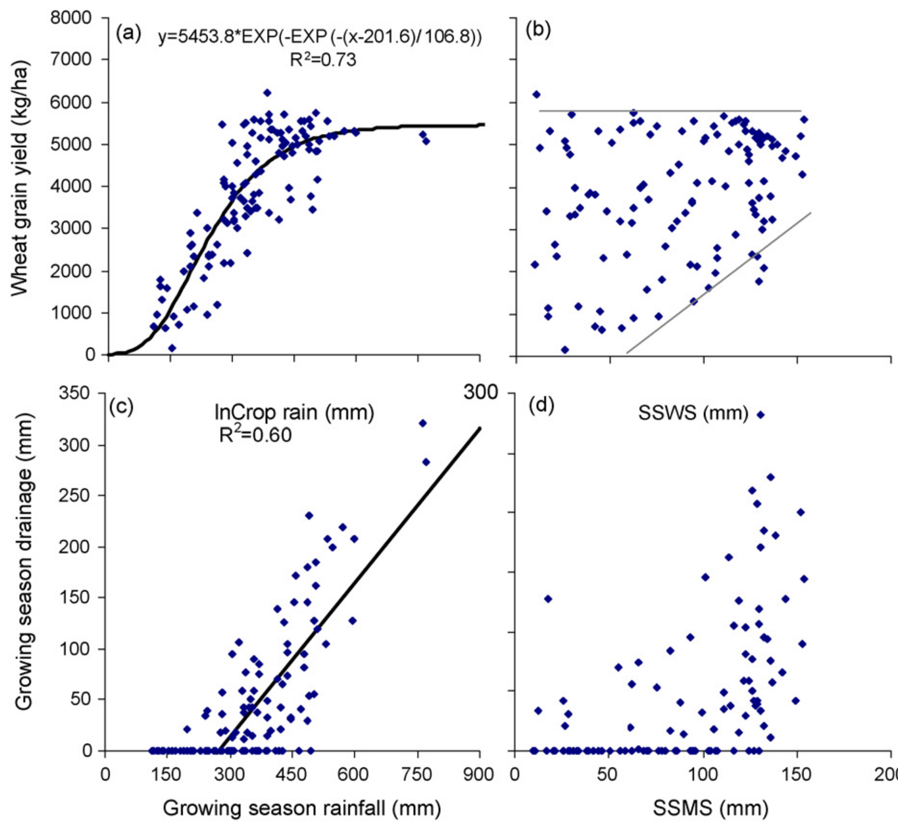

Fig. 2. Simulated effects of rainfall in the wheat growing season and stored soil moisture at sowing time (SSMS) on wheat grain yield and growing season drainage in a wheat–fallow system (WFS) at Simmons Creek. Regression lines in (a) and (c) were fitted for the purpose of R^2 and trend assessment. The two grey lines in (b) were drawn by eye to indicate the maximum and minimum grain yield for a given SSMS. The linear regression line in (c) was derived using data points with growing season rainfall greater than 200 mm.

200 mm, little drainage occurred (Fig. 2c). Growing season drainage increased with moisture storage at sowing, and if the soil profile was full at sowing time, drainage in the growing season was likely to occur (Fig. 2d). Growing season rainfall and SSMS together explained 73% of the variation of growing season drainage for the years with growing season rainfall greater than 200 mm (Fig. 3b). On average, drainage within the wheat growing season accounted for 72% of the total annual drainage, while the remainder was in the summer fallow period.

3.2. Rainfall in the summer fallow period, simulated biomass and water use of summer forage crop

The ranges of rainfall within the wheat growing season and the summer fallow period for years 1891–2005 are given

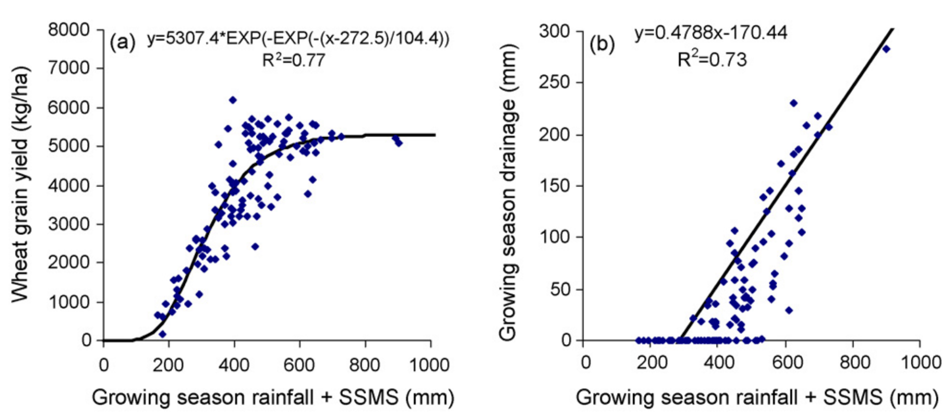

Fig. 3. Simulated effects of growing season rainfall and stored soil moisture at sowing time of wheat (SSMS) on (a) wheat grain yield and (b) growing season drainage in a wheat–fallow system (WFS) at Simmons Creek. Regression lines were fitted for purposes of R^2 assessment. The linear regression line in (b) was derived using data points with growing season rainfall greater than 200 mm.

Table 1
Rainfall distribution in the wheat growing season and summer fallow period (1891–2005)

	Rainfall (mm/year)		
	Annual	Wheat growing season	Summer fallow
Median	547	343	206
Mean	557	350	207
Min	200	111	74
Max	1030	772	437

in Table 1 and as probability of exceedance in Fig. 4a. On average, rainfall within the growing season and fallow period accounted for 63% and 37% of annual total rainfall, respectively. However, the 37% of annual rainfall during the fallow period could not be fully utilised by forage crops due to the variable temporal distribution of this rainfall and the fixed harvest date of the simulated forage crop.

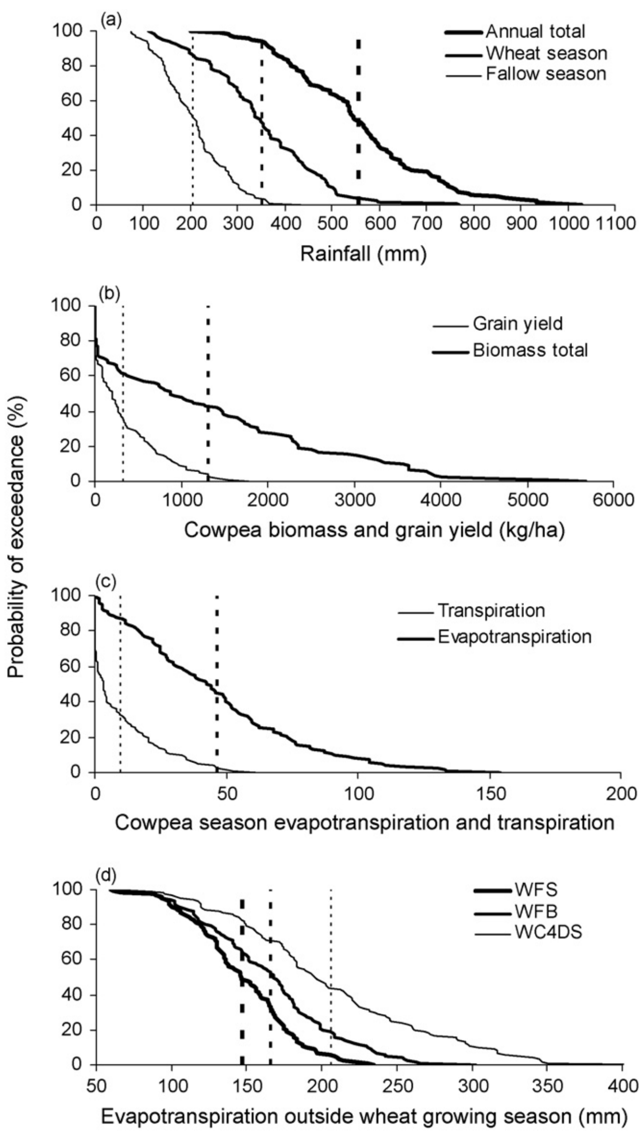

Fig. 4. Probability distribution of: (a) annual, wheat and fallow season rainfall in a wheat–fallow system (WFS); (b) simulated cowpea biomass and grain yield (WC4DS); (c) transpiration and evapotranspiration in the cowpea season (WC4DS); and (d) evapotranspiration outside of the wheat season in three simulated systems. The vertical dotted lines indicate the average values. Definition of scenarios see Table 3.

The different sowing strategies for cowpea resulted in different summer cropping frequencies as shown in Table 2. As sowing strategies became more conservative, i.e., requiring rainfall before sowing and then rainfall plus stored profile water: (a) the frequency of summer cropping decreased; (b) the percentage of crops that failed due to inadequate water decreased; and (c) the mean biomass yield per crop sown increased.

Sowing a cowpea crop every summer (WC4DS), resulted in a 19% probability (22 years) of complete crop failure (Table 2). The requirement for at least 20 mm of rainfall in 10 days preceding sowing (WCR20) resulted in 43 less summer crops sown over 115 years, avoiding 16 crops with no biomass production at all. The WCS50 and WCS75 sowing rules further restricted the number of cowpea crops sown, limiting plantings to 'wet-start' summer seasons and reducing the risk of low forage yield or complete crop failure.

There were some summers with a dry start and good subsequent rainfall. In these years, crops sown in the WC4DS scenario yielded well, but all or some of the other scenarios were not planted and hence missed the opportunity for forage yield and increased water use. Maximum cowpea biomass yield achieved was almost 5.7 t/ha although mean biomass yields (calculated per cowpea crop sown) for the WC4DS and WCR20 sowing strategies were 1.3 t/ha and 1.6 t/ha, respectively. The WC4DS option produced at least 2.0 t/ha biomass in 1 season out of 4 (Fig. 4b). Growing a smaller number of larger yielding summer crops, achieved for example by the WCS50 and WCS75 sowing rules, is likely to be more economically attractive given sowing and fertilisation costs. However, additional livestock feed may be of more value in dry seasons than in wetter years when feed is more plentiful.

The simulated cowpea growing duration did not vary greatly between the different sowing strategies (Table 2). The growing periods reflected crops with shortened season due to water stress, or late attainment of rainfall and water storage sowing requirements.

The simulated evapotranspiration outside of the wheat growing season, referred to as 'out-of-season' water use, is shown in Table 3. Summer cowpea crop season duration is only part of the out-of-season period—there is 4 days between wheat crop harvest and cowpea sowing and then an additional fallow period from cowpea harvest through until the sowing of the next wheat crop. Fig. 4 includes water use data for both out-of-season (Fig. 4d) and cowpea growing season (Fig. 4c).

Sowing cowpea crops increased the out-of-season evapotranspiration (ET) relative to that achieved through fallowing. Compared to the WFS option, the WFB strategy (removing stubble earlier) increased ET by 12% (18 mm), and the WC4DS strategy increased ET by 40% (59 mm).

Table 2
Simulated cowpea biomass under different management strategies in the summer fallow period at Simmons Creek (1891–2005)

Treatment	Cowpea sown years and mean growing period			Predicted biomass per cowpea crop sown			
	Crops sown (years)	Zero biomass (years)	Duration (days)	Median (kg/ha)	Mean (kg/ha)	Min (kg/ha)	Max (kg/ha)
WC4DS	115	22	88	867	1309	0	5679
WCR20	72	6	84	1279	1614	0	4795
WCS50	34	2	85	2505	2479	0	4795
WCS75	21	1	84	3260	3023	0	5206

WC4DS – wheat–cowpea rotation with cowpea sown 4 days after wheat harvest every year. WCR20 – wheat–cowpea rotation with cowpea sown in a sowing window between 4 days after wheat harvest and 31 January only when 20 mm of rain accumulated in 10 consecutive days. WCS50 – same as WCR20, but cowpea sown only when soil water reaches 50% of plant available water capacity. WCS75 – same as WCR20, but cowpea sown only when soil water reaches 75% of plant available water capacity.

The WCR20, WCS50 and WCS75 increased ET by 30% (45 mm), 26% (39 mm) and 23% (34 mm), respectively (Table 3, Fig. 4d). The more conservative summer crop sowing strategies resulted in a comparatively smaller number of crops, with larger per crop biomass yield and per crop evapotranspiration.

3.3. Impact of summer forage crops on stored soil moisture and deep drainage

Introduction of a summer forage crop reduced stored soil moisture at wheat sowing (Table 4; Fig. 5a). Compared with the wheat–fallow system (WFS), sowing cowpea every year (WC4DS) was predicted to reduce the stored plant available soil moisture at wheat sowing time by a mean of 47 mm (53%). Evapotranspiration from the cowpea crop accounted for 44% of the reduction in SSMS whilst early removal of wheat stubble (4 days after harvest) contributed the remaining 9%. The reduction in SSMS became less as cowpea cropping frequency decreased (Table 4; Fig. 5a).

Sowing a cowpea crop every year (WC4DS) reduced the annual variation in SSMS as well as the mean value (Fig. 5a) in comparison with the tactical (opportunistic) sowing rules and the wheat–fallow systems. Carry-over effects from changes in SSMS after summer forage cropping resulted in a maximum 8% reduction in stored soil moisture at wheat harvest (WC4DS), and this effect was reduced as cowpea crop frequency decreased in the more conservative sowing strategies (Table 4, Fig. 5b). Where tactical cowpea sowing decisions were adopted to avoid summer crops in dry seasons (e.g., WCS50, WCS75), there was almost no stored soil water carryover effects beyond the first wheat crop following the cowpea.

Under the wheat–cowpea systems, the increased out-of-season ET and reduced soil water storage at wheat sowing resulted in reductions in annual deep drainage (Table 4; Fig. 5d). Compared to a wheat–summer fallow (WFS) sowing a cowpea crop every year (WC4DS) increased out-of-season ET from 149 mm to 208 mm (Table 3). It reduced annual deep drainage from 64 mm/year to 24 mm/year (62%). Invoking tactical sowing rules for cowpea reduced the cowpea crop frequency and thus the overall impact on annual deep drainage, but the decrease in drainage was large in proportion to the number of cowpea crops sown. For example, the WCS50 strategy results in a 42% reduction in deep drainage (compared to the WFS), achieved by sowing a summer crop in less than 1 year in three. The WCS75 strategy gave a 38% reduction in deep drainage from a cowpea crop sown less than 1 year in 5 (Tables 2 and 4).

Comparing the statistical distribution of annual deep drainage values (Fig. 5d) shows the effectiveness of the summer forage crop in mitigating large less frequent drainage events. Sowing cowpea every year (WC4DS) substantially reduces the 75, 90 and 95 deep drainage percentiles compared to the wheat–summer fallow systems (WFS). There is evidence that these large, less frequent drainage events are significant in terms of groundwater recharge in some locations (e.g., Hekmeijer and Dawes, 2003). That the tactical sowing rules missed sowing summer forage crops in some seasons (dry start) with substantial summer rainfall reduced the overall effectiveness of these deep drainage control strategies. Removal of wheat stubble four days after wheat harvest (WFB), instead of end of March (WFS) was predicted to reduce annual deep drainage by 12 mm/year (19%) (Table 2, Fig. 5d).

Table 3
Mean out-of-season water use (mm)

Treatment	All years				Years when cowpea crop was sown			
	E	T	ET	E/ET	E	T	ET	E/ET
WFS	149	0	149	1.00	0	0	0	–
WFB	167	0	167	1.00	0	0	0	–
WC4DS	156	52	208	0.75	156	52	208	0.75
WCR20	159	35	194	0.82	174	56	230	0.75
WCS50	162	26	188	0.86	189	88	278	0.68
WCS75	163	19	183	0.89	209	105	314	0.67

WFS – wheat–fallow with wheat stubble burnt at end of March. WFB – wheat–fallow with wheat stubble burnt directly after harvest. All other treatments see Table 2. (Note that prediction of zero transpiration in the wheat–fallow (WFS, WFB) treatments simply reflects the assumption of no weeds being present).

3.4. Impact of summer forage crops on wheat yield

Reduction in wheat grain yield, due to less stored soil water after a summer crop, is the trade-off for the reduced

Table 4
Simulated wheat grain yield, annual drainage, stored plant available soil moisture at wheat sowing and harvesting time under different management strategies in the summer fallow period at Simmons Creek (1891–2005)

Treatment	Wheat yield (kg/ha)	Annual drainage (mm)	Soil moisture at sowing (mm)	Soil moisture at harvest (mm)
WFS	3832	64	88	48
WFB	3759	52	80	49
WC4DS	3325	24	41	44
WCR20	3460	35	54	47
WCS50	3589	37	61	48
WCS75	3684	40	67	48
Percent change (%) relative to WFS				
WFS	0	0	0	0
WFB	−2	−18	−9	2
WC4DS	−13	−62	−53	−8
WCR20	−10	−46	−38	−3
WCS50	−6	−42	−31	−2
WCS75	−4	−38	−24	0

Definition of treatments see Tables 2 and 3.

deep drainage achieved by the summer forage cropping system. The simulations suggest that growing a cowpea crop every summer (WC4DS) would confer a 13% reduction in wheat grain yield—a 507 kg/ha yield penalty on average when compared to wheat–summer fallow (WFS). The effectiveness of the tactical cowpea sowing strategy in avoiding double cropping in the drier seasons was demonstrated by the reduced wheat yield penalty with those treatments as shown in Table 4.

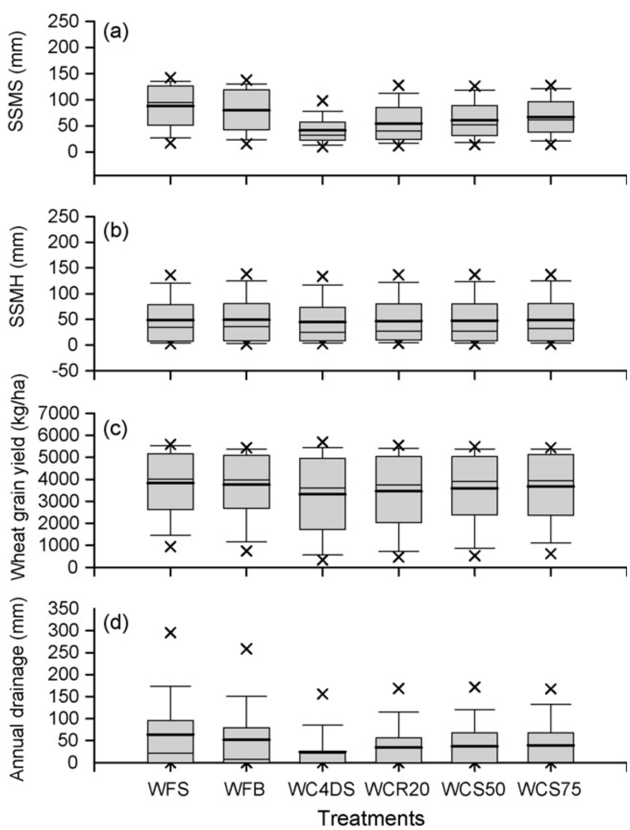

Fig. 5. Simulated distribution of (a) stored plant available soil water at wheat sowing time (SSMS); (b) stored plant available soil water at harvesting time (SSMH); (c) wheat grain yield; and (d) annual drainage under different management strategies in the summer fallow period. Horizontal bars and lower and upper edges of the boxes indicate the 10, 25, 75 and 90 percentiles, thin and thick lines in the box are the median and averages, the thin crosses are the 5 and 95 percentiles. For other abbreviations see Table 4.

The more risky sowing of a summer crop every year (WC4DS) increased the annual variation in wheat grain yield (Fig. 5c). As summer cropping reduced stored soil moisture at wheat sowing time, it made the wheat crop more reliant on growing season rainfall. In dry years, this increased the likelihood of poor wheat yield. Increasingly variable wheat yields are undesirable both in terms of cash flow and judging appropriate levels of inputs such as nitrogen fertiliser. The tactical sowing strategies for cowpea reduced the annual variation in wheat yield as well as the size of the yield penalty in comparison with continuous double cropping.

4. Discussion

Introducing summer crops into winter wheat systems (i.e., double cropping) in wet seasons appears to offer substantial reductions in annual deep drainage; but tradeoffs between drainage reductions and forage production on the one hand and wheat yield reductions on the other are unavoidable. However, different tactical (opportunistic) sowing strategies change the trade-off. Adopting a tactical approach as compared to continuous double cropping resulted in more forage production per crop, less failed summer crops, and less reduction in wheat grain yield, but also lessened the degree of deep drainage mitigation. Sowing rules could be further enhanced, for example the development of tactical sowing rules that incorporate rainfall forecasting could better match summer crops to summer season water availability. Accurate medium term weather forecasting would be required. A companion project is investigating the value of current and improved climate forecasts in assisting such decision-making.

Impacts on crop production from waterlogging were not considered in the simulation analysis presented here. Waterlogging is relevant however, cowpea crop yield is reduced in wet conditions, and a summer crop could have positive effect by reducing waterlogging yield loss in a subsequent wheat crop during a wet season. On soils subject to waterlogging, there might be (wet) seasons in which both cowpea forage production and wheat grain production have been overestimated in this analysis. The Red Kandosol soil used for this feasibility analysis is well structured and its development reflects well drained landscape positions. Crop waterlogging is not common on this soil.

Phase farming systems with lucerne have been investigated recently, also with the objective reducing deep drainage while retaining practicality for farmers. Verburg and Bond (2003) modelled the impact of lucerne phase farming on average annual drainage at Wagga Wagga (NSW) including consideration of weeds in the fallow period and removal of wheat residue at wheat harvest. Their study pertained to a similar soil in a nearby location but considered a different climatic period (1957–2005) compared to the study reported here (1891–2005). Results of the two studies are broadly consistent given differences in the time periods and the scenarios considered. Lucerne phase farming achieved a 59% reduction in drainage but it was accompanied by lost cropping opportunities in 50% of the years (fixed 3-year phases) (Verburg and Bond, 2003).

In comparison, the summer forage cropping was predicted to deliver up to 62% reduction in annual drainage (mean annual drainage from 64 mm/year under WFS to 24 mm/year under WC4DS), similar to the impact of lucerne phase farming with tactical decision-making. It would however only reduce mean wheat yield by 13% and does not preclude the sowing of any wheat crops. In contrast with lucerne, the summer forage is a short-term proposition that can be implemented on a year-by-year basis. It does not require locking into a multi-year forage phase. While lucerne phase farming has been considered as an effective option to mitigate deep drainage and retain economic productivity, summer forage cropping would seem a more flexible management option.

Drawing research findings from other studies and local farmers' experiences together with the results of this study, summer cowpea forage crops in combination with winter cereal cropping would appear to have potential advantages and disadvantages including the following:

4.1. Advantages

- Reduced deep drainage.
- Provision of high quality summer livestock feed (Muldoon, 1985) (also suitable for haymaking).
- Weed control (Postlethwaite and Coventry, 2003).
- Contribution to soil fertility through nitrogen fixation and organic matter addition (note that there could be a net export of nitrogen if a cowpea crop uses readily available nitrogen and the dry matter is removed from the field).
- Reduction in yield losses in wheat through mitigating waterlogging.

4.2. Disadvantages

- Wheat grain yield penalty.
- Costs associated with producing an extra crop.
- Extra labour requirement some of which is around the New Year holiday period.
- Extra nutrient demands and pressure on the soil resource through increased farming intensity.
- Additional farm management complexity.

Whilst this feasibility study has addressed only some of the advantages and disadvantages for summer forage cropping, the other considerations listed above require further investigation as part of a broader assessment of the feasibility and profitability of such systems. An economic cost–benefit analysis would be worthwhile, particularly given uncertainty about how the cost of lost winter crop yield might compare with returns from forage biomass and benefits from improved weed control. High forage biomass would be produced in wet seasons, likely coinciding with other sources of stock feed being available and stock feed prices being lower. This might be offset by the suitability of cowpea for high quality hay.

The predictions reported here, although they come from a robust and well-verified modelling platform, would also benefit from further testing, especially in relation to the performance of the cowpea model in southern NSW.

5. Conclusions

Opportunistic summer forage cropping would seem to be a management option with good potential for farmers seeking to reduce deep drainage and thereby help prevent further dryland salinity in Southeast Australia. The amount of summer rainfall plus the stored soil moisture available at the study location was predicted to support average summer forage biomass production of more than 1.3 t/ha (ranging from 0 to 5.7 t/ha) for the cowpea cultivar considered. Sowing such a forage crop every summer increased evapotranspiration outside the wheat-growing season by 40% (59 mm) compared with customary fallow, lowering stored soil moisture at wheat sowing time by 53% (47 mm). This reduced the predicted annual drainage by 62% (from 62 mm/year to 24 mm/year) but at the cost of a 13% (507 kg/ha) decrease in wheat grain yield. Growing a summer crop every year would not be desirable. However, less frequent, tactical sowing is feasible and can improve the trade-off. Summer forage cropping appears to have advantages over lucerne phase farming, which is recognised as an effective strategy to reduce deep drainage—drainage reduction is comparable, associated winter wheat yield loss is smaller, and the system is more flexible to manage. Summer forage cropping systems could be enhanced by identifying better summer crop sowing decision rules using early rainfall patterns and soil moisture content in conjunction with improved long-term weather forecasting.

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