CSIRO PUBLISHING

Crop & Pasture Science, 2013, **64**, 922–934
http://dx.doi.org/10.1071/CP13237

Summer fallow weed control and residue management impacts on winter crop yield through soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia

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Abstract. The majority of rain used by winter grain crops in the Mallee region of Victoria, Australia, falls during the cooler months of the year (April–October). However, rain falling during the summer fallow period (November–March) and stored as soil moisture contributes to grain yield. Strategies to better capture and store summer fallow rain include (*i*) retention of crop residues on the soil surface to improve water infiltration and evaporation; and (*ii*) chemical or mechanical control of summer fallow weeds to reduce transpiration. Despite the widespread adoption of no-till farming systems in the region, few published studies have considered the benefits of residue management during the summer fallow relative to weed control, and none quantify the impacts or identify the mechanisms by which summer fallow weeds influence subsequent crop yield.

Over 3 years (2009–11), identical experiments on adjacent sand and clay soil types at Hopetoun in the southern Mallee were conducted to quantify the effect of residue management (standing, removed, or slashed) and summer fallow weed control (± chemical control) compared with cultivation on soil water and nitrogen (N) accumulation and subsequent crop yield. The presence of residue (2.4–5.8 t/ha) had no effect on soil water accumulation and a small negative effect on grain yield on the clay soil in 2011. Controlling summer weeds (*Heliotropium europaeum* and volunteer crop species) increased soil water accumulation (mean 45 mm) and mineral N (mean 45 kg/ha) before sowing on both soil types in 2 years of the experiment with significant amounts of summer fallow rain (2010 and 2011). Control of summer weeds increased grain yield of canola by 0.6 t/ha in 2010 and wheat by 1.4 t/ha in 2011. Using the data from these experiments to parameterise the APSIM model, simulation of selected treatments using historical climate data (1958–2011) showed that an extra 40 mm of stored soil water resulted in an average additional 0.4 t/ha yield, most of which was achieved in dry growing seasons. An additional 40 kg/ha N increased yield only in wetter growing seasons (mean 0.4 t/ha on both soil types). The combination of extra water and N that was found experimentally to result from control of summer fallow weeds increased subsequent crop yield in all season types (mean 0.7 t/ha on sand, 0.9 t/ha on clay). The co-limitation of yield by water and N in the Mallee environment means that yield increases due to summer weed control (and thus returns on investment) are very reliable.

Additional keywords: APSIM, cultivation, herbicide, no-till, residue retention.

Received 21 December 2012, accepted 9 September 2013, published online 11 November 2013

Introduction

Rainfall distribution in the Mallee region of north-western Victoria, Australia, is Mediterranean, with cool wet winters and hot dry summers. Land use in the region is dominated by broadacre, dryland grain crops, primarily wheat and barley, which are grown in sequence with broadleaf break-crops, including canola, field peas, lentils, chickpeas, and vetch. Crops are planted in late autumn, grow during the winter and spring, and they are harvested in early summer. The 4–6-month period between harvest of one crop and planting of the subsequent crop is defined as the summer fallow (Fischer 1987).

In contrast to the summer-dominant rainfall environment of northern Australia, rain in southern Australia that falls during the summer fallow period has not traditionally been valued as a resource for winter crops (French 1978*a*, 1978*b*; French and Schultz 1984*a*; Freebairn *et al*. 2006) because in-crop rainfall has generally been adequate to achieve the attainable yield of cereal crops as determined by non-water-limiting factors such as nutrient availability and root disease (French and Schultz 1984*a*, 1984*b*; Cornish and Murray 1989; Angus and Good 2004; Sadras and Angus 2006). However, recent improvements in productivity under modern conservation farming systems, increased use of fertiliser nitrogen (N), and control of pathogens with break crops (Passioura and Angus 2010), combined with decreased growing-season rainfall (Pook *et al*. 2009; Cai *et al*. 2012), have re-focussed awareness on the potential contribution of summer fallow rain to crop yield in southern Australia. Hunt and Kirkegaard (2011) demonstrated with simulation over a 120-year period that, in contrast to the assertions of French (1978*a*, 1978*b*), summer fallow rain does make a significant contribution to grain yield in regions with winter-dominant rainfall, contributing 37–42% of grain yield of N-unlimited crops on average in the Mallee depending on location and soil type.

Better capture and use of summer fallow rain has been proposed as a means by which yield of winter crops in the Mallee can be increased. Management practices that influence capture and storage of summer fallow rain include control of summer weeds, retention of crop residues, and tillage. Ephemeral, summer-growing weeds (e.g. *Heliotropium europaeum* L., *Tribulus terrestris* L., *Cucumis myriocarpus* E. Mey. ex Naud.) are able to germinate and grow on summer fallows following episodic summer rain (Hunt *et al*. 2009). These weeds transpire water that could otherwise be used by subsequent crops (Fromm and Grieger 2002; Hunt 2006; Verburg *et al*. 2012). Significant amounts of organic N mineralise following rain during the summer fallow, and this is a major source of N for subsequent crops (Angus *et al*. 1998). Summer fallow weeds reduce mineral N by drying the soil and by accumulating N which is not immediately available for subsequent crop growth. Soil water and N effects have been variously proposed as the main mechanisms by which summer weeds reduce crop yield. In the cropping belt of South Australia, a region with winter-dominant rainfall, Fromm and Grieger (2002) found experimentally that summer fallow weed control with retained residue increased soil water stored at sowing by 6–21, mm depending on weed density and rainfall pattern, but they did not measure any significant effect of weed control on soil N concentration at sowing. Subsequent grain yield increases varied from 0 to 0.68 t/ha, depending on the amount and distribution of in-crop rainfall and soil N status. Osten *et al*. (2006) conducted experiments in summer-dominant (Emerald, Queensland), equi-seasonal (Wagga Wagga, New South Wales), and winter-dominant (Merredin, Western Australia) rainfall environments and, with residue retained across all treatments, observed a negative effect of weed biomass on soil N accumulation, which they considered sufficient to explain negative effects of weed growth on crop yield. Osten *et al*. (2006) did not report any soil water effects and concluded that N availability had an overriding effect on crop yield, stating that in-crop rain would have been sufficient to negate any water benefit from controlling summer weeds.

In the Mallee, cultivation was traditionally used to control summer fallow weeds, with disastrous consequences for soil organic matter content, structural stability, and topsoil loss via wind erosion (Tisdall and Oades 1982; Chan and Pratley 1998). In response to widespread soil degradation under this system, no-till farming with residue retention began to be adopted in the region from 1980. Adoption of no-till increased from <10% of farms in 1990 to 68% of farms by 2008 (Llewellyn *et al*. 2012). Summer weed control is now achieved primarily through the use of knock-down (glyphosate, 2,4-D amine, and low-volatile ester, triclopyr, oxyfluorfen, paraquat) and residual (metsulfuron-methyl, atrazine) herbicides. Tillage influences soil water and N accumulation through numerous mechanisms that depend on site and season relating to weeds, surface residues, soil structure, and micro-relief; these factors have been extensively described and reviewed (Fischer 1987; Hatfield *et al*. 2001). Most authors agree that the greatest and most reliable influence of tillage on fallow efficiency has been through weed control (Fischer 1987).

In no-till systems, excessive amounts of residue can interfere with sowing operations and reduce subsequent crop yields through various mechanisms (Scott *et al*. 2010). Research in the summer-dominant rainfall regions of Australia has shown that plant residues retained on the soil surface improve fallow efficiency by minimising the physical impact of raindrops on the surface soil, maintaining structural integrity and infiltration rates, and reducing runoff (Felton *et al*. 1987; Whitbread *et al*. 2000; Foley and Silburn 2002; Scott *et al*. 2010). Residues slow the flow of water on the soil surface, allowing more time for infiltration (Freebairn and Boughton 1981), as well as slowing soil evaporation following rainfall events. However, if conditions remain dry for an extended period, total evaporation will be unaffected by residues (Felton *et al*. 1987; Verburg *et al*. 2012). As a result, increases in fallow efficiency due to reduced evaporation are minor, and they occur only when large amounts of residue are present and rainfall patterns are favourable (Bond and Willis 1970; Schultz 1972; Felton *et al*. 1987; Kirkegaard *et al*. 2007; Browne and Jones 2008). The majority of existing literature on the effect of residue retention on soil water and N accumulation and subsequent crop performance in southern Australia pertains to the practice of ‘long’ fallowing, in which a crop is not planted during the cool season for the purpose of accumulating soil water and N over a 16–18-month period for use by a subsequent crop (Schultz 1972; French 1978*a*, 1978*b*; Ridge 1986; O’Leary and Connor 1997*a*, 1997*b*, 1997*c*). O’Leary and Connor (1997*a*, 1997*c*, 1997*b*) compared water and N accumulation under long fallows with factorial residue retention and cultivation treatments with weeds controlled in all treatments during the summer fallow. They contrasted these treatments to a continuous cropping sequence of field pea followed by wheat with a cultivated summer fallow. They found that, although the retention of residues during the long fallow did not increase soil water accumulation on the sandy loam soils of the Mallee, there were significant increases measured in the heavy clay soils of the Wimmera region to the south. Furthermore, they observed that residue retention reduced soil mineral N in the surface layers of soil, possibly due to immobilisation and denitrification. Subsequent wheat yields were increased by retention of residue in 3 of 4 years in the Wimmera, but only in 1 of 4 years in the Mallee.

Long fallowing foregoes a year of cropping income from a given field, and the adoption during the 1990s of adapted varieties of profitable break-crops such as canola, lentil, and chickpea, which allow weeds and diseases of wheat crops to be controlled and in the case of legume species N to be fixed, replaced the functional role that long fallow had played in Mallee farming systems. Studies on the effects of surface residues during the summer fallow in the continuous crop sequences that now dominate in southern Australia are limited. Browne and Jones

(2008) reported a small increase in summer fallow water accumulation, a reduction in soil N accumulation, and a small increase in crop yield from applying extra residue to plots with low levels of existing residue, but they did not compare these to a bare earth control. They concluded that residue loads in excess of those typically grown in the Mallee (~3 t/ha) were required in order to measure a significant water conservation or crop yield effect during summer fallows. Verburg *et al*. (2012) also found through experiments and simulation in the equi-seasonal rainfall environment of Wagga Wagga that retaining residues had a limited effect on soil water accumulation during the summer fallow period and that control of summer growing weeds was more effective. They did not measure a significant effect of residue management or summer weeds on soil N. Over a single season with exceptionally high summer rain at three locations in the equi-seasonal rainfall environment of central west NSW, Haskins and McMaster (2012) demonstrated that control of summer fallow weeds with herbicides and retained residues in a continuous crop sequence increased both soil water (0–53 mm) and N accumulation (32–57 kg/ha) and subsequent wheat grain yield (0.7–1.7 t/ha). They concluded that yield responses were largely driven by N availability given the wet growing season of 2010 in that environment. They also considered the effect of different residue management treatments (slashing, incorporation with cultivation) and found that cultivating to incorporate residue at the start of the summer fallow increased yield relative to full residue retention by 10% at one site, and increased N accumulation by 5–7 kg/ha relative to standing residue (but not slashed residue) at another site without affecting yield. However, that study did not include a bare earth control, therefore confounding the effect of residue incorporation by tillage with its effects on weed control and N cycling.

The above studies leave uncertainty regarding the relative effects of residue management and weed control on soil water and N accumulation, as most of the experiments focussed on either residues and tillage (O'Leary and Connor 1997*a*, 1997*b*, 1997*c*; Browne and Jones 2008) or weeds (Fromm and Grieger 2002; Osten *et al*. 2006). The studies that considered weeds offer conflicting explanations of either increased water or N availability for the observed effects on wheat yield and do not consider how their results may have been influenced by conditions other than those experienced in the subsequent cropping season. Studies that considered both weeds and residues are from temperate environments and present experimental results from only one season, which in the case of Verburg *et al*. (2012) was the extremely dry growing season of 2006, and in the case of Haskins and McMaster (2012) the extremely wet summer fallow and growing season of 2010. Based on these deficiencies in understanding, the study presented here therefore aims to:

(1) Experimentally verify the relative effects of residue management and weed control on both soil water and nitrogen accumulation;
(2) Quantify the relative importance of, and the interactions between, fallow soil water and nitrogen effects at sowing for performance of the subsequent crop.

To achieve this, partial factorial experiments with residue and weed removal treatments were established on two contrasting soil-texture types found within the Mallee to explore the soil-type differences in water and N accumulation observed by O'Leary and Connor (1997*a*, 1997*b*) and French (1978*a*). Previous studies have demonstrated that seasonal response to additional water and N at sowing is dependent on rainfall amount and distribution in the following growing season (French 1978*b*; Moeller *et al*. 2009; Oliver *et al*. 2010). In order to overcome season-specific factors over-riding the conclusions from our experimental data, crop simulation is used to extend findings across multiple seasons.

Methods

Site description

Identical experiments were established at two sites 2.3 km apart and ~13 km ESE of the township of Hopetoun, Victoria. The 'sand' site was on top of an east–west dune with sandy topsoil overlying clay (35°46′26″S, 142°29′28″E), and the 'clay' site was on a lower lying flat with clay-loam topsoil with saline clay subsoil (35°45′53″S, 142°30′47″E). The soil type at the sand site was a Brown, Hypocalcic, Mottled, Chromosol, while the clay was a Hypercalcic, Pedal, Melanic-vertic, Calcarosol (Isbell 2002).These soil types were chosen as they are typical of soils used for grain crop production in the Mallee (Victorian Department of Primary Industries 2012) and provided contrasting textures and water dynamics.

Soil plant-available water capacity (PAWC) was characterised at each site using the methods of Dalgliesh and Foale (1998), and values of bulk density and crop lower limit (CLL) for wheat and drained upper limit (DUL) are presented in Table 1. The CLL is a field measurement derived from soil samples taken at maturity under a well-managed crop sown into a full profile of water and in which rain is excluded from anthesis. It thus integrates both soil (texture, salinity, boron, sodicity) and plant limitations to soil water extraction. Samples from all depths from the first soil

Table 1. Soil hydraulic and chemical properties at the sand and clay sites

BD, Bulk density; WLL, wheat lower limit; DUL, drained upper limit; PAWC, Plant available water capacity; EC, electrical conductivity

Depth (m)	BD (Mg/m^3)	WLL (mm/mm)	DUL (mm/mm)	PAWC (mm)	EC (dS/m)	pH (H_2O)	Chloride (mg/kg)
			Sand site				
0–0.1	1.66	0.07	0.23	16	0.08	7.9	8
0.1–0.2	1.57	0.11	0.27	16	0.11	8.8	8
0.2–0.4	1.50	0.16	0.31	30	0.16	9.1	13
0.4–0.7	1.51	0.17	0.32	45	0.24	9.3	17
0.7–1.0	1.73	0.21	0.28	21	0.29	9.4	17
1.0–1.3	1.67	0.20	0.28	24	0.31	9.4	17
Total				152			
			Clay site				
0–0.1	1.4	0.10	0.37	27	0.21	8.8	72
0.1–0.2	1.38	0.15	0.39	24	0.44	9.0	291
0.2–0.4	1.32	0.24	0.42	36	0.71	9.3	559
0.4–0.7	1.28	0.27	0.45	54	1.09	9.4	960
0.7–1.0	1.27	0.37	0.43	18	1.46	9.2	1228
1.0–1.3	1.31	0.40	0.45	15	1.66	8.3	1343
Total				174			

sampling for the experiment (see below) on 10 December 2008 were analysed for pH, electrical conductivity (EC), and chloride concentration (Table 1). Samples from 0–0.1 m depth were also analysed for organic carbon (C), phosphorus (Colwell-P), P buffering index (PBI), and plant-available sulfur (S) concentration (KCl-40). Colwell-P and PBI were 24 mg/kg and 35, respectively, at the sand site, and 29 mg/kg and 147 at the clay site. Organic C was 0.87 and 1.29% w/w, and extractable S concentration 4.1 and 6.9 mg/kg, at the sand and clay sites, respectively. The clay site would be considered moderately responsive to P and S fertiliser application and the sand site responsive to S fertiliser application.

Climate in the region is Mediterranean, with cool, wet winters and hot, dry summers (Fig. 1). Mean growing season (April–October) rainfall at the township of Beulah (18 km SSW of the experiment) for the period 1898–2011 was 252 mm. Mean summer fallow (November–March) rainfall for the same period is 90 mm, but rain during this time is characterised by large, irregular events interspersed with prolonged dry periods (Hunt 2006).

Experimental design

Six fallow management treatments were first applied on 10 December 2008 to plots 4 m by 14 m arranged in a randomised block design with four replicates. The treatments were: (1) standing residue + no summer weeds; (2) standing residue + summer weeds; (3) slashed residue + no summer weeds; (4) bare earth + no summer weeds; (5) bare earth + summer weeds; (6) cultivation + no summer weeds.

These treatments were selected as they present the range of summer fallow management options available to growers in the continuous cropping systems that dominate in the Mallee. Residue may be removed by grazing, burning, or baling and sold for animal bedding or forage. Weeds may be controlled with herbicides, or left to grow to avoid incurring herbicide costs. Cultivation is still practiced as a form of weed control and residue management on a minority of farms in the region.

The previous crop at both sites was wheat and prior residue load was estimated by removing residue from two 1 m by 1 m quadrats systematically positioned in all replicates of treatments 4 and 5. For the standing residue treatments (1 and 2), previous residue was allowed to remain standing. For the bare earth treatments (4 and 5), residue was cut at ground level using a line-trimmer and raked from the plots. For the slashed residue treatment (3), residue was cut with a line-trimmer and allowed to remain on the plots. The cultivation treatment (6) was applied using a cultivator bar with Janke tynes (Janke Australia, Mt Tyson, Qld) fitted with sweep-points spaced 300 mm apart as necessary to achieve complete control of weeds during the summer fallow period. Summer-growing weeds were controlled with herbicides soon after emergence in the remaining weed-free treatments (1, 3, and 4), and weeds were allowed to grow unchecked in weedy treatments (2 and 5) until seed-bed preparation and planting of the subsequent crop. Treatments were re-applied to the same plots at both sites following harvest in 2009 and 2010. Dates for treatment application for the duration of the experiment are summarised in Table 2.

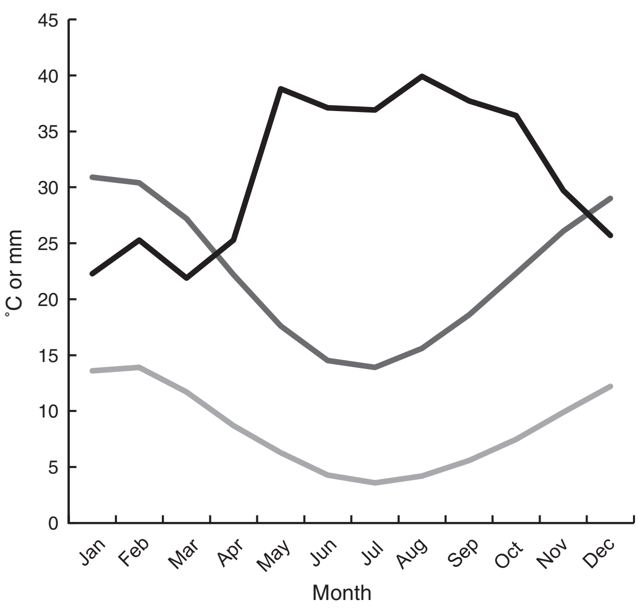

Fig. 1. Mean monthly rainfall (black line, 1898–2012), minimum (light grey line, 1898–1975), and maximum temperature (dark grey line, 1898–1975) for the township of Beulah (Bureau of Meteorology station No. 077004), 18 km SSW of the experiment (www.bom.gov.au).

Crop management

After the summer fallow in each year of the experiment, a winter grain crop was grown with consistent management across all treatments (Table 3). As treatments and measurements were repeated on the same plots across seasons, a crop sequence typical of the region was chosen (barley–canola–wheat). All crops were sown with a cultivator bar with Janke tynes (Janke Australia, Mt Tyson, Qld) fitted with knife-points and press-wheels spaced 300 mm apart connected to a Simplicity air-seeder (Simplicity Australia, Dalby, Qld). Rate of topdressed N application was determined using the Yield Prophet® (Hochman *et al*. 2009*b*) web service at a level of risk typically accepted by farmers in the region. This recognises that farmers do not pursue a yield-maximising strategy, rather a profit-maximising strategy (Asseng *et al*. 2012). In-crop weeds and foliar diseases were controlled using appropriate selective herbicides and fungicides such that yields were not adversely affected.

Measurements and monitoring

Two segmented soil cores to 1.3 m depth were taken in each plot before sowing and following harvest in each year of the experiment; see Table 2 for sampling dates. The cores were divided into depths of 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.7, 0.7–1.0, and 1.0–1.3 m, and depths from each core were bulked. For both sites, bulked samples were mixed and subsamples analysed for gravimetric water content and mineral N.

Summer-fallow weed density of all treatments was estimated before and after each weed-control treatment by identifying and counting all weeds within four 1 m by 1 m quadrats systematically positioned in each plot. Total dry matter at maturity of winter crops was estimated by harvesting all plants within four 0.39 by 1.2 m quadrats systematically positioned in each plot (1.87 m^2

Table 2. Dates of treatment application for the duration of the experiment
Herbicide rates are given as concentration of product active ingredient (g/L or g/kg) and rate of product applied (L/ha, mL/ha, or g/ha)

	2008–09		2009–10		2010–11	
	Sand	Clay	Sand	Clay	Sand	Clay
Residue treatments	10 Dec. 08	11 Dec. 08	18 Nov. 09	18 Nov. 09	2 Dec. 10	02 Dec. 10
Cultivation	15 Dec. 08	15 Dec. 08	18 Dec. 09	18 Dec. 09	25 Jan. 11	25 Jan. 11
	21 Jan. 09	21 Jan. 09			03 Mar. 11	
	18 Mar. 09	18 Mar. 09				
Herbicide	16 Jan. 09[A]	16 Jan. 09[A]	07 Dec. 09[B]	07 Dec. 09[B]	25 Jan. 11[D]	25 Jan. 11[D]
			03 Mar. 10[C]		09 Feb. 11[E]	09 Feb. 11[E]
					11 Mar. 11[F]	11 Mar. 11[F]
Soil sampling	11 Dec. 08	11 Dec. 08	30 Mar. 10	30 Mar. 10	28 Mar. 11	28 Mar. 11
	22 Apr. 09	22 Apr. 09	14 Dec. 10	14 Dec. 10	02 Dec. 11	08 Dec. 11
	12 Nov. 09	12 Nov. 09				

[A]450 g/L of glyphosate @ 1.5 L/ha + 680 g/L of 2,4-D LV ester @ 0.4 L/ha + 600 g/L of triclopyr @ 80 mL/ha.
[B]510 g/L of glyphosate @ 2.0 L/ha + 600 g/kg of metsulfuron-methyl @ 7 g/ha.
[C]625 g/L of 2,4-D amine @ 2.0 L/ha.
[D]625 g/L of 2,4-D amine @ 0.6 L/ha.
[E]450 g/L of glyphosate @ 1.5 L/ha + 240 g/L of oxyfluorfen @ 75 mL/ha.
[F]450 g/L of glyphosate @ 1.5 L/ha + 240 g/L of oxyfluorfen @ 75 mL/ha.

harvested per plot), drying at 70°C for 48 h, and recording dry weight. Grain was threshed from these samples and weighed to estimate the amount of residue being returned to plots of the next summer fallow. Grain from the middle six rows of all plots was machine-harvested to estimate yield once crops were harvest-ripe.

The effects of the treatments on all data were analysed using a one-way analysis of variance (ANOVA) in the GENSTAT 14 software package (VSN International Ltd, Hemel Hempstead, UK). Some data from treatments 1, 2, 4, and 5 were also analysed as a two-way factorial ANOVA with weeds and residue as factors. Significance is assumed at $P \leq 0.05$ unless otherwise stated. Tests of mean separation were made using Fisher's least significant difference (l.s.d.) test calculated at the $P = 0.05$.

Investigating the yield effects of sowing N and water resulting from fallow management using simulation

The Agricultural Production Systems Simulator (APSIM v. 7.3; Keating *et al.* 2003) was used to complement the field experiments by modelling the effect of additional water and N at sowing resulting from fallow management strategies over the 1958–2011 growing seasons on the sand and clay soil types at Hopetoun. The APSIM modules used in the analysis were Wheat (wheat crop growth and development), SoilWat (soil water balance), SoilN (soil N dynamics), SurfaceOM (surface residue dynamics), and Manager (management rules) as described by Hunt and Kirkegaard (2011). The use of APSIM for the simulation of wheat response to soil water and N has been widely tested and validated in southern Australian cropping systems (Lilley *et al.* 2004; Lilley and Kirkegaard 2007; Verburg *et al.* 2007, 2012; Carberry *et al.* 2009; Hochman *et al.* 2009*a*). The APSIM yield prediction assumes that P and all nutrients other than N are non-limiting and does not incorporate the effects of the presence of pests, disease, weeds, or heat and frost shock. The historical weather data (1957–2011) were obtained from the SILO Patched Point Dataset (Jeffrey *et al.* 2001) for the nearby Australian Bureau of Meteorology station 077018 (Hopetoun). Using data collected in the field trials, validation model runs for the growing seasons for 2009–11 (barley, canola, and wheat) had a root mean-squared error (RMSE) for grain yield of 0.36 t/ha.

The APSIM-Manager rules used were based on observed district practice for the Hopetoun region. Mid–late-maturity wheat (APSIM-Wheat vernalisation sensitivity 2.8, photoperiod sensitivity 3.0) was sown annually at 120 plants/m^2, with 30 kg/ha of starter N applied as urea following 10 mm of rain falling within a 3-day period between 20 April and 15 June. If the rainfall event did not occur, the crop was sown on 15 June so that a crop was grown in every year of the simulation. Soil inputs of CLL, DUL, bulk density, and organic C were all derived from the measured properties presented in Table 1. While the model simulated a fully residue-retained summer fallow without weeds, the soil water, N, and surface organic matter were reset on 1 April, effectively defining the outcome of different fallow management strategies. Surface organic matter was reset to 1.5 t/ha based on estimates of breakdown of harvest-measured residue load over the fallow period. Four different soil water and N resets were chosen to test the yield benefits of increased water and/or N available at sowing on both the sand and clay soil types over a range of season types. Additional soil water and N were evenly distributed down the soil profile. The soil water and N resets for the different simulations were as follows: (1) 40 mm PAW and 80 kg/ha of soil mineral N; (2) 80 mm PAW and 80 kg/ha of soil mineral N; (3) 40 mm PAW and 120 kg/ha of soil mineral N; (4) 80 mm PAW and 120 kg/ha of soil mineral N.

Simulations 1 and 4 are based on the effect that summer-fallow weeds had in the experiment at the sand site in 2010 and 2011 (treatments 1 *v.* 3, 4 *v.* 5). Simulations 2 and 3 allow the water and N effects to be separated. Simulation 2 represents a situation where water was saved in the fallow but not N (Sadras *et al.* 2012). Simulation 3 could represent a situation where weeds were not controlled, but their effect on soil N is compensated by extra fertiliser. Simulation 4 represents a wet summer where controlling summer weeds resulted in extra water and N (e.g. 2011). Although APSIM is a daily time-step model,

Table 3. Agronomic treatment of plots including crop type, cultivar, starter fertiliser, and N topdressing rates and dates
MAP, Mono-ammonium phosphate; $(NH_4)_2SO_4$, ammonium sulfate

	2009		2010		2011	
	Sand	Clay	Sand	Clay	Sand	Clay
Crop species and cultivar	Barley cv. Hindmarsh	Barley cv. Hindmarsh	Canola cv. GT Scorpion RR	Canola cv. GT Scorpion RR	Wheat cv. Correll	Wheat cv. Correll
Target plant density (plants/m^2)	120	120	50	50	130	130
Sowing date	22 April 2009	23 April 2009	24 April 2010	24 April 2010	29 April 2011	29 April 2011
Sowing fertiliser	MAP, 35 kg/ha (4 kg N/ha, 8 kg P/ha)	MAP, 35 kg/ha (4 kg N/ha, 8 kg P/ha)	MAP, 55 kg/ha (6 kg N/ha, 12 kg P/ha)	MAP, 55 kg/ha (6 kg N/ha, 12 kg P/ha)	MAP, 55 kg/ha (6 kg N/ha, 12 kg P/ha)	MAP, 55 kg/ha (6 kg N/ha, 12 kg P/ha)
Topdressed fertiliser	Urea, 43 kg/ha (20 kg N/ha); 26 June 2009 $(NH_4)_2SO_4$, 100 kg/ha (21 kg N/ha, 24 kg S/ha); 9 July 2009	–	$(NH_4)_2SO_4$, 100 kg/ha (21 kg N/ha, 24 kg S/ha); 24 June 2010 Urea, 80 kg/ha (37 kg N/ha); 28 July 2010	$(NH_4)_2SO_4$, 100 kg/ha (21 kg N/ha, 24 kg S/ha); 24 June 2010 Urea, 80 kg/ha (37 kg N/ha); 28 July 2010	$(NH_4)_2SO_4$, 100 kg/ha (21 kg N/ha, 24 kg S/ha); 1 July 2011	$(NH_4)_2SO_4$, 100 kg/ha (21 kg N/ha, 24 kg S/ha); 1 July 2011

only the grain yield at maturity in every season was used to demonstrate the effects of differences between different levels of pre-sowing N and water.

Results

Field experiments

The initial residue loads at the sand and clay sites were 2.7 and 2.4 t/ha, respectively. As treatments were applied to the same plots in all years of the experiment, there was the possibility that treatment effects would accumulate and that residue load in subsequent seasons would be different for different treatments. However, the only significant difference ($P = 0.002$) measured was at the clay site following harvest in 2010 when the weedy treatments had ~1 t/ha less residue than the treatments in which weeds were controlled (Table 4).

The summer fallow (March–November) rain for 2008–09 matched the regional average of 90 mm, with the single largest event comprising 27 mm over several days in December 2009. Summer-growing weeds, primarily common heliotrope (*Heliotropium europaeum*) and volunteer wheat germinated following this rain, were controlled in the cultivation and weed-free treatments (Table 2). Prior to control on 14 January 2009, there were 3 plants/m^2 of common heliotrope and 38 plants/m^2 of volunteer wheat at the sand site. There were 32 plants/m^2 of common heliotrope and 65 plants/m^2 of volunteer wheat at the clay site. By the time that weed densities were re-assessed on 4 March 2009, volunteer wheat in all uncontrolled treatments had died from drought and there remained an average of 5 plants/m^2 of common heliotrope in treatments 2 and 5 at the sand site, and 18 plants/m^2 at the clay site. Growing season (April–October) rainfall was 213 mm at the sand site and 202 mm at the clay site, which was slightly below average. Despite the measured weed burden, there was no significant effect of treatment on PAW or mineral N before sowing in 2009 at either site, and no difference in crop grain yield or protein (Table 5). When analysed as a two-way factorial with weeds and residue as factors, weeds significantly reduced PAW by 29 mm ($P = 0.011$) before sowing at the sand site, and there was a corresponding near-significant ($P = 0.126$) reduction in grain yield (Table 6). There was no significant effect of weeds at the clay site and no significant effect of residue management or interaction between weeds and residue at either site (Table 6).

The summer fallow for 2009–10 was uncharacteristically wet, with the sand site receiving 224 mm and the clay site 254 mm, both of which included individual rainfall events of >100 mm. Summer weeds established several times throughout the fallow and grew in the weedy treatments at both sites, and required continued control in the non-weedy treatments. On 22 February 2010 at the sand site, there were, on average, 11 plants/m^2 of common heliotrope and 5 plants/m^2 of volunteer barley in the two weedy treatments; all other treatments were weed-free. This weed density reduced PAW and mineral N by 39 mm and 46 kg/ha when measured before sowing in 2010 (Tables 5 and 6). Growing season rainfall was above-average in 2010, with both sites receiving 264 mm. Differences in PAW and mineral N did not translate into significant differences between grain yields of individual treatments at the sand site (Table 5), but the effect of weeds on grain yield was near-significant when

Table 4. Residue loads (t/ha) as measured at harvest for different treatments at both sites for 2009–10 and 2010–11 summer fallow periods before removal in the bare earth treatments

Values followed by the same letter are not significantly different ($P > 0.05$)

Treatment	Sand		Clay	
	2009–10 (barley)	2010–11 (canola)	2009–10 (barley)	2010–11 (canola)
1. Standing residue + no summer weeds	3.6	5.7	4.4	5.2a
2. Standing residue + summer weeds	3.2	4.7	3.9	4.2b
3. Slashed residue + no summer weeds	3.8	5.4	4.0	5.2a
4. Bare earth + no summer weeds	3.5	5.3	4.1	5.1a
5. Bare earth + summer weeds	3.6	4.9	3.7	3.7bc
6. Cultivation + no summer weeds	4.1	5.8	4.0	4.6ab
P-value	0.679	0.189	0.559	0.002
l.s.d. ($P = 0.05$)	1.2	1.0	0.8	0.7

Table 5. Plant available water (PAW) and total mineral N (Min N, nitrate + ammonium) to 1.3 m measured before sowing, grain yield, and grain protein content for the different summer fallow management treatments at each site 2009–2011

Within column and year, values followed by the same letter are not significantly different ($P > 0.05$)

	Sand				Clay			
	PAW (mm)	Min N (kg/ha)	Grain yield (t/ha)	Grain protein (%)	PAW (mm)	Min N (kg/ha)	Grain yield (t/ha)	Grain protein (%)
2009, Barley								
1. Standing residue + no summer weeds	8	127	3.7	10.9	16	174	2.9	11.7
2. Standing residue + summer weeds	–22	122	3.3	11.0	–8	148	2.7	11.9
3. Slashed residue + no summer weeds	6	121	3.5	10.9	12	135	2.7	10.4
4. Bare earth + no summer weeds	9	134	3.4	11.7	–14	165	2.8	12.7
5. Bare earth + summer weeds	–21	131	3.3	11.4	–6	167	2.8	12.4
6. Cultivation + no summer weeds	–6	107	3.3	10.5	1	190	2.7	11.3
P-value	0.060	0.611	0.468	0.224	0.432	0.316	0.123	0.356
l.s.d. ($P = 0.05$)	26	34	0.4	1.0	34	52	0.2	2.3
2010, Canola								
1. Standing residue + no summer weeds	70a	152a	3.3	–	117a	173a	2.8a	–
2. Standing residue + summer weeds	27b	101b	2.5	–	31b	115bc	2.2b	–
3. Slashed residue + no summer weeds	79a	135ab	2.9	–	116a	168a	2.8a	–
4. Bare earth + no summer weeds	70a	149a	3.0	–	97a	153ac	2.8a	–
5. Bare earth + summer weeds	35b	110b	2.8	–	31b	109b	2.1b	–
6. Cultivation + no summer weeds	64a	131ab	3.2	–	100a	140abc	2.6a	–
P-value	0.008	0.034	0.152		0.009	0.047	0.003	
l.s.d. ($P = 0.05$)	29	34	0.6		53	43	0.4	
2011, Wheat								
1. Standing residue + no summer weeds	97ab	131a	3.7a	9.9	145	145	2.6a	12.1a
2. Standing residue + summer weeds	78bc	77bc	2.6b	10.2	99	97	1.4b	12.9b
3. Slashed residue + no summer weeds	113a	123ad	3.8a	9.8	133	148	2.8ac	11.8a
4. Bare earth + no summer weeds	101ab	105ab	3.7a	9.6	125	143	2.9c	11.9a
5. Bare earth + summer weeds	67c	70c	2.1b	9.9	96	111	1.4b	12.2a
6. Cultivation + no summer weeds	96ab	101bd	3.4a	9.8	133	164	3.0c	12.0a
P-value	0.028	0.003	<0.001	0.923	0.127	0.053	<0.001	0.006
l.s.d. ($P = 0.05$)	27	29	0.5	1.1	42	45	0.2	0.5

analysed as a two-way factorial ($P = 0.068$). There was also a significant ($P = 0.027$) negative relationship between common heliotrope density during summer and subsequent grain yield that accounted for 59% of observed variation in yield between plots (data not shown).

At the clay site, there were 8 plants/m^2 of common heliotrope on 22 February 2010 in the weedy treatments, which caused a reduction in PAW and mineral N of 77 mm and 51 kg/ha relative to the weed-free treatments (Tables 5 and 6). Grain yield in the weedy treatments was correspondingly reduced by 0.7 t/ha (Table 6). There was no significant effect of residue treatment (amount or orientation) on PAW, mineral N, or grain yield at either site in 2010.

The summer fallow of 2010–11 was one of the wettest on record (387 mm at both sites), but subsequent growing-season rainfall was well below average, with 198 mm recorded at both

Table 6. Plant available water (PAW) and total mineral N (Min N, nitrate + ammonium) measured before sowing, grain yield, and grain protein content for the weedy (treatments 2 and 5) and non-weedy treatments (1 and 4) at each site 2009–2011

Analysis is a two-way factorial ANOVA with weeds and residue as factors

	Sand				Clay			
	PAW (mm)	Min N (kg/ha)	Grain yield (t/ha)	Grain protein (%)	PAW (mm)	Min N (kg/ha)	Grain yield (t/ha)	Grain protein (%)
				2009, Barley				
No weeds	8	130	3.5	11.3	1	170	2.8	12.2
Weeds	–21	126	3.3	11.2	–7	157	2.8	12.1
P-value	0.011	0.683	0.126	0.691	0.533	0.401	0.280	0.947
l.s.d. ($P = 0.05$)	21	28	0.3	0.8	27	32	0.1	1.7
				2010, Canola				
No weeds	70	151	3.1	–	108	163	2.8	–
Weeds	31	105	2.7	–	31	112	2.1	–
P-value	0.001	0.002	0.068		0.002	0.012	0.001	
l.s.d. ($P = 0.05$)	20	24	0.5		36	36	0.3	
				2011, Wheat				
No weeds	99	118	3.7	9.7	135	144	2.7	12.0
Weeds	73	74	2.3	10.0	98	104	1.4	12.5
P-value	0.035	0.002	<0.001	0.394	0.025	<0.001	<0.001	0.012
l.s.d. ($P = 0.05$)	24	24	0.3	0.7	31	15	0.2	0.4
				Residue treatment				
No residue	84	88	2.9	9.7	111	125	2.2	12.1
Residue	88	104	3.1	10.0	122	121	2.0	12.5
P-value	0.757	0.161	0.113	0.355	0.439	0.138	0.044	0.030
l.s.d. ($P = 0.05$)	24	24	0.3	0.7	13.8	15	0.2	0.4

sites. On 25 January 2011, there were 16 plants/m^2 of common heliotrope and 12 plants/m^2 of volunteer canola at the clay site. At the sand site, the mean density of volunteer canola was 83 plants/m^2 and of common heliotrope 79 plants/m^2, but residue management significantly affected density of both species ($P = 0.030$ for volunteer canola and $P = 0.022$ for common heliotrope), with 98 canola and 106 common heliotrope plants/m^2 in the residue treatments and 68 canola and 53 common heliotrope plants/m^2 in bare earth treatments. Weeds at the clay site reduced PAW by 37 mm, mineral N by 40 kg/ha, and wheat grain yield by 1.3 t/ha, but increased grain protein content by 0.5% (Table 6). For the first time in the duration of the experiment, there was a significant effect of residue on grain yield and protein; treatments with standing residue yielded 0.2 t/ha less than those with bare earth but had 0.4% more grain protein (Table 6). At the sand site, weeds reduced PAW by 26 mm, mineral N by 44 kg/ha, and wheat grain yield by 1.4 t/ha with no effect on protein (Table 6). In contrast to the clay site, there was no significant effect of residue treatment.

In the years in which there was a significant effect of weeds on PAW and mineral N (2010 and 2011), there was a strong positive relationship between these two variables, which was consistent across both sites (Fig. 2).

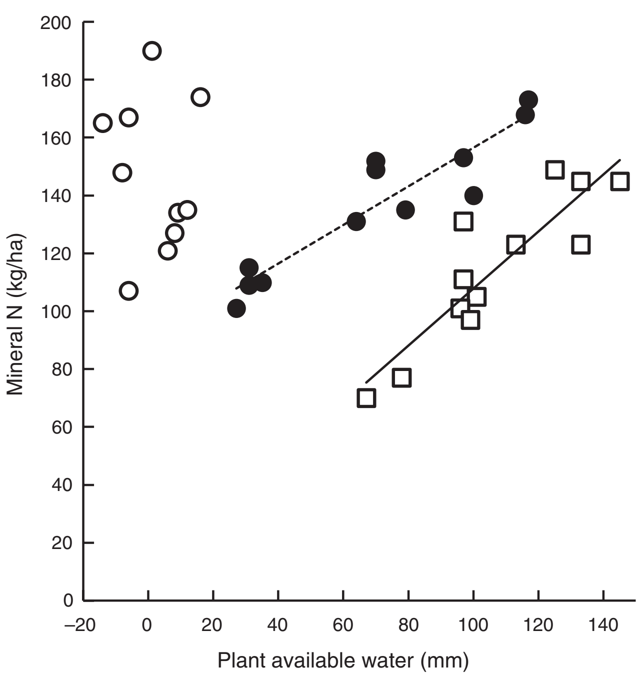

Fig. 2. Relationship between treatment means from both sites of plant-available water and mineral N in 2009 (○), 2010 (●), and 2011 (□). The linear function fitted by least-squares regression is of the form: $y = 0.67x + 86.91$ ($R^2 = 0.79$) for 2010; and $y = 0.99x + 9.35$ ($R^2 = 0.78$) for 2011.

Simulation experiments

The simulation experiments showed that the increase in wheat grain yield due to an extra 40 mm PAW, in the absence of any extra N, was largest in seasons with low in-season rain and

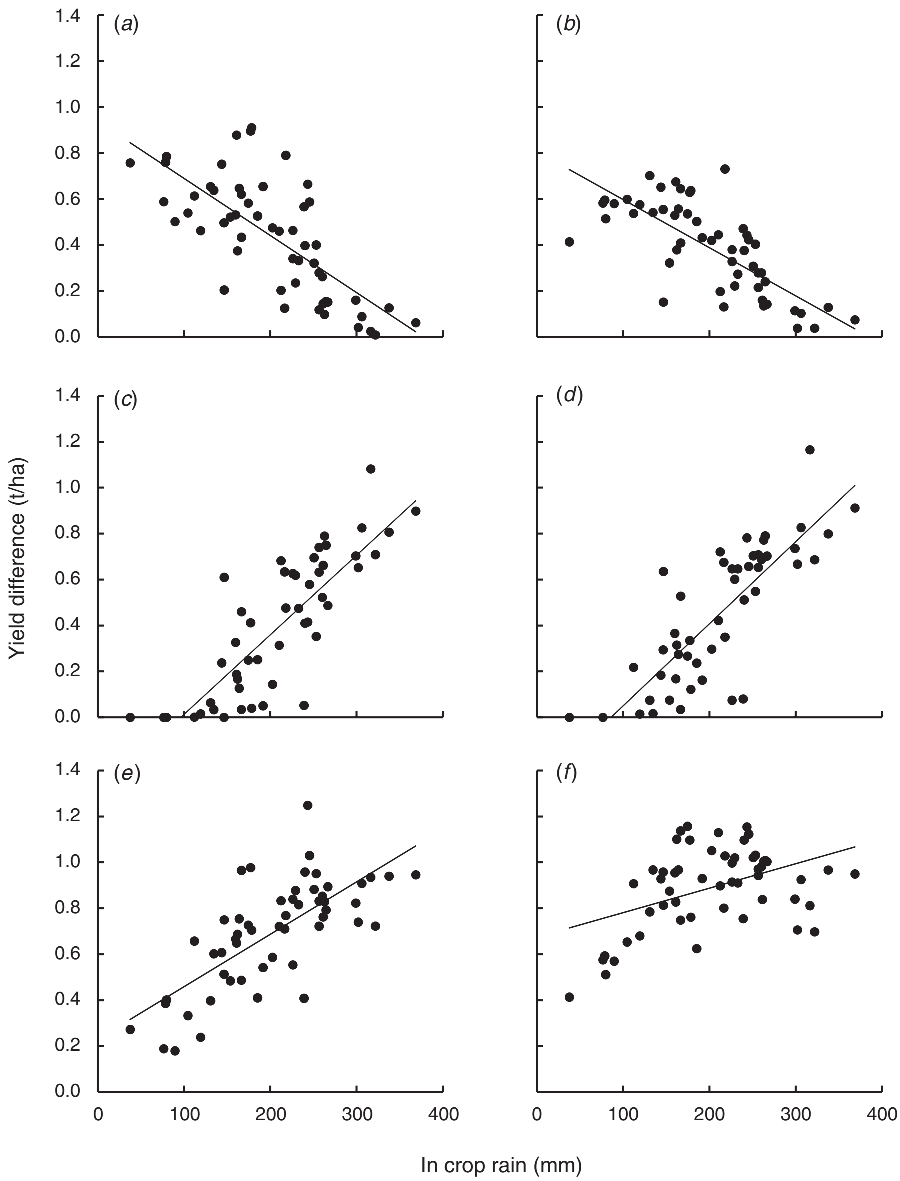

Fig. 3. Simulated wheat yield increase due to an extra 40 mm pre-sowing plant-available water at the (*a*) sand and (*b*) clay site; an extra 40 kg/ha of pre-sowing mineral N at the (*c*) sand and (*d*) clay site; the combined effect of an extra 40 mm plant-available water and 40 kg/ha of pre-sowing mineral N at the (e) sand site and (*f*) clay site. The linear functions fitted by least-squares regression are of the forms: (*a*) $y = -0.0025x + 0.9377$ ($R^2 = 0.53$); (*b*) $y = -0.0021x + 0.8062$ ($R^2 = 0.55$); (*c*) $y = 0.0035x - 0.3347$ ($R^2 = 0.68$); (*d*) $y = 0.0036x - 0.2989$ ($R^2 = 0.71$); (*e*) $y = 0.0023x + 0.2298$ ($R^2 = 0.52$): (*f*) $y = 0.0011x + 0.6747$ ($R^2 = 0.20$).

negligible in years with high in-season rain. This relationship and the mean benefit (0.4 t/ha) was similar at both the sand and clay sites (Fig. 3*a*, *b*). In the absence of extra PAW, an extra 40 kg/ha of mineral N was of greatest benefit in seasons with higher in-season rainfall and thus yield potentials which increase crop N requirement, and negligible in years with low in-season rainfall (Fig. 3*c*, *d*). The mean yield increase due to extra N was also 0.4 t/ha at both sites. A representation of summer weed control with increases in both PAW (40 mm) and N (40 kg/ha) demonstrates the interactive effects of these benefits through a higher magnitude of yield difference: 0.7 t/ha at the sand site and 0.9 t/ha at the clay site. Although the trend was for the yield benefit to increase with in-season rainfall, as was the case for having extra pre-sowing mineral N, significant yield responses also occurred in seasons with low in-season rainfall (Fig. 3*e*, *f*).

Discussion

In the summer fallow of 2008–09, enough rain fell to establish weeds but not to be stored for use by the subsequent crop. This represents a worst-case scenario for growers managing summer fallows, as investment in weed control is not met with a return in the form of additional crop yield. However, modelling by Hunt and Kirkegaard (2011) over 119 years of climate data indicates that this outcome is rare (3–29% of years depending on soil type), and certainly the large yield benefits resulting from control of summer weeds on both soil types in 2010 and 2011 support the notion that complete control of summer-fallow weeds is a beneficial strategy in the long-term. There may be some opportunity for growers to use the pulse paradigm proposed by Verburg *et al*. (2012) to assess the likelihood of the 2008–09 outcome during the fallow period and decide tactically whether to control emerging cohorts of weeds, but by far the easiest and most reliable approach will be to control all weed cohorts as they emerge (Haskins and McMaster 2012). The analysis of profitability and risk of loss conducted by Hunt and Kirkegaard (2011) in the absence of N limitation suggests that this is the case.

In 2009–10 and 2010–11, summer fallow rain was well above average, and the yield increases achieved by controlling summer weeds (0.3 t/ha of canola yield at the clay site in 2010, and 1.4 and 1.3 t/ha wheat yield in 2011) arguably overstate the long-term average productivity gains that are possible. Hunt and Kirkegaard (2011) report that for a 'light' and 'heavy' soil at Hopetoun, the predicted long-term contribution of summer fallow rain to wheat yield was 1.2 and 0.7 t/ha, respectively. Hunt (2006) estimated the mean amount of stored soil water from summer rainfall based on rainfall records during 1976–2002 at the nearby townships of Lascelles (18 km NNE of the Hopetoun site) and Beulah (18 km SSW) as 31 and 18 mm, respectively. Assuming that yield is water-limited and assuming a transpiration efficiency for wheat grain of 22 kg/ha.mm (Sadras and Angus 2006), this translates into 0.7 and 0.4 t/ha of wheat grain yield at Lascelles and Beulah, respectively. However, the studies of both Hunt and Kirkegaard (2011) and Hunt (2006) ignored the potential effect of summer weeds on mineral N availability, and calculated yield benefits on subsequent wheat crops in the absence of N limitation.

Growing-season rainfall was above average in 2010 and below average in 2011. However, the large yield increases due to summer weed control that were achieved in both years indicate that the resultant yield responses are reliable across a broad range of subsequent growing-season conditions. Simulation modelling predicted that in high-rainfall growing seasons such as 2010, the yield response was largely driven by the additional N available (Fig. 3*c*, *d*) where weeds were controlled as per the findings of Osten *et al*. (2006) and Haskins and McMaster (2012). In drier growing seasons such as 2011, the predicted yield response was driven by the additional water as shown in Fig. 3*a*, *b* (Fromm and Grieger 2002; Kirkegaard and Hunt 2010; Hunt and Kirkegaard 2011; Verburg *et al*. 2012), and in average growing seasons, the yield response arises from both additional water and additional N, reflecting the co-limitation postulated by Sadras *et al*. (2012). The strong relationship between water and N from controlling weeds evident in Fig. 2 highlights the reliability of a yield response, in contrast to practices that increase only the amount of water available to a subsequent crop (Sadras *et al*. 2012). This shows that, even in a region with winter-dominant rainfall, the practice of controlling summer weeds is a low-risk management option with a strong likelihood of considerable financial return in additional grain yield (the average return on investment in herbicide control across 3 years of the experiment was 320% at the sand site and 476% at the clay site). This was the same conclusion reached by Haskins and McMaster (2012), who recorded returns on investment in herbicide costs of 220–500%.

The results of this study add experimental weight to the re-evaluation of the contribution that summer-fallow rain makes to wheat yield in southern Australia made in the simulation by Hunt and Kirkegaard (2011), and further contradict the assertion of French (1978*a*, 1978*b*), French and Schultz (1984*b*, 1984*a*), and Freebairn *et al*. (2006) that, in winter-rainfall dominant environments, summer-fallow rainfall does not contribute to winter crop water use. French (1978*a*) concluded that summer-fallow rain is only stored for subsequent crop water use if total rain for the period exceeds 300 mm, or falls in heavy rains of short duration. In the present study, 29 mm of water was stored at the sand site by controlling summer weeds in 2008–09 following only 90 mm of rain for the total period, and the largest single fall was only 27 mm over several days. The summer fallows of 2009–10 did feature heavy rain of short duration, and total summer-fallow rain in 2010–011 exceeded 300 mm. However, the average amount of water stored in this study during the summer fallow alone (45 mm) well exceeds the average reported by French (1978*a*) for 18-month-long fallow (28 mm) in regions of equivalent rainfall, perhaps implying that prompt weed control by herbicide in no-till soils with structural integrity can achieve much higher fallow efficiencies than repeatedly cultivated 'bare' long fallows. This study also contradicts the finding by French (1978*a*) that water storage was not possible on coarse-textured soils. Water storage at the sand site was in fact superior to the clay site in 2009, inferior in 2010, and equivalent in 2011.

Further research is required to ascertain whether sheep grazing weeds can significantly reduce their water and N use, and whether any loss to the cropping enterprise of a mixed farm due to retention of summer weeds is offset by gains in the livestock enterprise. Whole-farm simulation suggests that retaining even a highly palatable C_3 summer weed for grazing by livestock is detrimental to both crop and livestock enterprises at Hopetoun, but may have some small benefit to a livestock enterprise at Temora in south-eastern NSW, an environment with higher and more evenly distributed rainfall (Moore and Hunt 2012).

At no time during the experiment did any residue treatment have a significant effect on PAW or N, and only in 2011 at the clay site was yield reduced by the presence of residue. It has been demonstrated in the cropping areas of Queensland and northern NSW that the principal mechanism by which crop residues increase fallow efficiency is by minimising the physical impact of raindrops on the surface soil, maintaining structural integrity and infiltration rates, and reducing runoff (Felton *et al*. 1987; Foley and Silburn 2002; Scott *et al*. 2010). Intensity and energy of rainfall is much higher in northern cropping areas of Australia than in the Mediterranean climate of north-western Victoria, so the likelihood of residue improving summer-fallow efficiency by increasing infiltration is far less (Scott *et al*. 2010).

Crop residues slow but do not eliminate evaporative losses from the soil surface, and wheat residue loads >5 t/ha are required to achieve significant soil-water savings over extended dry periods (Bond and Willis 1970). Residue levels at either site only exceeded 5 t/ha immediately following harvest in 2010, which was an exceptional year for crop (and residue) production. It could be speculated that, if higher levels of residue could be generated, soil water accumulation could be increased by reducing evaporative losses from the summer fallow. However, as discussed by Browne and Jones (2008), rainfall in the Mallee infrequently allows production of residue levels >5 t/ha, so the capacity for residue to increase fallow efficiency and crop yields in this region via this mechanism is limited, and they advocate zero-till seeding systems, which allow residue from multiple seasons to accumulate. Cover crops could be used to increase residue levels, but Ward *et al.*(2012) demonstrated that cover crops did not reduce summer-fallow evaporation in a Mediterranean environment, and were less profitable than continuous grain cropping (Flower *et al*. 2012). In the only season of the present experiment (2011) where preceding residue levels were >5 t/ha (Table 4), there was no effect of residue on soil water accumulation (possibly due to the residue in question being from canola, which generates less soil cover per unit weight of residue than cereals and thus would be less effective at slowing evaporation; Scott *et al*. 2010) and a negative effect of residue on wheat yield at the clay site (Table 6). Although Ward *et al*. (2009) recorded a small increase in evaporation rates from standing wheat residue compared with bare earth during the summer fallow, in the present experiment there would have been nutrient cycling (Scott *et al*. 2010), biological (Kirkegaard *et al*. 1995) and temperature (Bruce *et al*. 2006) effects of residues on crop growth, and it is not possible to attribute the yield reduction to any single cause.

The principal benefits of retaining residues in the Mallee appear to be logistic (i.e. no time or financial cost is incurred removing residue), and for resource protection (prevention of wind erosion). Prevention of wind erosion requires only 70% cover or ~2 t/ha of anchored cereal residue (Felton *et al*. 1987), levels which can be achieved in the majority of seasons. Mixed farmers wishing to graze livestock on residues should be able to confidently graze to this level without expecting a reduction in fallow efficiency or subsequent crop yield, and thus maximise whole-farm profitability. While the present study did not use livestock to remove residue, yield effects due to livestock and manual removal of residue appear to be equivalent (N. Fettell, unpubl. data), as yield losses due to soil compaction from grazing sheep are small and rare (Bell *et al*. 2011), and reductions in soil water accumulation are due to the removal of cover rather than soil physical damage due to treading (Hunt *et al*. 2011).

As the value of summer fallow rain in this region and the case for weed control has been demonstrated in this study, productivity gains could be made by adapting current management to take advantage of the additional stored soil water and N resulting from summer weed control. This could include planting higher risk/value crops such as canola in response to higher levels of stored soil water, planting slower maturing wheat varieties earlier to better use stored soil water as proposed by O'Leary and Connor (1997*c*) and demonstrated by Hunt *et al*. (2012), or establishing crops on stored soil water in the absence of surface moisture to ensure that anthesis occurs at a time most beneficial to yield (Kirkegaard and Hunt 2010). The proportion of annual rain falling during the summer fallow period increases under modelled climate change scenarios (CSIRO and BOM 2007), and research in this area will make an important contribution to adaption of Mallee farming systems to a future climate.

Conclusion

Even in a region with a Mediterranean climate, summer-growing weeds significantly reduce the amount of soil water and mineral N that is available to a subsequent crop. Controlling summer weeds either by herbicide or by cultivation resulted in large and reliable yield increases of winter crops due to the provision of both additional soil water and additional mineral N. The co-limitation of yield by water and N in the Mallee environment means that yield increases due to summer weed control (and thus returns on investment in control) are very reliable. Complete residue retention in the Mallee is unlikely to increase summer fallow efficiency or yield due to low rainfall intensities and, consequently, low potential for net losses due to runoff.

Acknowledgements

This research was funded by GRDC Water-Use Efficiency Initiative projects BWD00012 and CSP00111. We thank David Moody for instigating the project, Warakirri Bullarto Downs for hosting the experiments, Ian Delmenico of CropRite Pty Ltd for site EM survey, Daryl Burdett of BCG for site management, Damian Mowat and Brett Cocks of CSIRO for soil water characterisations, John Stuchbery of JSA Independent for agronomic advice, Brad Rheinheimer and Laura Watson of CSIRO for soil analyses, Mel Cann of DPI Victoria for providing soil descriptions, and Merv Probert of CSIRO for advice on fallow modelling. Yvette Oliver, Phil Ward, and John Kirkegaard provided helpful comment on an earlier version of the manuscript.

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