Do spring cover crops rob water and so reduce wheat yields in the northern grain zone of eastern Australia?

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Abstract. During the 14-month-long fallow that arises when moving from summer to winter crops, stubble breakdown can denude the soil surface and leave it vulnerable to erosion. Cover crops of millet have been proposed as a solution, but this then raises the question, how often is there sufficient water in the system to grow a cover crop without reducing the soil water reserves to the point of prejudicing the following wheat crop? An on-farm research approach was used to compare the traditional long fallow (TF) with a millet fallow (MF) in a total of 31 commercial paddocks over 3 years. Each treatment was simulated using the simulation-modelling framework (APSIM) to investigate the outcomes over a longer timeframe and to determine how often a millet fallow could be successfully included within the farming system.

The on-farm trials showed that early-sown millet cover crops removed before December had no effect on wheat yield, but this was not true of millet cover crops that were allowed to grow through to maturity. Long-term simulations estimated that a spring cover crop of millet would adversely affect wheat yields in only 2% of years if planted early and removed after 50% cover had been achieved.

Additional keywords: simulation modelling, fallow management.

Introduction

The northern grains region of eastern Australia lies on the western side of the Great Dividing Range and extends from northern New South Wales to central Queensland. A highly variable summer-dominant rainfall, with high evaporation rates and high rainfall intensity, characterises the region (Felton *et al*. 1995). The dominant grain-producing soils are high in clay, self-mulching, and have a plant-available water capacity (PAWC, wheat) of between 150–300 mm and 1.8 m. These soils are characterised as Vertosols (Australian soil classification system, Isbell 1996) or Vertisols (IUSS Working Group WRB 2006).

The main dryland crops produced in the region are divided into summer (sorghum, *Sorghum bicolor* L.; maize, *Zea mays* L.; cotton, *Gossypium hirsutum* L.) and winter (wheat, *Triticum aestivum* L.; barley, *Hordeum vulgare* L.; chickpea, *Cicer arietinum* L.). A typical rotation will incorporate both summer and winter phases and a mixture of cereal, pulse, and fibre crops. The rotation is designed to maximise the storage of water, because stored water is a key feature in determining yields in this region (Waring *et al*. 1958; Whish *et al*. 2005, 2007).

A typical rotation will include a summer crop after a long fallow, a summer crop after a short fallow, then a winter crop after a long fallow, and a winter crop after a short fallow. Generally, a short fallow is 6–8 months and a long fallow is 14–16 months. Some variation to this pattern occurs when early-planted summer crops and late summer rains provide the opportunity for a double crop between summer and winter, thus eliminating the need for a long fallow. A common practice in the more marginal western parts of the region is to plant sorghum in a skip formation (Whish *et al*. 2005). This system plants 2 rows of crop and then skips 2 rows, which results in a lower, but more reliable yield; however, it produces markedly less stubble cover for the following long fallow and so increases the erosion potential of the soil.

Stubble is an important component of crop production on Vertosols because crop residues on the soil surface reduce runoff, erosion, rain drop impact, and maintain infiltration rates (Freebairn and Wockner 1986*a*, 1986*b*; Wockner and Freebairn 1991), thus improving the soil's fallow efficiency (Radford *et al*. 1995; Thomas *et al*. 2007). In the northern cropping zone, maintaining high infiltration rates and reducing soil erosion is the main motivation for growing cover crops during the summer fallow.

The logic of including a spring cover crop within the current cropping sequence is to grow cover to protect the soil, with this crop being terminated in time for the soil water to be replenished by summer rainfall. However, the dilemma is that the more cover produced, the more water used, and the more rainfall needed to refill the soil. This dilemma evokes the question, is there sufficient water within the system to produce both a useful cover crop and to

© CSIRO 2009 10.1071/CP08397 1836-0947/09/060517

meet the needs of a following wheat crop? Our work will show that there is, provided specific management rules are followed.

Methods

General comments

Plant-available water (PAW) at millet sowing and removal, wheat sowing and harvest, as well as percent soil cover, wheat crop biomass, and yield were monitored and compared with a conventional weed-free fallow on 31 commercial paddocks (Fig. 1). The monitoring involved a participatory collaboration between farmers, consultants, and researchers to collect data in a timely and efficient manner.

Crop establishment

Crops were established using commercial seeders and following the cultural practices of individual farmers. Timing of sowing was decided by participating farmers and their consultants, with the aim of maximising cover crop cover while minimising the effect on the following winter crops. White French millet (*Panicum miliaceum* L.) was sown at all sites during the spring and was followed by wheat in winter. White French millet was selected as the cover crop species because it grew efficiently in the subtropical spring climate, produced biomass quickly, was readily available within the area, and the participating farmers were familiar with its agronomy.

Experimental design

Between 2004 and 2007, 31 paddocks under long fallow were sown with millet (millet fallow, MF) and compared with unplanted fallow strips (conventional fallow, CF). Two experimental designs were used. Firstly, a completely random experiment (random experiment) was conducted across the sites. At each site the two treatments of bare fallow and sown millet (spray out 1) were established, each site constituting a replicate (11 sites 2004, 12 sites 2005, and 8 sites 2006). Wheat crops were established at the end of the fallow and the difference in wheat yield was used to assess the effect of the fallowing treatments. Secondly, at 5 sites in 2004 a split-plot design was established with commercial equipment (split-plot experiment). Main plots (~20 m by 120 m) comprised millet fallow (MF) and conventional fallow (CF). Subplots (~20 m by 40 m) comprised different millet spray-out times (sprayed in November, spray out 1; sprayed in December, spray out 2; or allowed to grow through to maturity).

Monitoring of sites

At each site, changes in PAW were measured by collecting soil cores within each treatment. In the split-plot experiment, 2 cores were collected to a depth of 1.5 m from each plot. Cores were collected at millet sowing, millet removal, wheat sowing, and wheat harvest. Cores were collected from within a 2-m^2 area within each plot, at each of the sampling times. In the random experiment, a 1.5-m core was collected within a 2-m^2 area

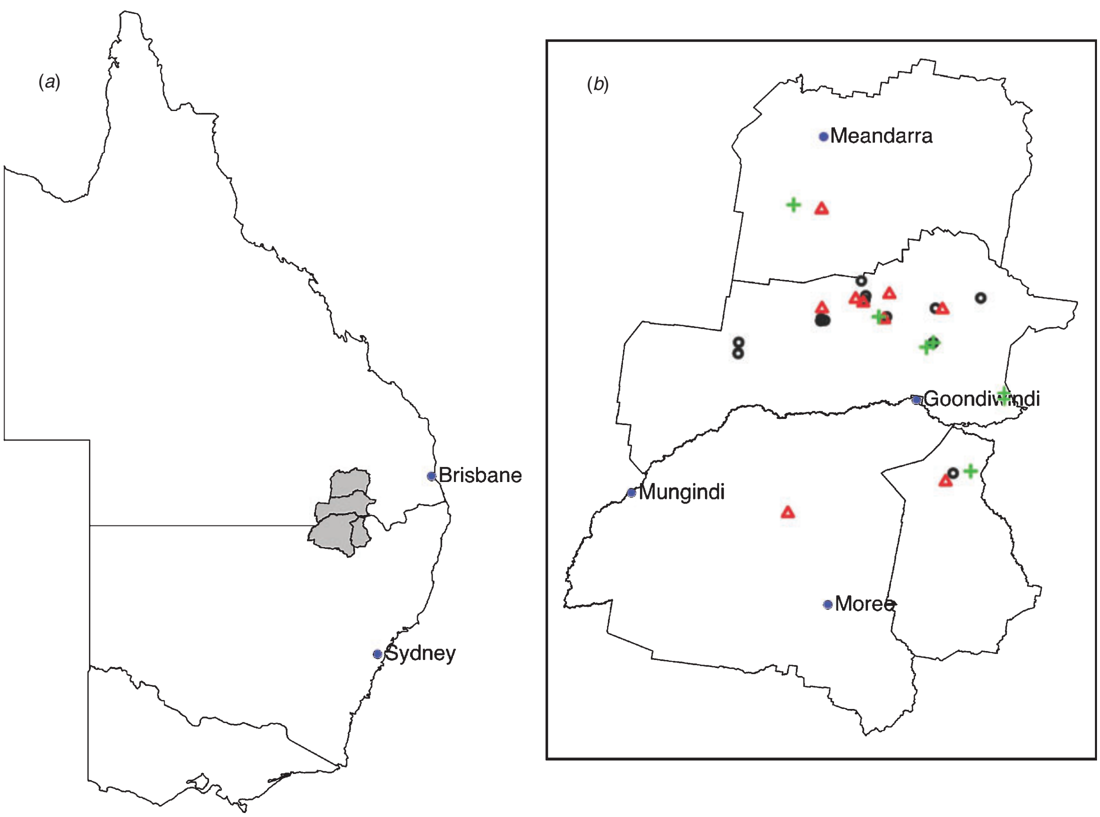

Fig. 1. The Goondiwindi study region and its position in relation to the states of Queensland, New South Wales, and local shire boundaries. Monitored sites are indicated by triangles (2004), circles (2005), and crosses (2006).

around 5 randomly selected fixed sampling points within each treatment. Soil water was sampled at wheat sowing and wheat harvest for all sites and at millet sowing and removal for some of the sites.

Soil for PAW measurement was collected using a hydraulic sampling rig pushing either a 50-mm or 38-mm (depending on soil moisture) sampling tube to a depth of 1.5 m. Cores were divided into 0–0.15, 0.15–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20, and 1.20–1.50 m layers. For each core, layer samples were placed in paper bags and weighed to obtain field moisture content. This layer structure was used as it matched the bulk density measurements used for the soil characterisation.

Soil was dried at 105°C for a minimum of 48 h to calculate gravimetric water content (g/g). Volumetric water (mm) content for each layer was calculated using bulk density values from the site soil characterisation (Gardner 1985; Dalgliesh and Foale 1998).

Plant-available water content (PAWC) for each of the soils was calculated following the methods described by Dalgliesh and Foale (1998). Soils were characterised by calculating a drained upper limit (DUL, the upper water storage limit for a soil after drainage has practically ceased) by establishing a ponded area by slowly wetting up the soil through drip irrigation tape until DUL to a depth of 1.8 m had been achieved. The crop lower limit (LLcrop) was calculated in the field by installing rain exclusion tents over actively growing wheat crops and measuring soil water (SW) content after terminal drought. Bulk density (BD) was measured within the pond site after the soil had reached DUL. Cylindrical cores of 600–800 mm length and known diameters of 125 mm, 100 mm, and 75 mm were hydraulically pushed into the wet soil. Cores were extracted and dried at 105°C for 48 h. Sites that were not characterised used characterisation data from previous characterisations or nearby sites. The characterisations for each of the sites allowed the gravimetric soil water measurements to be expressed as PAW.

The soils of the monitored sites were broadly classified as Grey Vertosols (Australian soil classification system, Isbell 1996), or Sodic Vertisols (IUSS Working Group WRB 2006). These soils generally contain high subsoil salt levels and gilgai (Isbell 1962; Tunstall and Connor 1981).

Wheat emergence, biomass, and yield were measured in both experiments. Six 1-m lengths of row were used as the standard measure from each plot in the time of removal split-plot experiment, and 10 to 18, 1-m lengths of row were used for the fallow comparison random experiment.

Emergence was measured by counting the number of emerged seedlings from the standard measure 3 weeks after sowing. Biomass was measured by cutting plants at ground level from a randomly selected section of crop row. Plants were dried at 80°C in a fan-forced oven for 48 h and weighed. Grain weight was determined by passing the dried samples through a stationary thresher.

Climate data

Daily rainfall was collected at all sites by the collaborating farmers using standard rain gauges. Meteorological data from the closest meteorological station (Jeffrey *et al*. 2001) were used for simulations of sites. If rainfall records of the nearest meteorological station and the farmer differed, then the farm records were used. Simulation scenario analysis used patched point data (Jeffrey *et al*. 2001) from the regional centre and simulated from 1 January 1900 to 31 December 2006.

Model testing

All modelling was completed using the simulation framework APSIM (Keating *et al*. 2003). APSIM-Wheat (V5.1) was tested against the observed data from 21 sites; 10 sites were not simulated because complete datasets were not collected or soil characterisation data were not available. Each treatment of wheat after a bare fallow or wheat after a millet fallow was simulated, including the different times of millet removal. This resulted in 72 simulations. A summary of the observed site data used to initiate the model is presented in Table 1.

Insufficient data were available to conduct a similar yield and biomass test to that of wheat with the millet crops. However, from the split-plot experiments, sufficient soil water measurements were collected to test if the millet model used water at a rate similar to that of the observed crops. Millet simulations were developed for these sites.

Simulation scenario analysis

The simulation scenario analysis was a factorial designed simulation experiment to examine the influence of soil water conditions, millet sowing date, and the length of millet cultivation

Table 1. Summary of plant-available water (PAW) and the length of time that millet was grown before termination, for data collected from the completely random and randomised block on-farm experiments

Thirty-one sites were monitored over the 3 years, but not all sites had all treatments. Values refer to the mean ($\bar{x}$), the number of observations (n), and the range of observations in parentheses

Year	Treatment	No. of treatments monitored	PAW sowing (mm) Millet	PAW sowing (mm) Wheat	Length of millet growth (days)
2004	Spray out 1	11	$\bar{x}$ = 159 (125–175) n = 4	$\bar{x}$ = 140 (91–170) n = 11	$\bar{x}$ = 64 (50–92) n = 10
2004	Spray out 2	5	$\bar{x}$ = 173 (145–198) n = 4	$\bar{x}$ = 144 (138–157) n = 4	$\bar{x}$ = 78 (71–92) n = 3
2004	Maturity	5	$\bar{x}$ = 137 (137–185) n = 4	$\bar{x}$ = 92 (50–129) n = 5	$\bar{x}$ = 102 (101–103) n = 5
2004	Fallow	11	$\bar{x}$ = 156 (127–179) n = 4	$\bar{x}$ = 130 (86–170) n = 10	
2005	Spray out 1	12	$\bar{x}$ = 120 (82–170) n = 9	$\bar{x}$ = 130 (89–175) n = 9	$\bar{x}$ = 57 (35–81) n = 10
2005	Fallow	12	$\bar{x}$ = 120 (82–170) n = 9	$\bar{x}$ = 115 (68–174) n = 11	
2006	Spray out 1	8	$\bar{x}$ = 67 (57–76) n = 2	$\bar{x}$ = 54 (36–108) n = 6	$\bar{x}$ = 88 (77–91) n = 7
2006	Fallow	8	$\bar{x}$ = 104 (94–120) n = 3	$\bar{x}$ = 102.6 (55–154) n = 6	

on the grain yield of wheat crops produced the following winter. The aim of the simulation analysis was to extend the field-observed data by testing over a greater number of seasons. The simulation analysis was designed to represent the Goondiwindi region (Fig. 1*b*). A Grey Vertosol with a PAWC for wheat of 234 mm was used as a representative soil for the simulations at all sites. The factors for the simulation analysis were: 7 starting PAW conditions (10 mm, 25 mm, 50 mm, 75 mm, 100 mm, 150 mm, 200 mm), 7 sowing dates (1 Sept., 15 Sept., 1 Oct., 15 Oct., 1 Nov., 15 Nov., 1 Dec.), and 4 lengths of millet production (no millet (convention fallow), millet removed after 40 days, millet removed after 60 days, and millet harvested at maturity). The simulation analysis ran from 1 January 1900 to 31 December 2006.

Statistics

Statistical analysis was conducted using the linear regression Kolmogorov–Smirnov test, and analysis of variance methods as utilised by the statistical software package R Version 2.5.1 (R Development Core Team 2007).

Results and discussion

Observed field measurements from 31 commercial farms

The PAW measurements at wheat sowing showed no significant differences between the conventional fallow (CF) treatments and the millet-fallows (MF) where the millet crops had been killed at spray out 1 at 30–70 days after sowing and spray out 2 at 70–90 days after sowing. A significant difference ($P < 0.05$; CF mean = 138 mm, s.d. = 32 mm, $n = 9$; and MF mean = 89 mm, s.d. = 42 mm, $n = 10$) in soil PAW was observed for those millet fallows allowed to progress to millet harvest. No significant difference was observed between the wheat yields from any of the treatments; however, the small sample size of the maturity treatment and good in-crop rain may account for the significant difference in PAW at sowing not translating into a significant yield difference. Allowing crops to progress to maturity was not part of the original experimental design (farmers made the decision within the season to harvest the millet crops), hence the low sample number (Table 2). The unusually high PAW at millet sowing may also explain why the wheat yields were not affected, with nearly all the sites having above 150 mm PAW when sown (Table 1). It is unlikely that in a commercial situation a millet crop would be sown with over 120 mm of PAW in the soil; normal farming practice would be to sow a cash-returning grain crop not a cover crop. The variation between sites and the limited 3-year time frame meant that drawing conclusions from the observed data was difficult. To extend the value of these observed data, simulation modelling was used to firstly reproduce the observed data and then extend these data by simulating the experiment over a longer time period.

Testing the ability of APSIM to reproduce observed data

APSIM-Wheat reproduced the observed wheat yields well (Fig. 2), with a significant correlation between the observed and predicted yields and the observed and predicted biomass ($P < 0.001$). The coefficient of determination for grain yield was 0.70, which demonstrates an adequate prediction capacity given that the data were collected from on-farm experimental sites established with commercial equipment. The validation datasets used to test APSIM-Wheat were collected from constrained small-plot experiments and show a coefficient of determination of 0.77 in Western Australia (Asseng *et al*. 1998), 0.66 in southern Queensland (Wang *et al*. 2003) and, more recently, 0.93 Australia-wide (APSIM 2008). APSIM tended to under-predict the high-end yields; however, some doubt about the two highest points does exist. These two observed yields were from hand-cut quadrats and were much higher than the recorded machine yields, which were closer to the yields predicted by APSIM.

A validated white French millet model does not exist in APSIM and insufficient data were collected within this study to build one; however, using the generic plant module (Robertson *et al*. 2002; Wang *et al*. 2002) and published data, a pseudo-millet model was constructed. This model was tested against the observed water use. Data from two of the detailed experiments are presented (Fig. 3) showing that over time the model was able to reproduce the water use observed for the CF and MF treatments including the MF with different times of removal. At some points the timing of responses by the model may be inaccurate, but this is most likely an artefact of inaccurate model phenology, or delayed rainfall recordings from manual rain gauges. Generally the model reproduced the total water used by the millet crops and the refilling of the fallow well.

Modelling the effect of different millet fallows on wheat yields

The large factorial design of the scenario analysis was initially analysed to assess the influence of millet production factors on the yield of the following wheat crop. Each factor (PAW at millet sowing, sowing time of the millet crop, and length of time the millet was grown) significantly ($P < 0.001$) influenced the yield of the following wheat crop. Two interactions (millet termination × sowing water and millet termination × sowing date) were also significant ($P < 0.001$) and highlight the

Table 2. No significant differences were observed between the mean wheat yield from conventional fallows (CF) and millet fallows (MF) following different lengths of millet growth

Spray out 1, millet killed 30–70 days after sowing; spray out 2, millet killed 70–90 days after sowing; maturity, millet allowed to grow to maturity

	Spray out 1		Spray out 2		Maturity	
	CF	MF	CF	MF	CF	MF
Mean	2.32	2.72	2.33	2.39	2.29	2.46
Median	2.33	3.18	2.5	2.2	2.9	2.2
	(s.d. = 1.17, $n = 15$)	(s.d. = 1.2, $n = 15$)	(s.d. = 0.76, $n = 9$)	(s.d. = 0.80, $n = 9$)	(s.d. = 0.93, $n = 7$)	(s.d. = 0.84, $n = 7$)

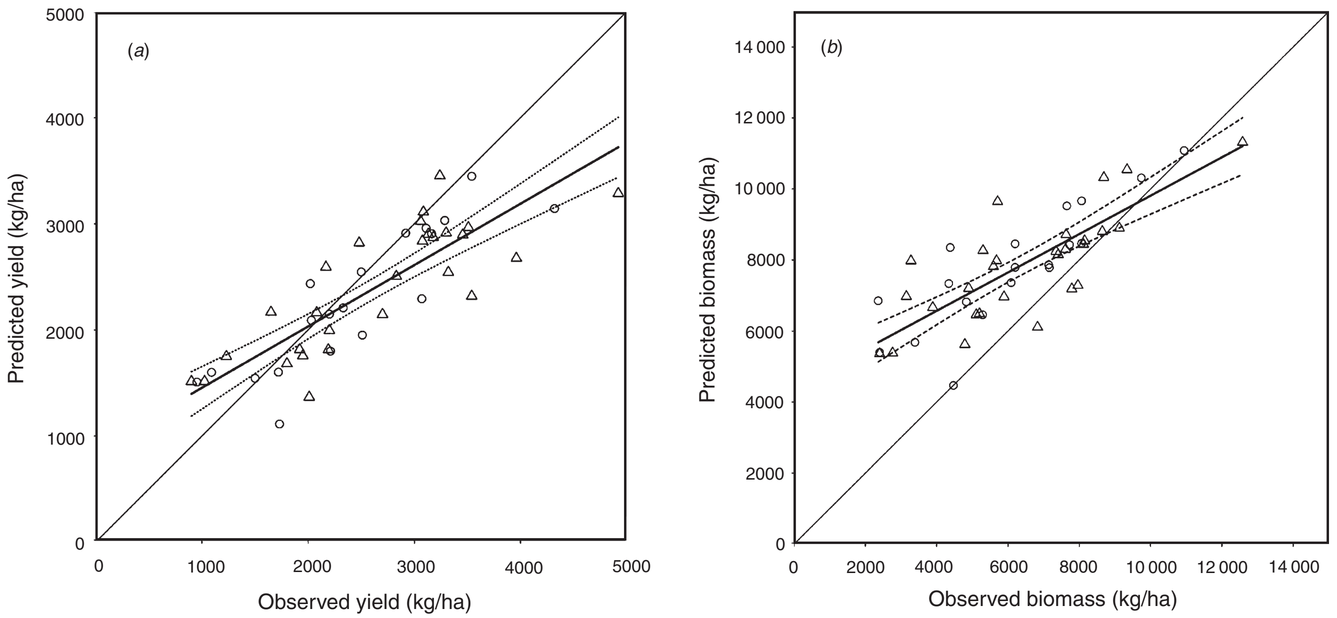

Fig. 2. Observed *v.* predicted yield and biomass at physiological maturity for commercial wheat crops after a conventional fallow (○) and a millet fallow (△). Results were collected from crops grown in the 2005, 2006, and 2007 wheat seasons and show a relationship comparable with other simulation studies reported in the literature. The solid diagonal line is the 1 : 1 line, the bold line is the linear regression, and the broken lines are the 95% confidence limits. Yield: $y = 0.58\ (\pm 0.05)x + 876.72\ (\pm 151.2)$, $r^2 = 0.70$, $P < 0.001$; Biomass: $y = 0.0.54\ (\pm 0.06)x + 4405\ (\pm 403.5)$, $r^2 = 0.64$, $P < 0.001$.

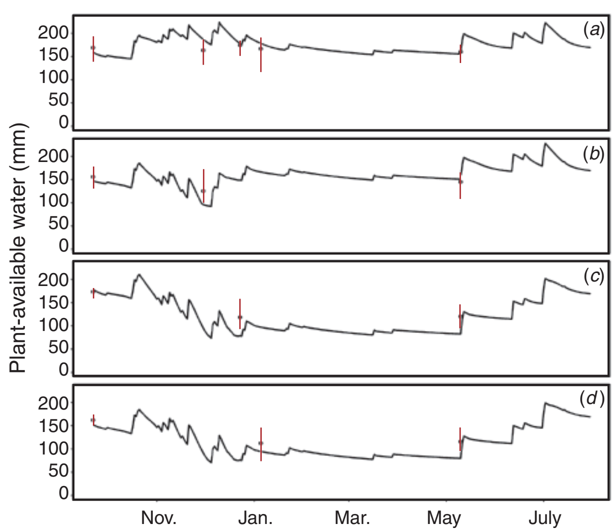

Fig. 3. Plant-available water (PAW) accumulation within the (*a*) CF, the (*b*) MF spray out 1, (*c*) MF spray out 2, and (*d*) MF allowed to reach maturity. The solid line represents the predicted water use by APSIM. The points show the observed mean, and the lines mark the range of observed PAW within the soil over time.

importance of managing the millet crop to reduce later wheat yield losses (Fig. 4).

The simulation scenario analysis reset the PAW to one of the 7 options on the day of millet sowing; this same reset was also performed on the control (CF). This resulted in a decline in PAW with later sowing dates that would not normally occur. This decline is a result of the reduction in time between millet sowing and wheat sowing reducing the time for rain to refill the soil profile, which in turn reduced the soil PAW at wheat sowing, resulting in a lower yield. Including a millet crop further reduced this time and increased the size of the soil water deficit. The longer the millet crop was grown and the later the millet crop was sown the greater the effect on wheat yields (Fig. 4*a*).

The PAW at millet sowing also influenced wheat yields: the greater the quantity of water in the profile at millet sowing the smaller the quantity of water required to refill the profile after the millet crop. The length of the millet crop had the same effect: the longer the crop was grown the more water it used and the greater the reduction in wheat yields. When the millet was allowed to grow to maturity it reduced the soil PAW to the millet lower limit, resulting in a similar reduction in wheat yields irrespective of the millet starting PAW (Fig. 4*b*). Similar results have been seen with delayed termination of different cover crops in corn production in the USA (Holderbaum *et al*. 1990; Corak *et al*. 1991; Ewing *et al*. 1991; Decker *et al*. 1994). This suggests there is insufficient water within the farming systems of the northern grains region to consistently produce two consecutive crops.

Examination of means from 100 years of simulation data can be misleading because in many years, wheat yields after millet were equal to those of the CF control. It is one thing to know the potential or long-term average of a yield reduction, but a more interesting question is how often, and under what circumstances, will a yield reduction occur.

To answer this question, probability of exceedence curves for the difference between wheat yield after MF and CF were

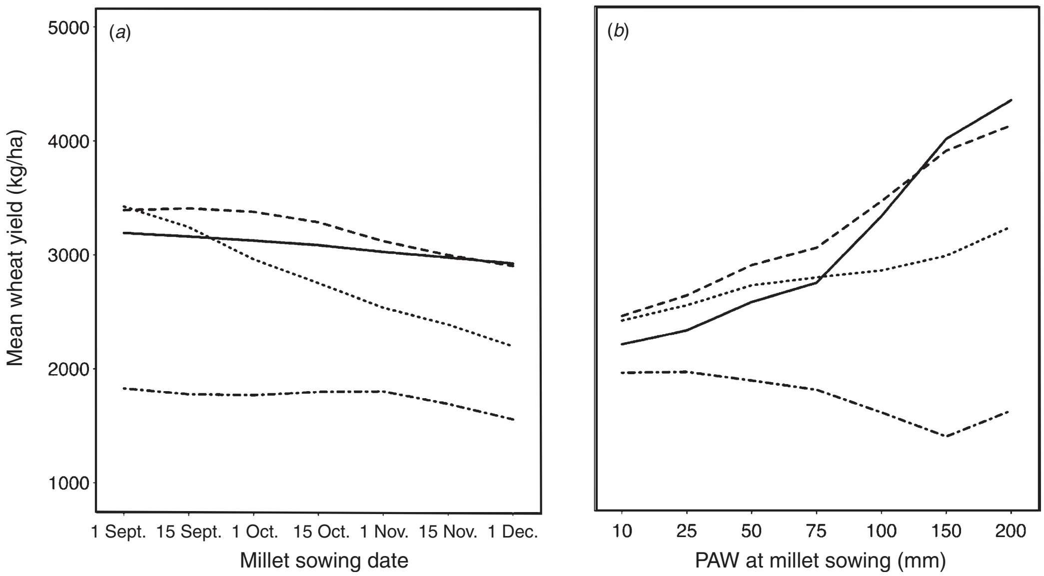

Fig. 4. Interaction plots of the simulated data showing (*a*) the longer the millet crop was allowed to grow, and the later it was planted, the greater the decline in the following wheat crop yield; (*b*) increased soil water at millet sowing and short periods of millet growth increased the yield of the following wheat crops. The four lengths of millet growth were: grown to maturity (-·-), removed after 60 days (···), removed after 40 days (--), and the control conventional fallow (—).

prepared. The difference curves highlight when no difference occurred between wheat yields following a millet or conventional fallow. Wheat crops following MF, which were sown early and removed early (Fig. 5*a*), produced equal or better wheat yields to those following a CF around 90% of the time. However, if the millet was sown late (1 Dec.) then the chance of no difference

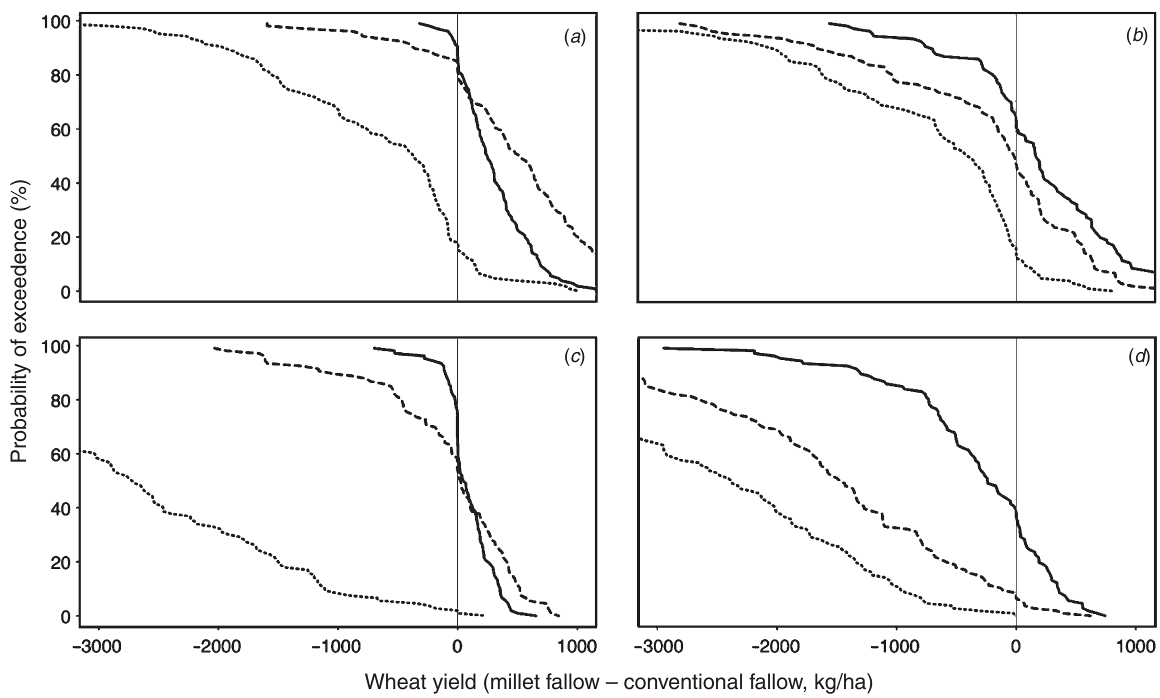

Fig. 5. Probability of exceedence plots showing the importance of early millet termination to wheat yields following a fallow (millet fallow – conventional fallow) for millet fallows removed after 40 days (—), 60 days (--), or maturity (···): (*a*) early sowing on a wet profile (1 Sept., PAW at millet sowing of 150 mm), (*b*) late sowing on a wet profile (1 Dec., PAW at millet sowing of 150 mm), (*c*) early sowing on a dry profile (1 Sept., PAW at millet sowing of 50 mm), (*d*) late sowing on a dry profile (1 Dec., PAW at millet sowing of 50 mm).

between the fallow treatments was reduced to ~56% (Fig. 5*b*). Having an increased PAW at the time of millet sowing improved the chance of no yield difference for early sowings (Fig. 5*c*), but not for the later sowing due to the greater water use by the older crop in a hotter part of the year (Fig. 5*d*).

Can effective soil cover be grown when millet is sown early and removed early?

Minimising the effect of the millet on the wheat crop is an important consideration; however, the reason for growing a cover crop and spraying it out is to prevent erosion during the summer storm season. Soil covered with growing crops or plant residue has a reduced erosion or runoff potential (Freebairn and Wockner 1986*a*). The relationship between sediment content in runoff and surface cover is exponential, and tails off at around 30% cover (Freebairn and Wockner 1986*b*). The time to protect Vertosols in the Goondiwindi region from high-intensity storm damage is during summer, but especially during early autumn when residual cover is at its lowest.

A value of 30% soil surface cover on the first day of March was considered to be a realistic target for the millet cover cropping approach. The long-term simulations showed that a millet crop grown for 60 days, sown on any date, and with sowing PAW of 10–200 mm, produced on average more than 30% cover (Fig. 6*a*, *b*). However, if the millet crop was grown for only 40 days then the early sowings (1 Sept., 15 Sept.) or the lowest sowing soil PAW (10–25 mm) struggled to produce an average cover greater than 30% by the 1 March assessment time. However, if the crops were allowed to keep growing, more water was used, resulting in a yield reduction of the wheat crop (Fig. 5).

What are the practical consequences of using a millet cover crop to protect the soil?

The key messages from the factorial analysis were that sowing millet early and removing it early minimised wheat yield loss, but sowing early produced an ineffective quantity of biomass, defeating the purpose of growing a cover crop altogether.

Armed with this knowledge a single management strategy was designed. This strategy was to sow millet when greater than 25 mm of PAW was present in the soil (assuming a 1.5-m profile filled from the surface) between 1 September and 1 December. Millet was removed when the surface cover of the soil reached 50% or the millet began to flower. These rules were simulated for 100 years in a simulation that was initiated on 1 March with the soil at a PAW equivalent to the crop lower limit of sorghum (CLL sorghum). A significant wheat yield improvement was observed between the CF and MF (2-sample Kolmogorov–Smirnov test, $P < 0.001$, mean CF = 2132 kg/ha, MF = 3000 kg/ha, s.d. CF = 970, MF = 982, $n = 106$; Fig. 7*a*). The inclusion of the millet within the fallow significantly reduced soil surface runoff compared with the CF control (2-sample Kolmogorov–Smirnov test, $P < 0.001$, mean CF = 171 mm, MF = 107 mm, s.d. CF = 91, MF = 65, $n = 106$; Fig. 7*b*). The increased surface cover as a result of the millet increased water infiltration, resulting in water movement below the wheat root zone. This caused significantly higher drainage in the MF treatment compared with the CF treatment (2-sample Kolmogorov–Smirnov test, $P < 0.001$, mean CF = 2.6 mm, MF = 48 mm, s.d. CF = 8.4, MF = 65, $n = 106$; Fig. 7*c*). Finally, an estimate of soil loss as a result of erosion was calculated. This estimate assumed a common slope and erosion factor, so has not tried to quantitatively predict erosion, but to show a

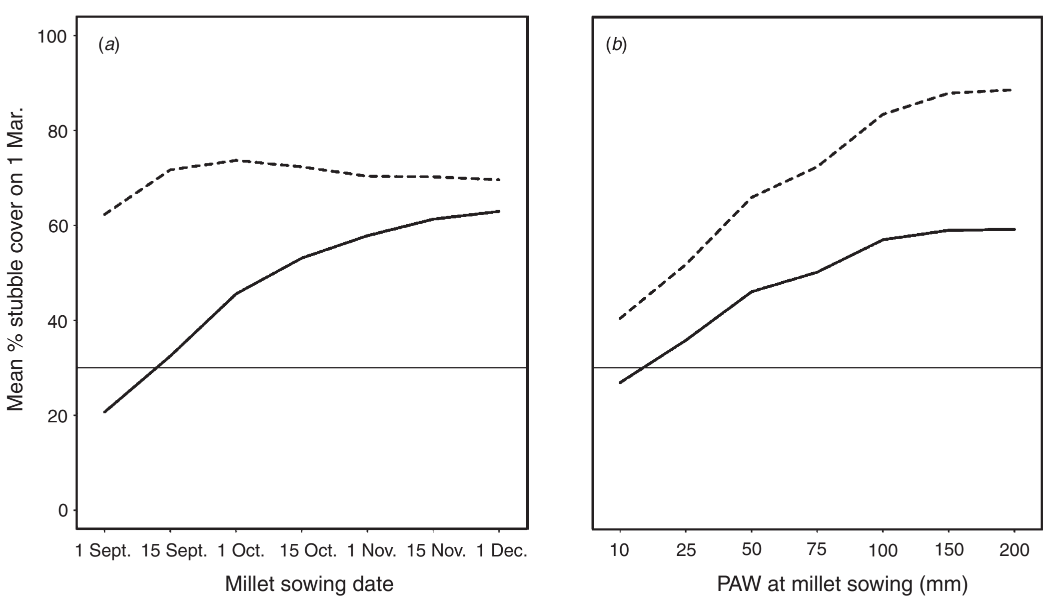

Fig. 6. Interaction plots showing (*a*) millet sown and removed after 40 or 60 days and (*b*) sown at various starting PAWs. The two lengths of millet growth were: removed after 60 days (--) and removed after 40 days (—). The horizontal line shows the targeted 30% cover on 1 March, which was not achieved by the early-sown millet or sowing on less than 20 mm PAW for the 40-day removed crops.

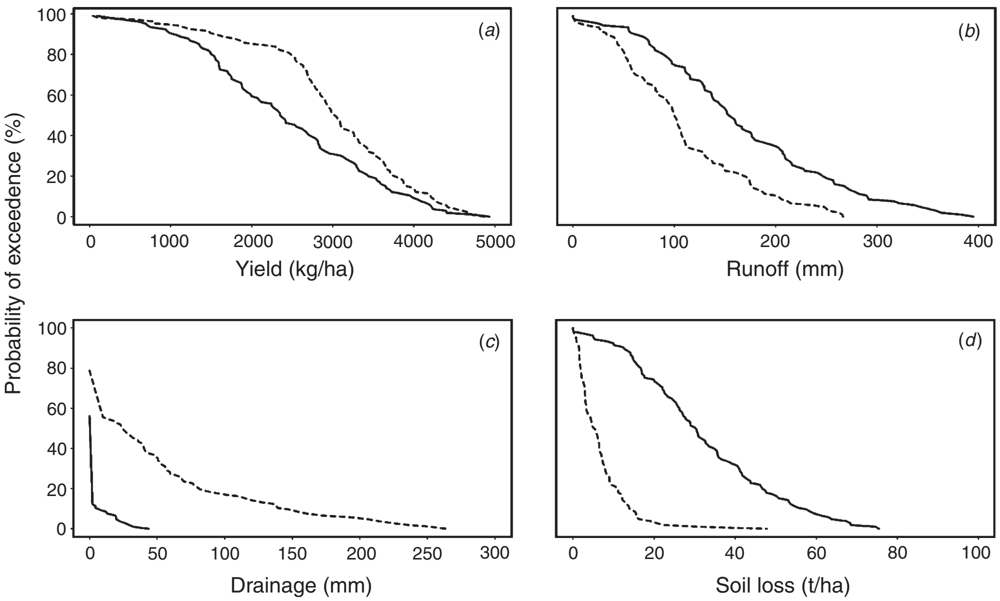

Fig. 7. Probability of exceedence figures showing that the strategic management of a millet fallow (--) improved wheat yield, reduced runoff and soil loss, but increased deep drainage when compared with a conventional long fallow (—) for (*a*) the following wheat yield, (*b*) cumulative runoff between 1 March of Year 1 and wheat harvest of Year 2, (*c*) cumulative drainage below the wheat root-zone between 1 March of Year 1 and wheat harvest of Year 2, and (*d*) cumulative soil loss between 1 March of Year 1 and wheat harvest of Year 2.

proportional loss between the two treatments. The low cover levels and increased runoff under the CF treatment removed proportionately more soil than under MF.

The results show that there is sufficient water within the system to produce a millet cover crop within a northern cropping sequence, without detrimental effects on the yields of following crops. In fact millet had a positive effect on wheat yields, provided the millet crops were sown early in spring and terminated once 50% cover had been achieved. Visually determining cover is considered a better method of identifying termination than phenological stage because it ensures that adequate biomass is produced. The main motivation for farmers in the northern grains region to sow cover crops is to maintain infiltration rates and reduce soil erosion. However, is it worth the $50/ha cost of establishing the cover crop? This work shows that it is. Wheat yield difference between the MF and CF is significant and could be used to offset the costs of millet establishment. The cost of soil erosion is significant, but can be hidden by climatic variability and improved technology, so it is hard to substantiate within a single-season gross margin. Erosion costs in the northern grains region have, however, been estimated to be ~8% of production per decade (Loch and Silburn 1997). Farmers and their enthusiasm for cover crops have driven this research project, suggesting that they currently do value erosion prevention at $50/ha irrespective of any yield improvement in following wheat crops.

Acknowledgments

We thank the staff of Michael Castor and Associates (MCA), Agricultural Consultants, Goondiwindi and their farmer clients, and technical staff of CSIRO Toowoomba and Queensland DPI who participated in this project. We also acknowledge the financial support of GRDC through the eastern farming systems project, MCA Goondiwindi, Queensland DPI, and CSIRO.

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Manuscript received 6 November 2008, accepted 31 March 2009