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Long-term cropping system studies support intensive and responsive cropping systems in the low-rainfall Australian Mallee

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Abstract. Continuous-cropping systems based on no-till and crop residue retention have been widely adopted across the low-rainfall cereal belt in southern Australia in the last decade to manage climate risk and wind erosion. This paper reports on two long-term field experiments that were established in the late 1990s on texturally different soil types at a time of uncertainty about the profitability of continuous-cropping rotations in low-rainfall environments. Continuous-cereal systems significantly outyielded the traditional pasture–wheat systems in five of the 11 seasons at Waikerie (light-textured soil), resulting in a cumulative gross margin of AU\$1600 ha^{-1} after the initial eight seasons, almost double that of the other treatments. All rotation systems at Kerribee (loam-textured soil) performed poorly, with only the 2003 season producing yields close to 3 t ha^{-1} and no profit achieved in the years 2004–08. For low-rainfall environments, the success of a higher input cropping system largely depends on the ability to offset the losses in poor seasons by capturing greater benefits from good seasons; therefore, strategies to manage climatic risk are paramount. Fallow efficiency, or the efficiency with which rainfall was stored during the period between crops, averaged 17% at Kerribee and 30% at Waikerie, also indicating that soil texture strongly influences soil evaporation. A 'responsive' strategy of continuous cereal with the occasional, high-value 'break crop' when seasonal conditions are optimal is considered superior to fixed or pasture–fallow rotations for controlling grass, disease or nutritional issues.

Additional keywords: climate variability, continuous cropping, crop modelling, low rainfall cropping, risk management, rotations.

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Introduction

Cereal production in the low-rainfall Mallee region of south-eastern Australia (annual rainfall 250–350 mm) has been typically managed using low-input farming systems, which often fail to maximise yield potential and utilise the available rainfall during the better seasons (Sadras *et al*. 2003; Sadras and Roget 2004; Monjardino *et al*. 2013). This management system has developed in response to highly variable patterns of rainfall and low-soil water storage (Sadras *et al*. 2002). Soils in the Mallee region are inherently low in soil organic matter and thus low in nutrient (nitrogen, N) supply potential; hence, crops under low-input systems are limited by lack of adequate nutrition to utilise the available water (Sadras and Roget 2004; Gupta *et al*. 2011). Traditionally, the most commonly practiced rotation system consisted of 1–3 years of cereal followed by a pasture based on self-regenerating medics (e.g. barrel medic, *Medicago truncatula* Gaertn.; strand medic, *M. littoralis* Rohde ex Lois.; disc medic, *M. tornata* (L.) Mill.; burr medic, *M. polymorpha* L.) or a pasture–weed-free-fallow phase. The poor performance of the pasture phase, largely the consequence of declining pasture-management efforts, and the high wind-erosion risks associated with low groundcover during summer–autumn were significant impediments to the sustainability of the system (Leys and McTainsh 1994; Denton and Bellotti 1996).

In order to improve sustainability and profitability, more intensive crop rotations based on reduced tillage and higher inputs were promoted by researchers such as Rovira (1992) and were slowly adopted. For example, by 2008, 35–40% of farmers in the South Australian and Victorian Mallee had adopted no-till on ≥90 of crop land (Llewellyn *et al*. (2012). This shift to cropping was also associated with the reduction in sheep numbers in the region, which dropped by half from the 1980s to the 2000s because of the collapse in the wool price. Further technological innovations in no-till planting equipment that could handle higher stubble loads, increased herbicide options (Llewellyn *et al*. 2012), the availability of cereal varieties resistant to cereal cyst nematode

(Vanstone *et al*. 2008) and planting techniques to minimise root disease (Roget *et al*. 1996) all made continuous cropping more feasible.

In response to the relatively slow adoption of modern conservation farming methods and low productivity gains in the Mallee regions of southern Australia during the early 1990s, a major research project funded by the grains industry, the Mallee Sustainable Farming Project, commenced in 1997 (Sadras *et al*. 2002). A core component of this work was implementation of long-term rotation experiments on two representative landforms of the region to compare the 'traditional-practice' rotations, consisting of tillage to control weeds and prepare the seed bed and pasture phases between sequences of cereals, with 'continuously cropped' rotations, which included reduced tillage, continuous cereal or cereal–canola rotations with higher inputs. The main objective of the field experiments was to investigate the potential to improve the sustainability and profitability of Mallee farming systems significantly, based on the hypothesis that productivity gains of up to 100% could be made by more efficient utilisation of the available rainfall with more intensive cropping and improved tillage and fertiliser strategies. It was assumed that intensive cropping and increased productivity, combined with stubble retention and no tillage, would increase carbon (C) inputs required for the soil biological functions necessary for plant health and nutrition (Roget and Gupta 2004) but would not necessarily lead to an overall increase in C sequestration because of the lack of protection for soil organic matter and crop residues from microbial decomposition in the sandy-textured Mallee soils (Dalal and Chan 2001). An extensive review by Chan *et al*. (2003) of the potential of light-textured soil to sequester C under conservation tillage practices found no change and even continued reductions in soil C, particularly for the drier cropping regions.

This paper compares the yield, soil water and soil mineral N dynamics, water-use efficiency (WUE) and partial economic performance of traditional practice and continuously cropped rotation systems over several seasons at the two sites in Mallee regions. The central research question addressed was whether intensive cropping strategies with or without break crops can be more productive and water-use-efficient than the traditional, low-input systems.

Materials and methods

Site locations and histories

In order to compare the common traditional farming practices of the time (late 1990s) with alternative practices based on more intensive management of rotations, reduced tillage and the application of higher fertiliser inputs, two long-term plot experiments were established at Waikerie in South Australia (34°17′S, 140°02′E) in 1998 and at Kerribee Station near Paringi in New South Wales (34°61′S, 142°22′E) in 2002. The climate at both sites is Mediterranean-type, characterised by hot, dry summers and winter-dominant rainfall. Growing-season rainfall (GSR, April–October) is, on average, only 164 mm at Waikerie and 172 mm at Kerribee, together the sites represent the geographical and climatic extremes of the south-eastern Australian cropping region.

The experimental site at Waikerie was on a sandy soil associated with the dune component of the dune–swale system typical of the northern Mallee environment and classified as Endohypersodic, Regolithic, Hypercalcic Calcarosol (Isbell 1996). Soil texture is sandy, with sand content ranging from 92% to 80% from the surface to a depth of 0.8 m (data not shown). The site at Kerribee was on a flat swale between low dunes and classified as Epibasic, Pedal, Calcic Calcarosol. The soil texture is sandy loam to loam with sand content declining progressively with depth from 80% in the top layer to <60% in layers deeper than 0.6 m, with a concomitant increase in clay content (data not shown). Prior to these field experiments, the sites had been part of a cereal–pasture (Waikerie) or cereal–fallow (Kerribee) based farming operation for several decades, before which the original mallee vegetation was cleared.

Both sites share the common features of Calcarosols, which include sandy or sandy loam textures, low organic C concentration (topsoil <0.7%) and increasing pH values with depth associated with the increases in $CaCO_3$. Exchangeable sodium percentage (ESP) was >19% at a depth of 0.6 m at Waikerie and >28% at depths >0.8 m for both sites (Tables 1 and 2). Boron reaches concentrations of >15% at depths >0.8 m at both sites. Electrical conductivity remained low (<0.38 $dS\,m^{-1}$) at all depths. All soil chemical analyses followed the procedures outlined in Rayment and Lyons (2011). These chemical characteristics are not considered to be at the extreme levels of subsoil chemical constraints according to Shaw (1999) or Nuttall *et al*. (2003). Plant-available water capacity (PAWC) to 1 m depth was based on the difference between soil water content at drained upper limit (DUL) and crop lower limit (CLL) (lowest soil water content during a wheat crop) following the methodology described by Dalgliesh and Foale (1988) and found to be 69 mm at Waikerie (Table 1) and 99 mm at Kerribee (Table 2).

Rotation comparisons

Waikerie

The Waikerie site was established in 1998 following a wheat crop that was harvested for grain, and the residues and volunteer pasture were intermittently grazed over the summer period from November 1997 to March 1998. Using a randomised block design, several treatments, replicated four times, were established to contrast the traditional practice with alternative management systems. The traditional practice consisted of two phased treatments of a cultivated pasture–wheat rotation in alternate years with low sowing inputs of fertiliser (5 kg N, 11 kg phosphorus (P) ha^{-1}) and seed (45 kg ha^{-1}). In this rotation, the pasture comprises self-sown forbs and herbs (*Chondrilla juncea*, *Raphanus raphanistrum*, *Heliotropium europaeum*), summer-growing annual grasses (*Polypogon* spp., *Tragus australianus*) and *Medicago* spp. that emerge in response to rainfall. This may occur late in the cereal phase when weeds are no longer controlled with herbicides, or any time in response to rainfall events through the next autumn and winter season. Such pastures are typically grazed by sheep, although in this experiment grazing was simulated by mowing pasture two or three times during a phase and spray-topping in the months before a cereal phase. At the end of the pasture phase, typically early summer, cultivation was used to control weeds in preparation

Table 1. Properties of the Waikerie experimental sites related to soil water-holding capacity and selected soil chemical characteristics
TAW, Total available water; PAWC, plant-available water capacity; DUL, drained upper limit; CLL, crop lower limit during a wheat crop; EC, electrical conductivity; ESP, exchangeable sodium percentage. Standard errors for data measured on multiple samples ($n = 9$) are given in parentheses

Depth	BD	DUL	CLL	Inorg. C	Org. C	EC	pH$_{Ca}$	Boron	ESP
(m)	(g cm^{-3})	(mm)		(g kg^{-1})		(dS m^{-1})		(mg kg^{-1})	
0–0.1	1.52 (0.02)	7.8 (0.6)	2.0	0.1 (0.1)	6.1 (0.3)	0.06 (0.01)	7.2	1.1	0.8
0.1–0.2	1.68 (0.02)	7.5 (0.3)	2.4	0.5 (0.3)	3.4 (0.4)	0.06 (0.01)	8.1	1.5	0.8
0.2–0.4	1.63 (0.01)	17.4 (1.0)	7.0	1.6 (0.6)	2.3 (0.6)	0.07 (0.01)	8.3	1.4	0.8
0.4–0.6	1.60 (0.01)	23.2 (2.0)	8.4	2.9 (1.0)	1.1 (0.2)	0.08 (0.01)	8.4	1.1	5.6
0.6–0.8	1.59 (0.05)	31.3 (5.4)	16.8	8.7 (2.5)	0.4 (0.1)	0.18 (0.03)	8.5	6.5	18.7
0.8–1.0	1.66 (0.02)	42.9 (3.7)	24.2	18.4 (4.4)	0.3 (0.1)	0.37 (0.05)	8.6	21.0	31.4
TAW (mm):		130	61						
PAWC (mm):			69						

Table 2. Properties of the Kerribee experimental sites related to soil water holding capacity and selected soil chemical characteristics
TAW, Total available water; PAWC, plant-available water capacity; DUL, drained upper limit; CLL, crop lower limit during a wheat crop; EC, electrical conductivity; ESP, exchangeable sodium percentage. Standard errors for data measured on multiple samples ($n = 9$) are given in parentheses; n.a., samples not available

Depth	BD	DUL	CLL	Inorg. C	Org. C	EC	pH$_{Ca}$	B	ESP
(m)	(g cm^{-3})	(mm)		(g kg^{-1})		(dS m^{-1})		(mg kg^{-1})	
0–0.1	1.29 (0.02)	12.8 (0.1)	2.8	0.3 (0.0)	6.7 (0.2)	0.07 (0.01)	7.1	3.8	0.3
0.1–0.2	1.53 (0.02)	17.0 (0.4)	6.5	0.9 (0.3)	5.1 (0.2)	0.10 (0.01)	7.8	n.a	n.a
0.2–0.4	1.44 (0.02)	37.1 (0.1)	18.6	3.1 (1.1)	4.0 (0.3)	0.10 (0.00)	8.0	2	0.3
0.4–0.6	1.49 (0.03)	43.2 (0.5)	21.0	11.3 (1.6)	3.0 (0.3)	0.13 (0.01)	8.2	1.9	0.7
0.6–0.8	1.57 (0.03)	44.6 (0.3)	23.4	20.8 (1.0)	2.5 (0.5)	0.23 (0.01)	8.4	7.0	12.8
0.8–1.0	1.63 (0.02)	42.5 (1.8)	25.6	22.5 (1.5)	3.8 (0.5)	0.38 (0.02)	8.5	15.0	28.3
TAW (mm):		197	98						
PAWC (mm):			99						

for the cereal phase, with up to four cultivations in summer and early spring (March–April) before sowing. The traditional practice treatment was compared with direct-drilled (no-till) continuous-cropping treatments, cereal after wheat or cereal after canola (where cereal is barley or wheat). The cereal after canola treatment was available only twice during the trial, following the canola crops grown in 2000 and 2006, in response to starting conditions that were perceived as favourable to a canola break crop. The continuous-cropping treatments received higher fertiliser (27 kg N, 16.5 kg P ha^{-1}) and seeding rates (70 kg ha^{-1}) than the traditional practice. All fertiliser was applied at seeding at fixed annual rates, not adjusted according to starting nutrient levels or seasonal conditions. Stubble was retained in all continuous-cropping treatments. The experiment at Waikerie continued for 11 consecutive seasons, with the treatment comparisons wheat after pasture and cereal after wheat possible in every season. The treatment wheat after canola was not available in 1998, 1999, 2003 and 2005 because no canola crop was grown in the previous year due to unfavourable starting conditions for this break crop.

Kerribee

The experimental site was established in August 2001, with existing pasture or weeds sprayed with knockdown herbicide (glyphosate) and the site left fallow (either cultivated or sprayed depending on the treatment) until the first treatments were sown in June 2002 in a similar design to the Waikerie experiment. At Kerribee, the traditional treatment was a cultivated (and/or sprayed) fallow–wheat system with low fertiliser inputs at sowing (6 kg N, 13 kg P ha^{-1}) and a low wheat sowing rate of 30 kg ha^{-1}, reflective of local practice. At this site, only knockdown herbicide (glyphosate) and cultivation were used to control weeds during the fallow phase. The phased ‘wheat after fallow’ treatments were compared with direct-drilled (no-till), continuous-cropping treatments consisting of wheat after canola and wheat after wheat with higher fertiliser inputs (27 kg N, 16.5 kg P ha^{-1}). All fertiliser was applied at seeding at fixed annual rates, not adjusted according to starting nutrient levels or seasonal conditions. Stubble was retained in all treatments. The experiment continued for seven consecutive seasons, with the treatment comparisons ‘wheat after fallow’ and ‘wheat after wheat’ possible in every season. The treatment comparison of ‘wheat after canola’ was possible in 2004, 2006 and 2008.

Field management and crop-sampling procedures

Treatments were laid out in a randomised block design in plots 1.6 m wide and 50 m long with four replicates. Plot direction was perpendicular to the dune–swale system, with the wheel tracks of the tractor confined to permanent tramlines for all cultivation, sowing and spraying operations. A range of standard herbicides was used to control weeds; however, the dry conditions meant that requirements to control weeds were generally low. A pre-sowing knockdown (mainly glyphosate) was the predominant herbicide, with pre-emergence (e.g. trifluralin 480 g L^{-1}) and post-emergence selective herbicides used as required. The traditional practice rotations were cultivated up to four times before a wheat phase with a tined cultivator, with residues from the previous crop or pasture incorporated. The no-till treatments were never cultivated, and all residues from the previous crops remained on the surface and weed control relied entirely on herbicide use. Sowing occurred in response to the first breaking rains of the season, with the earliest date of sowing 28 April in 2000 (Waikerie) and the latest 24 July in 2007. Sowing of all plots occurred on the same day using a seed drill with narrow points and press-wheels. In-season crop management was mainly concerned with controlling weeds by using selective herbicides or hand-weeding and monitoring for root disease. The latter was done in the cereals at 2-weekly intervals until flowering by scoring root development in a manner similar to Murray and Brown (1987). Grain was harvested after physiological maturity in the period from mid-November to late December by using a plot harvester. Approximately 3 m at each end of the plot was removed and the remaining 44 m of plot was harvested for grain. Grain yields are reported at field-weighed moisture content with grain samples collected during the harvest analysed for N concentration using a Dumas combustion method. Grain protein concentration was calculated as %N in grain × 5.7 (Mossé 1990).

Monitoring of soil mineral N and soil moisture

In the days before sowing and following harvest, a selection of treatments and all replicates were soil-sampled to depth in the layers 0–100, 100–200, 200–400, 400–600, 600–800 and 800–1000 mm. In the field, soil samples were sealed into plastic bags and immediately stored under cool conditions. On return to the laboratory, samples were weighed for field moisture content and split, with one-half dried at 100°C for dry weight determination. Subsamples of the soil were used to determine mineral N (NH_4 and NO_3) after extraction with 1 M KCl (1 : 3 soil to KCl ratio) using the colourimetric Method 7C2b (Rayment and Higginson 1992).

Partial economic analysis

Gross margins were calculated using average costs and grain prices of each system over the duration of the experiment (1998–2008). Wheat and canola prices were estimated at AU \$195 and \$375 t^{-1}, respectively, inclusive of freight, insurance and levies. Pasture (sheep) income was estimated at \$25 per dry sheep equivalent (DSE) assuming 1.5 DSE ha^{-1} (1 DSE represents the amount of feed required by a 2-year-old, 45-kg Merino sheep, which could be a wether or non-lactating or non-pregnant ewe, to maintain its bodyweight). Total variable costs for the low-input and high-input wheat phases of the experiments were ~\$100 and \$160 ha^{-1}, respectively, using a mono-ammonium phosphate (MAP) fertiliser price of \$600 t ha^{-1}. Average annual herbicide application costs in wheat were \$34 ha^{-1} for the continuous-cropping treatments and \$16 ha^{-1} for the low-input treatments. Wheat yields from the pasture–wheat and fallow–wheat treatments are from two phased treatments, and gross margins are from the average of both phases.

Estimating yield potential

Based on the French and Schultz (1984) frontier concept, yield potential (YP F&S) was calculated using the following equation:

$$\text{YP F\&S} = [(\text{GSR} + \Delta\text{SW} - \text{Es}) \times \text{WUE}]$$

where GSR is the sum of April–October rainfall, ΔSW is the change in soil water from sowing to harvest, Es is soil evaporation assumed to be 60 mm (Sadras and Roget 2004), and WUE assumes a slope of 22 kg grain ha^{-1} mm^{-1} according to Angus and van Herwaarden (2001). Attainable yield was obtained by dynamically simulating yield using the crop–soil model Agricultural Production Systems SiMulator (APSIM; www.apsim.info) (AY-APSIM) as constrained by N and water limitation but with no other yield-limiting abiotic or biotic effects, as described in the next section.

Crop simulation

In order to generate the AY-APSIM estimates, APSIM version 7.4 (Holzworth *et al.* 2014; www.apsim.info) was used to simulate the continuous-wheat treatments at both sites. The simulations for Waikerie began on 1 January 1998, initialised to soil water, mineral N and C values measured before the 1998 treatment and then run continuously until 31 December 2008. Only soil mineral N was reset yearly to the measured values at time of sowing. Simulation setup was similar for the Kerribee continuous-cereal treatment except that the simulations were initiated on 1 January 2002 and terminated 31 December 2008. Management practices such as sowing and tillage were implemented in the operations menu on the date the operation took place in the field. The soil-water balance uses a cascading water-balance model (SoilWat), which is described in detail by Probert *et al.* (1998) and is based on key parameters of PAWC calculated from estimates of CLL and DUL (Table 1). Maximum rooting depth of wheat at both sites was 1.5 m.

To analyse wheat after fallow or wheat after wheat rotations, simulations were set up to compare the systems for both sites. Separate simulations (1900–2008) of wheat–fallow, fallow–wheat and wheat–wheat were set up with annual sowing resets of soil N and residues to the initialisation values in the validation runs. After resetting soil water to the same starting values described for the validation runs, no further resets were implemented, and therefore the growth of wheat is in response to the amount of soil water accumulated to sowing and to in-crop rainfall.

Calculation of WUE and fallow efficiency

The WUE was calculated as grain yield divided by the amount of water available for the crop (sum of rainfall from day of sowing to day of harvest) – (difference between PAW at sowing and harvest) (units: kg grain ha^{-1} mm^{-1}). Losses via drainage and runoff are assumed negligible.

Fallow efficiency refers to the period between harvest of one crop and sowing of the crop the following season, and was calculated by the difference between PAW at sowing and PAW at the previous harvest, divided by the rainfall during that same period and expressed as a percentage, the same method used by Hunt and Kirkegaard (2011). For the first season, PAW at the previous harvest was assumed as zero because no data were available.

Statistical analyses

Within individual years of the field experiments, treatment differences in grain yield, soil mineral N and soil moisture measured at sowing were analysed with a one-way ANOVA. Where there was significance, the least significant difference (l.s.d.) at $P \leq 0.05$ was used to test for mean separation. All data were tested for the assumption of common variance and transformed if necessary. In the case of replicated summary data, the mean is followed by the standard error of the mean.

Results

Climate and water balance

Waikerie

Over the 11 years of the experiment, GSR (April–October) exceeded the long-term average of 165 mm in 3 years (2000, 2001, 2005), was well below in 5 years (2002, 2004, 2006, 2007, 2008) and average in the remainder (Table 3). Pre-season (previous harvest to sowing) rainfall was substantial in most years (49–175 mm), resulting in PAW ranging from 18 to 71 mm (0–1 m) at sowing with no significant difference between treatments (Table 4). Using the PAW at sowing for the cereal after wheat treatments, fallow efficiency varied from 10% in 1999 to 48% in 2007, with the major determinants of fallow efficiency being the timing and distribution of rainfall in the period between harvest and sowing.

Kerribee

In 6 of 7 years of the trial, GSR was well below the long-term average of 172 mm (Table 3). In 2005, although GSR was above the average at 193 mm, 57 mm fell during October when the crop was almost mature; therefore, effective rainfall was less than the total suggests. Pre-sowing rainfall ranged from 86 to 158 mm, and fallow efficiency calculated from the PAW at sowing of the continuous-wheat treatments was in the range 3–33%, again dependent on rainfall amount and timing between harvest and sowing but somewhat lower than that determined for the sandier soil at Waikerie.

Crop performance

Waikerie

The wheat after pasture treatments were not significantly different from the continuous-cropping treatments (cereal after wheat, wheat after canola) in 6 of 11 years but significantly lower than these treatments in 2000, 2001 and 2007 and lower than the cereal after wheat treatment in 2003 and 2005 (Fig. 1). As mentioned, PAW at sowing was substantial but the differences between treatments were generally small and not significant (Table 4). In the pasture years of the wheat after pasture treatments, pasture growth was substantial (dry matter 3–5 t ha^{-1}, data not shown), so a significant build-up of soil moisture during this phase was not expected. Similarly, soil mineral N at sowing was usually not significantly different between treatments, with N contents (0–1 m) ranging from 73 to 114 kg ha^{-1} in the wheat after pasture treatments (Table 5). The only exception to this was in the wheat following canola treatment in 2001, where significantly more mineral N was available, presumably from N unused by the previous canola phase (Table 5), and resulting in high grain protein (Table 6). It is noteworthy that NO_3-N accounted for the majority of mineral N, with NH_4-N accounting for generally <15% of mineral N across all times of sampling, and that profile distribution of mineral N and water was quite similar between treatments (data not shown). Although significantly higher yields achieved in the cereal after wheat and wheat after canola treatments were not due to differences in PAW or mineral N at sowing, higher sowing applications of fertiliser N and P (27 kg N, 16.5 kg P ha^{-1}) compared with the wheat after pasture treatment (5 kg N, 11 kg P ha^{-1}) resulted in increased yields, in particular in the seasons less constrained by water. Grain protein concentrations measured until 2006 were always >11.4%, with no significant difference found between treatments except in 2000 (Table 6). The dry and low-yielding years of 2002 and 2004 resulted in high grain protein contents, ranging from 14.2% to 16.8%, due to very small grain size. Regardless of treatment, WUE was low and calculated for the cereal after wheat treatments was <10 kg grain ha^{-1} mm^{-1} in 5 of 11 years, and 11–15 kg grain ha^{-1} mm^{-1} for the other year, with the exception of 1998 (Table 3). Of the seven canola crops grown over the 11 seasons, only those in 2000 and 2001 yielded >1 t ha^{-1} (Fig. 1). In the case of 2001, high soil moisture at sowing and an average GRS (178 mm) resulted in >2 t ha^{-1} in yield.

Kerribee

Grain yields in the wheat following fallow treatments were significantly higher (1.8–>3 times) than in the continuous-cropping treatments (wheat after wheat and wheat after canola) in 2002, 2005, 2006 and 2007 (Fig. 2). This is despite higher fertiliser N and P applications at sowing to the continuous-cropping treatments. In 2003, 2004 and 2008, there were no significant differences between treatments. Significantly higher PAW at sowing in the wheat after fallow treatments was a major driver of the yield differences in 2002 and 2006 (Table 4), in particular providing an advantage to these treatments in those dry seasons. Mineral N in the wheat after fallow treatments was also significantly higher in 2002 and 2006, providing another possible reason for higher growth. Higher wheat yields of the wheat after fallow treatment in 2005 and 2007 could not be explained by higher mineral N or PAW at sowing. The wheat after wheat treatments in 2005 yielded much lower than expected, most likely due to crop damage from a pre-sowing trifluralin herbicide application, which was necessary because of high grass-weed pressure. Grain protein concentration exceeded 12.6%, and from 2002–2005 no significant differences between treatments were found. In 2006 and 2007, the small grain size associated with the low yield resulted in high protein concentration, especially in the wheat after wheat treatment (Table 6). WUE calculated for the wheat after wheat treatment was extremely low and <6 kg grain ha^{-1} mm^{-1} in all years except 2003 when it was 15 kg grain ha^{-1} mm^{-1} (Table 3).

Partial economic performance

Waikerie

In the most seasons at Waikerie, the cereal after wheat treatment led to much higher gross margins than wheat after pasture or wheat after canola treatments. By 2008, the cumulative gross margin after 11 seasons of the wheat–pasture treatment was \$1083 ha^{-1} compared with cereal after wheat (\$1657 ha^{-1}) and wheat-canola (\$651 ha^{-1}) (Fig. 3). Although the returns from a fixed wheat–canola rotation were low, returns from an

Table 3. Characteristics of seasonal rainfall (mm), stored soil moisture (mm), measured grain yield (t ha^{-1}) and calculated estimates of fallow efficiency (FE, %), water-use efficiency (WUE, kg grain ha^{-1} mm^{-1} water) and calculated potential (YP F&S) (t ha^{-1}) and simulated attainable (AY-APSIM) yield for the continuous-cereal treatments at Waikerie (1998–2008) and Kerribee (2002–08)

n.a., Not available. For yearly means for PAW at sowing and harvest and grain yield, s.e.m. is presented in parentheses

		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
						Waikerie						
Cumulative rainfall	Harvest–sowing	73	124	175	124	49	98	68	165	108	150	56
	April–October	166	159	188	196	91	173	136	201	114	109	148
	Sowing–harvest	115	178	121	178	50	167	131	186	63	78	135
Soil moisture	PAW at sowing	26	39 (10)	57 (16)	39 (13)	31 (5)	48 (10)	18 (4)	43 (5)	40 (7)	71 (2)	n.a.
	PAW at harvest	26	–6 (2)	35 (7)	11 (5)	7 (8)	–12 (9)	n.a.	30 (3)	–5 (5)	–12 (4)	n.a.
Grain yield	(wheat after wheat)	2.46 (0.14)	1.56 (0.08)	2.13 (0.06)	3.00 (0.08)	0.05 (0.03)	2.86 (0.12)	0.33 (0.04)	2.29 (0.07)	0.97 (0.38)	1.22 (0.03)	0.83 (0.04)
FE		36	10	36	3	41	42	44	26	9	51	
WUE		21	7	15	14	0	13	2	12	1	11	5
Yield potential	YP F&S	2.32	3.04	3.31	3.61	1.20	3.55	2.06	3.40	2.08	2.64	2.97
Attainable yield	AY-APSIM	2.21	1.66	2.13	2.04	0.23	2.92	0.98	2.37	0.38	0.93	0.66
						Kerribee						
Cumulative rainfall	Harvest–sowing					86	136	111	103	158	125	102
	April–October					93	187	138	198	95	104	96
	Sow–harvest					56	168	139	184	37	60	79
Soil moisture	PAW at sowing					14 (6)	34 (5)	2 (5)	12 (4)	16 (6)	27 (3)	–9 (5)
	PAW at harvest					–11 (2)	–11 (4)	1 (3)	11 (6)	–14 (1)	–11 (4)	n.a.
Grain yield	(wheat after wheat)					0.09 (0.02)	3.14 (0.23)	0.78 (0.07)	0.98 (0.15)	0.37 (0.01)	0.29 (0.07)	0.19 (0.05)
FE						16	33	12	11	3	33	11
WUE						1	15	6	5	5	3	3
Yield potential	YP F&S					1.03	3.53	1.73	3.05	1.12	1.57	0.79
Attainable yield	AY-APSIM					0.02	2.04	1.00	1.38	0.72	0.32	0.13

Table 4. Plant-available water (mm, 0–1 m depth) of the rotation treatments measured on soil samples collected before sowing for Waikerie 1998–2006 and Kerribee 2002–08

n.s., Not significant ($P > 0.05$)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
					Waikerie						
Wheat after pasture	26	52	59	38	22	37	18	45	41	–	
Cereal after wheat	26	39	57	39	31	48	18	43	40	71	47
Wheat after canola	26		57	52	25		–	–	–	67	
l.s.d. ($P = 0.05$)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
					Kerribee						
Wheat after fallow					33	46	17	16	27	33	–7
Wheat after wheat					14	34	2	12	16	27	–9
Wheat after canola							3		7		–6
l.s.d. ($P = 0.05$)					12.8	n.s.	11.4	n.s.	10.7	n.s.	n.s.

Table 5. Mineral N (kg ha^{-1}) of the rotation treatments measured on soil samples collected before sowing (0–1 m) for Waikerie 1998–2006 and Kerribee 2002–08

n.s., Not significant ($P > 0.05$)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
					Waikerie						
Wheat after pasture	73	106		73	63	95	99	114	105		
Cereal after wheat	73	98		78	66	103	55	88	86	112	
Wheat after canola				139	74					101	
l.s.d. ($P = 0.05$)	n.s.	n.s.		27	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
					Kerribee						
Wheat after fallow					114	64	88	82	122	124	109
Wheat after wheat					46	70	55	55	111	147	203
Wheat after canola							54		73		217
l.s.d. ($P = 0.05$)					23	n.s.	n.s.	n.s.	35	n.s.	70

Table 6. Grain protein concentration (%) measured on subsamples collected at harvest for Waikerie 1998–2006 and Kerribee 2002–07

n.s., Not significant ($P > 0.05$)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
					Waikerie					
Wheat after pasture	10.3	12.6	11.9	11.5	14.2	11.9	16.8	13.6	13.0	
Cereal after wheat	11.0	12.9	11.9	11.4	14.2	12.0	15.5	13.4	12.5	
Wheat after canola			12.65	11.4	14.7		16.0		13.1	
l.s.d. ($P = 0.05$)	0.6	n.s.	0.6	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
					Kerribee					
Wheat after fallow					14.3	12.6		14.6	14.8	17.0
Wheat after wheat					14.3	13.5		14.0	18.2	18.2
Wheat after canola					–		–		16.3	
l.s.d. ($P = 0.05$)					n.s.	n.s.	n.s.	n.s.	1.6	0.8

opportunistic wheat–canola rotation (i.e. canola planted in response to an early-season break and high PAW, but wheat planted in other years) would have been similar to the cereal after wheat treatment. An example of this comparison was reported by Davoren *et al*. (2008).

Kerribee

Cumulative returns after seven seasons from the low-input wheat following fallow treatment (cumulative gross margin \$456 ha^{-1}) were higher than from wheat after wheat (\$176 ha^{-1}) and wheat after canola rotations (\$231 ha^{-1}) (Fig. 4). The series of dry seasons from 2005 resulted in the poor financial return of the continuous-cereal rotations.

Estimates of yield potential and attainable yield

Waikerie

Yield potential as estimated using the method following French and Schultz (1984) (YP F&S) in most seasons greatly exceeded measured yield (Table 3). Yield potential obtained by dynamically simulating yield (AY-APSIM) as constrained by N and water limitation but with no other yield-limiting abiotic or

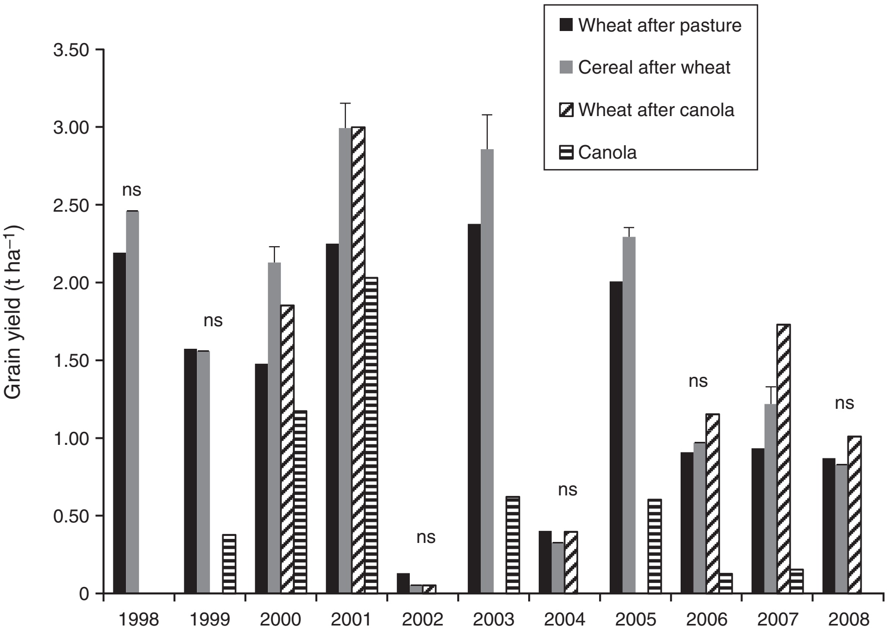

Fig. 1. Crop yields in the low-input pasture–wheat and higher input continuous-cropping (wheat with occasional canola and continuous cereal) farming systems at Waikerie, SA, 1998–2008. Within years, where treatments are significantly different, the capped line shows the l.s.d. at $P = 0.05$; ns, not significant. Canola grain yields are displayed in available years but not included in the analysis.

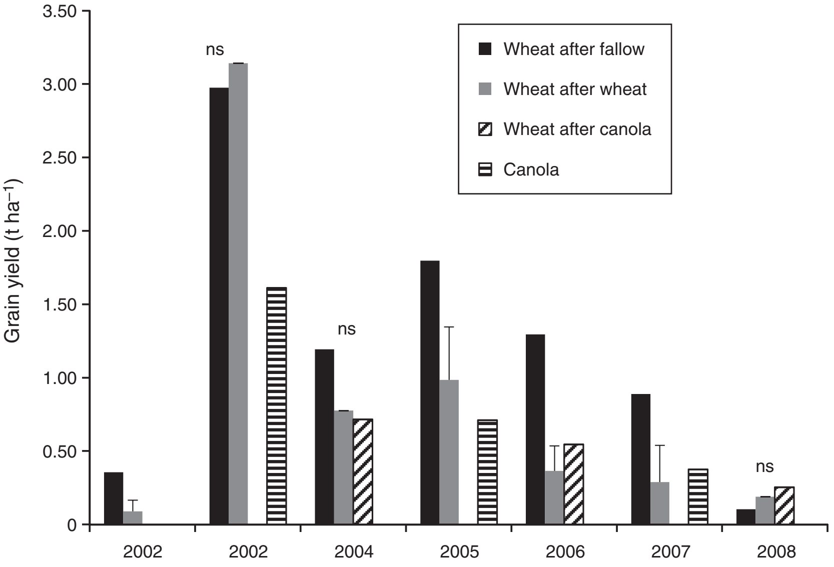

Fig. 2. Crop yields in the low-input fallow–wheat and higher input continuous-cropping (wheat after wheat or wheat after canola) farming systems at Kerribee, NSW, 2002–08. Within years, where treatments are significantly different, the capped line shows the l.s.d. at $P = 0.05$; ns, not significant. Canola grain yields are displayed in available years but not included in the analysis.

biotic effects was very close to (± 0.5 t ha^{-1}) measured yields in the years 1998, 1999, 2000, 2002, 2003 and 2005 but well below measured in 2001 and 2006 and well over measured in 2004. In the case of 2004, only 7.5 mm of rainfall was received for the entire period of September and October, with spring temperatures also reaching 30°C. This period coincides with flowering and grain filling, and therefore, its effects on grain yield were not captured by YP F&S (simple empirical yield prediction) or by AY-APSIM. The years where AY-APSIM was below that measured suggest that plants are able to access more soil

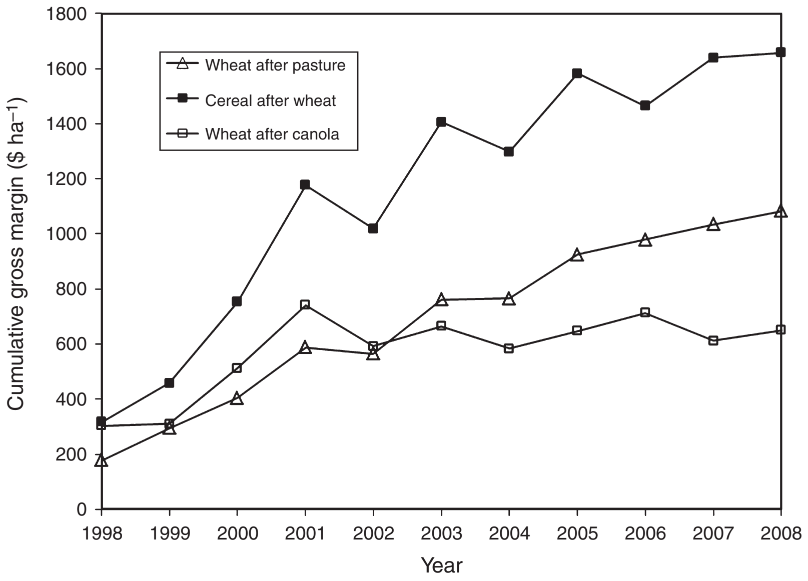

Fig. 3. Cumulative gross margin performance of the low-input pasture–wheat and higher input continuous-cereal or wheat–canola farming systems at Waikerie, SA, 1998–2008. Pasture–wheat gross margins show average of pasture and wheat phases in that year.

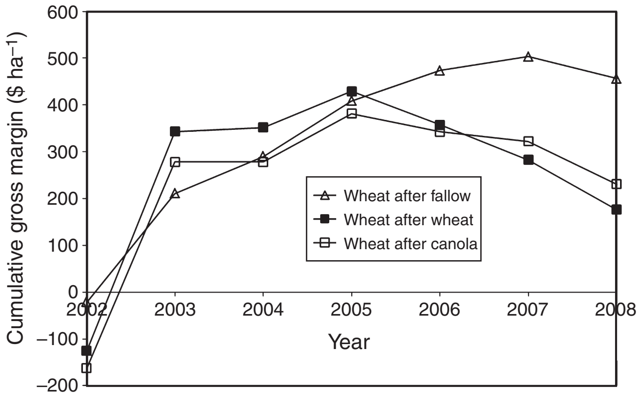

Fig. 4. Cumulative gross margin performance of the low-input fallow–wheat and higher input continuous-cereal or wheat–canola farming systems at Kerribee, NSW, 2002–08. Pasture–wheat gross margins show average of pasture and wheat phases in that year.

moisture than the CLL, or that water loss, probably via soil evaporation, in the water balance is overestimated.

Kerribee

Measured yield was much lower that the estimates made using the YP F&S calculations in most seasons except the only high yielding year, 2003. Generally, AY-APSIM was close to the measured yields, except in 2003, when the attainable yield was underestimated by 1.1 t ha^{-1}.

Simulation analysis

By utilising historical daily, long-term weather data back to 1900, APSIM was used to simulate the yield of wheat after fallow or wheat after wheat for 109 years. On average, simulations of wheat after fallow predicted 0.4 t ha^{-1} additional grain yield at Waikerie and 0.7 t ha^{-1} at Kerribee compared with wheat after wheat (Fig. 5). This was related to an additional mean 27 mm PAW at sowing at Waikerie and 37 mm at Kerribee. These simulations assumed no loss of stored soil water by weed growth, and thus, they represent a situation of frequent summer weed control with herbicide application. In agreement with the field results, the predicted yields at Kerribee with the wheat–fallow management were higher than with wheat after wheat in ~75% of seasons, reflecting the higher PAWC of this site and the greater capacity of the soil to store moisture that falls during the fallow.

Discussion

Productivity of rotations

Low-rainfall cropping systems the world over face major challenges associated with high variability in yield, profitability and sustainability. The field sites described in this paper represent the climatic limits of annual cereal production in Australia and are therefore useful in testing crop rotation systems and their implications for sustainable and profitable production. The precipitation : evaporation ratio is <0.26 at both sites. Furthermore, Waikerie sits ~60 km outside the iconic 'Goyder's Line', which represents historically identified limits of reliable wheat-growing land, and therefore is placed in a risky wheat-growing area; the drying and warming trends predicted beyond 2030 are likely to exacerbate this risk (Nidumolu *et al.* 2012).

As described by Sadras and Roget (2004), 'A conservative, low-input farming approach, which closes a reinforcing loop of low and unreliable yield and profit. . .' became the traditional and dominant approach to cropping for low-rainfall Mallee regions. As an alternative to this approach, a large proportion of farmers

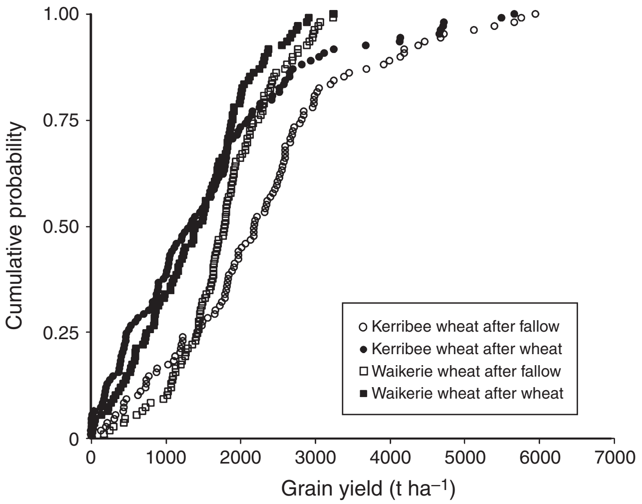

Fig. 5. Cumulative distribution function based on the simulated grain yield of wheat after fallow or wheat after wheat for the soils and long-term climate (1900–2008) at Waikerie and Kerribee.

over the last two decades have abandoned 'traditional' rotations (pasture–wheat) and replaced them with systems based on more intensive cropping, with relatively late (compared with other Australian cropping regions) but rapid increases in no-tillage cropping practices since 2000 (Llewellyn *et al.* 2012).

The field results from Kerribee (Fig. 2) and the simulated scenarios of the fallow–wheat systems from both sites (Fig. 5) support the notion of higher yields and less crop failures in such a system where weed management during the 'long' fallow phase is timely and effective. Although this result is widely acknowledged and is supported by early (Schultz 1971) and newer studies (Oliver *et al.* 2010), the high risk of wind erosion and soil organic matter loss means that such long-fallow practices are unsustainable, particularly on the sandier Mallee soils (Leys and McTainsh 1994).

For the 'traditional practice' pasture–wheat rotation example from Waikerie, with a volunteer pasture growing instead of cultivated fallow, there were no significant differences in PAW (Table 4) or soil mineral N (Table 5) at sowing compared with the continuous-cropping treatments. Grain yields were generally lower, but this effect was at least partly due to higher input levels applied to the continuous-cropping treatments and the typically low legume content of the volunteer pasture.

Of the six seasons at Waikerie and three seasons at Kerribee where wheat after canola was similar to wheat yield in the other rotations, on only one occasion (at Waikerie in 2007) did this treatment significantly outyield the continuous-cereal treatments. This effect was not related to higher PAW or soil mineral N concentrations at sowing (Tables 3 and 4) but may be related to the effects of canola on N mineralisation, microbial activity and microbial community composition (Gupta *et al.* 2011). Roget and Gupta (2004) reported that, at Waikerie, microbial biomass C and N and microbial activity levels were significantly higher in the canola–wheat rotation (after canola) than the pasture–wheat rotation. In addition, the microbial catabolic diversity in the surface soil (ability of microbes to utilise various C substrates) was generally higher after rotational crops such as pastures and canola than after wheat and fallow rotation (Gupta *et al.* 2010, 2012*a*). In the fallow rotation, the depletion of C-rich microsites shifts the balance between mineralisation–immobilisation processes, which would have resulted in the higher levels of mineral N in the soil profile at sowing in the Kerribee experiment. Brassica crops such as canola are also known to reduce populations of soilborne plant pathogens such as *Gaeumannomyces graminis* var. *tritici* (take-all fungus) and *Rhizoctonia solani* AG8 and their disease impacts (Kirkegaard *et al.* 2008; Gupta *et al.* 2012*b*; Lawes *et al.* 2013). In addition, canola plants also stimulate soil fungi such as *Trichoderma* spp., known beneficial fungi involved in the control of root diseases (V. V. S. R. Gupta, D. K. Roget, unpubl. data).

Economic performance

Managing climatic variability and business risk on farms with highly variable soil types poses difficult challenges to most farmers in the lower rainfall regions of the Mallee (Mudge and Whitbread 2010; Nuttall and Armstrong 2010). In these regions, production risk has historically been more important than price variation (Kingwell 2011); therefore, better managing the year-to-year variation in yield that is due to rainfall is crucial to profitable, low-rainfall farming systems. At Waikerie, the highest cumulative gross margins ($1658 ha^{-1}) were achieved with the cereal after wheat rotation (Fig. 3). It is worth noting that a cumulative gross margin of almost $1200 ha^{-1} was reached by 2001, with the negative returns in 2002, 2004 and 2006 corresponding with low in-crop rainfall. The worst performing rotation, wheat following canola, is an unrealistic comparison because canola would normally be planted opportunistically in response to favourable sowing conditions and therefore more likely to yield higher. Davoren *et al.* (2008), using the same trial but with treatments combining cereal with the inclusion of canola in 2000, reported a gross margin of $1639 ha^{-1} (up to 2007). This treatment, referred to as an intensive strategy, was also reported to be the most profitable up to 2001 (Sadras and Roget 2004). Clearly, the 'responsive' strategy of continuous cereal with the occasional, high-value break crop when seasonal conditions are favourable is a superior strategy to fixed rotations of break crop or pasture–fallow.

Prediction of yield potential and simulation

Establishing realistic yield potential targets is seen as critical to managing risk (Hochman *et al.* 2009*b*). A method published by French and Schultz (1984) based on a collection of data that defined the relationship between the efficiency of water transpired (20 kg ha^{-1} mm^{-1} for wheat grain) and April–October rainfall minus evaporation (estimated to be 110 mm) remains a commonly 'misused' benchmark for potential yield. There are many criticisms of its use in the literature—not accounting for the timing of in-season rain, not considering runoff or drainage or out-of-growing-season rainfall on the water budget, assuming constant seasonal evaporation—some of these simplifications are responsible for generally high yield potential (Table 3). Although improvements in the estimates of the water-loss factor, as described by Whitbread *et al.* (2011) or Oliver *et al.* (2009) have been shown to reduce likely overestimates in yield potential, models that account for the interactions between soil type, available soil water and crop growth on a daily basis give more robust yield-potential estimates (Hochman *et al*. 2009*a*). Methods that ignore these interactions therefore have a limited ability for predicting grain yield in low-rainfall regions, in particular where soil variation and subsoil constraints are inherent (Rab *et al*. 2009).

Although simulation is well suited to analysing risk in low-rainfall cereal systems, its limitations should be highlighted. Simulated crop growth is driven by radiation-use efficiency modified according to temperature, and with stress indices calculated from available water and N used to reduce yield further. In systems where water and N limitation are primary drivers of plant growth, models have been usefully applied (Hunt and Kirkegaard 2011; Moeller *et al.* 2014). However, the response of a crop to other nutrient constraints and biotic stresses is not captured by most models. Cereal responses to canola, for example, are well documented (Kirkegaard and Sarwar 1998; Kirkegaard *et al*. 2008) and can be due to reductions in root disease (Gupta *et al*. (2011). *Rhizoctonia solani* AG8 inoculum is generally concentrated in the surface layers of field soil (top 5 cm), especially in the no-till systems (Gupta *et al*. 2012*a*). In addition, recent changes in farming systems, particularly no-till and stubble-retention systems, have resulted in a change in the epidemiology of *Rhizoctonia*, extending the seedling symptoms to more infection on crown roots. The effects of later infection of *Rhizoctonia* on cereal crops, which may not be easily detected, can cause yield loss through reduced ability of plants to access water and nutrients (MacNish and Neate 1996; Gupta *et al*. 2012*b*). Model performance could also be improved by parameterising the particular varieties of wheat and canola used in low-rainfall areas.

Water balance of the continuous-cereal treatments

Fallow efficiency was remarkably different between the two sites. The fallow efficiency of the Kerribee soil (sandy loam to loam) ranged from 3% to 33%, averaging 17% over seven seasons (Table 3). This compares with average fallow efficiency of 30% at Waikerie, indicating that the efficiency with which rainfall is captured and stored during the fallow phase is much higher on the sandy Waikerie soil. This fallow efficiency is consistent with simulated estimates (34%) made by Hunt and Kirkegaard (2011). The differences in fallow efficiency between sites are also consistent with the simulated, long-term average fallow efficiencies found for light and heavy Mallee soils (Mudge and Whitbread 2010; Hunt and Kirkegaard 2011). Although the effect of texture on soil evaporation is well known (Jalota and Prihar 1986), it has rarely been considered in explaining differences in WUE between sites in similar environments.

In terms of WUE of the continuous-cereal systems, or in other words the efficiency of grain production in relation to available water, very few seasons approached the 20 or 22 kg grain ha^{-1} mm^{-1} benchmark often used as the target in the region. Although WUE varied widely from year to year (Waikerie range 0–21, Kerribee range 1–15 kg grain ha^{-1} mm^{-1}), average WUE at Waikerie was 10 kg grain ha^{-1} mm^{-1}, which was approximately double that found for Kerribee. The effect of soil texture therefore has a profound effect on the efficiency of capturing and storing rainfall within and between seasons. Although this is widely accepted, there are no publications to our knowledge considering this effect on WUE.

Responsive farming approaches to rotation strategies

The term ‘responsive farming’, first coined by Stewart and Faught (1984), describes a flexible decision-making approach that incorporates information such as seasonal forecasts, soil nutrient levels and stored soil moisture, pest and disease burden, and financial indicators to make decisions at planting time and in-season (Sadras *et al*. 2003). These decisions are typically choices about crop area, crop type, cultivar selection, and up-front and in-crop fertiliser rate, which can be an important component of risk management in highly risky environments. For example, the analysis of yield in response to planting time and PAW could be used to provide farmers with trigger points that enable them to make better planting decisions; this is similar to the conclusions of Mudge and Whitbread (2010). By combining recent advances in our understanding of seasonal climate forecasts (Hammer *et al*. 2001), historical analysis of ENSO influences on yield (Hayman *et al*. 2010), prediction of PAW at sowing (Oliver *et al*. 2009, 2010), in-season prediction of yield (Hochman *et al*. 2009*b*), inoculum levels of root disease (Ophel-Keller *et al*. 2008) and decision support, responsive approaches to crop sequencing are increasingly feasible.

Conclusion

In the northern Mallee region represented by this study, rainfall remains the major driver of attainable yield. The long-term field experiments presented in this study showed for the first time that intensive cropping strategies that include higher inputs, continuous cropping, residue retention and no-till could technically be established and remain economically viable over a period where annual average rainfall was below 230 mm. The fallow–wheat system at Kerribee outperformed the continuous-crop treatments in this period of particularly dry years (average April–October rainfall 115 mm); however, the results support the argument that fallow efficiencies are substantially lower on heavier soils than sandy soils. Under intensive cropping strategies, the major decisions become the crop and/or cultivar choice, quantity and timing of fertiliser inputs, and the need for break crops such as canola to respond to pressures such as grass weeds and disease, which are problematic in continuous-cereal systems. The decision about the seasonal conditions under which to implement such break crops can clearly be enhanced by combining information from seasonal climate forecasts, soil water, and outputs from well-validated crop models.

Acknowledgements

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