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Improving water productivity in the Australian Grains industry—a nationally coordinated approach

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Abstract. Improving the water-limited yield of dryland crops and farming systems has been an underpinning objective of research within the Australian grains industry since the concept was defined in the 1970s. Recent slowing in productivity growth has stimulated a search for new sources of improvement, but few previous research investments have been targeted on a national scale. In 2008, the Australian grains industry established the 5-year, AU$17.6 million, Water Use Efficiency (WUE) Initiative, which challenged growers and researchers to lift WUE of grain-based production systems by 10%. Sixteen regional grower research teams distributed across southern Australia (300–700 mm annual rainfall) proposed a range of agronomic management strategies to improve water-limited productivity. A coordinating project involving a team of agronomists, plant physiologists, soil scientists and system modellers was funded to provide consistent understanding and benchmarking of water-limited yield, experimental advice and assistance, integrating system science and modelling, and to play an integration and communication role. The 16 diverse regional project activities were organised into four themes related to the type of innovation pursued (integrating break-crops, managing summer fallows, managing in-season water-use, managing variable and constraining soils), and the important interactions between these at the farm-scale were explored and emphasised. At annual meetings, the teams compared the impacts of various management strategies across different regions, and the interactions from management combinations. Simulation studies provided predictions of both *a priori* outcomes that were tested experimentally and extrapolation of results across sites, seasons and up to the whole-farm scale. We demonstrated experimentally that potential exists to improve water productivity at paddock scale by levels well above the 10% target by better summer weed control (37–140%), inclusion of break crops (16–83%), earlier sowing of appropriate varieties (21–33%) and matching N supply to soil type (91% on deep sands). Capturing synergies from combinations of pre- and in-crop management could increase wheat yield at farm scale by 11–47%, and significant on-farm validation and adoption of some innovations has occurred during the Initiative. An *ex post* economic analysis of the Initiative estimated a benefit : cost ratio of 3.7 : 1, and an internal return on investment of 18.5%. We briefly review the structure and operation of the initiative and summarise some of the key strategies that emerged to improve WUE at paddock and farm-scale.

Additional keywords: drought, dryland farming, fallow, rotation, water-use efficiency, wheat.

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Introduction

Benchmarking performance and the water-use efficiency (WUE) concept

The trends in productivity of Australian dryland wheat throughout its 200-year history have been the subject of significant recent review (Fischer 2009; Kirkegaard and Hunt 2010; Richards *et al*. 2014, this issue). The motivation for these investigations has been to gain insight into the source of previous yield improvement, to assess the opportunity for further gain and to direct research effort accordingly. A hallmark of many such

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studies in Australia has been the widespread use of benchmarks, where a biophysically defensible estimate of yield potential is compared with performance in farmers' fields. The water-limited yield benchmark for wheat (20 kg grain/ha.mm water transpired above 110 mm evaporation) published by French and Schultz (1984) provided a valuable framework to assess crop yield against a water-limited potential. Although recently revised and updated to 22 kg grain/ha.mm water transpired above 60 mm evaporation (Sadras and Angus 2006), with modifications according to various climatic factors such as rainfall distribution and the evaporative demand of the environment (Rodriguez and Sadras 2007; Sadras and Rodriguez 2007), the French and Schultz benchmark remains an accessible basis from which growers, scientists and the grains industry can diagnose and address failure to achieve water-limited potential.

The original stimulus for the Grains Research and Development Corporation (GRDC) National Water-Use Efficiency Initiative came from an industry-wide study in which yield and rainfall data for grain-growing regions throughout Australia were used to derive estimates of the level of WUE achieved against potential using the French and Schultz approach (Beeston *et al*. 2005; Fig. 1). The study suggested that most regions of Australia were performing well below the nominated benchmark, a finding consistent with earlier, industry-wide assessments (Hamblin and Kyneur 1993) as well as those conducted at regional scale (Cornish and Murray 1989; Hochman *et al*. 2012). Despite the coarse nature of such industry-wide estimates it has been demonstrated that leading farmers in some locations are achieving benchmark yields (e.g. van Rees *et al*. 2014). As a result the study provided impetus for a nation-wide approach to improve water-limited yield and challenged growers, scientists and the wider industry to consider reasons for underperformance.

The simplicity and accessibility of the French and Schultz (1984) approach that links yield with seasonal evapotranspiration (ET) remains attractive, but its simplifying assumptions, in particular its failure to deal with rainfall distribution, can limit its interpretative power. More recently, crop simulation models such as APSIM (Keating *et al*. 2003) have permitted more site- and season-specific assessment of crop performance by accounting for seasonal rainfall distribution, evaporative demand, temperature, soil water-holding capacity and crop management (e.g. sowing time, plant density, nitrogen (N) applications). The model is available to growers and consultants via a simplified web interface known as Yield Prophet® (Hochman *et al*. 2009*b*). Such approaches can refine attainable yield targets by separating management from climatic factors beyond the farmer's control (Hochman *et al*. 2009*a*). Some studies have used and compared yield benchmarks using both French and Schultz and simulation approaches (Lisson *et al*. 2007; Oliver *et al*. 2009). The use of models such as APSIM for benchmarking is a more accurate way of realising the original intent of French and Schultz (1984) of estimating yield in relation to crop water use. Regardless of the benchmark used, a consistent approach to assessing water-limited crop performance is important where trends across regions and seasons are sought.

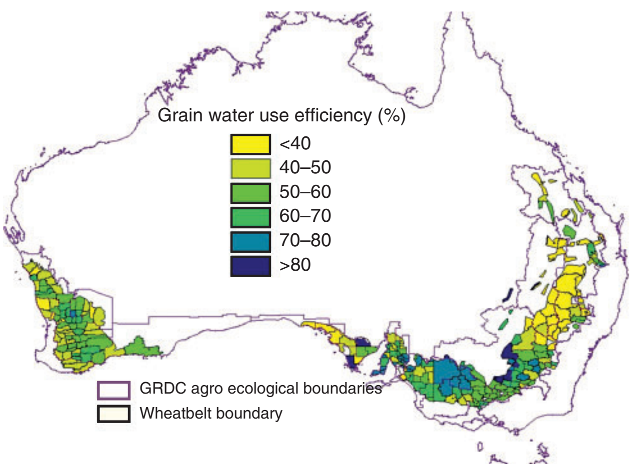

Fig. 1. National assessment of regional water-use efficiency achieved as a percentage of potential assessed using the French and Schultz (1984) approach as reported in the GRDC commissioned Beeston Report (Beeston *et al*. 2005), which stimulated GRDC Investment in a National WUE Initiative.

Initiative structure and operation

The GRDC was established in 1990 to capture and focus research, development and extension (RD&E) in the Australian grains industry through levied funds from growers and Commonwealth tax funds pooled for investment (www.grdc.com.au). In 2007, the GRDC's Research Investment Plan (GRDC 2007) included a call for tenders to a National Water Use Efficiency Initiative, which challenged growers and scientists throughout southern Australia and Western Australia to propose research projects that could achieve a 10% improvement in crop and system WUE over a 5-year period. Assuming no difference in average rainfall, the 2% per annum increase in production implied (i.e. yield gain) compares with the longer term industry achievement of 1.3% (Fischer 2009), although (Richards *et al*. 2014) demonstrate that much higher levels are possible on well-managed farms. The GRDC encouraged the network of organised grower groups (Gianatti and Carmody 2007; Llewellyn 2007) to collaborate with relevant science agencies to develop research proposals to achieve the 10% target. As a result of the tender process, 16 regional projects were funded as part of the initiative, covering areas receiving 300–700 mm annual rainfall and stretching from central-west New South Wales (NSW) in the east, to the northern sand-plain of Western Australia (Table 1, Fig. 2).

In addition to these regionally-focused project proposals, the GRDC commissioned a coordinating project with a national perspective to provide a common language and consistent analytical framework to assist regional efforts to improve WUE. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) led the coordination project with a team comprising agronomists, crop physiologists, soil scientists, and crop simulation and system analysts across southern Australia (Canberra, Adelaide and Perth) and usually embedded in specific regional team projects (Table 1). An agronomist was specifically employed on the project to act as the central contact for the grower group interactions, travelling widely to visit all groups frequently during the course of the project. This 'champion' role

Table 1. Details of the 16 region project teams involved in the GRDC National Water Use Efficiency (WUE) Initiative, collaborating agencies and the major issues proposed for investigation to improve the WUE of the farming systems in each region

Information sourced from websites where possible, or from group co-ordinators

Project leaders–groups	Centred around	Established	Members	Area (Mha)	Collaborators	Issues nominated for investigation
1. WA Sandplain (Liebe Group)	Dalwallinu	1997	120	1.0	CSIRO	Summer fallow management, managing in-season water use
2. WA Central (Kellerberrin Demonstration group, Bodallin Catchment Group, Green Hills farmer group)	Cunderdin	2004	35	4.0	CSIRO	Managing paddock variability
3. WA South West (Southern DIRT)	Kojonup, WA		30	2.0	CSIRO	Managing in-season water use
4. WA South Coast (SEPWA, Precision Agronomics Australia)	Esperance, WA	1993	200	2.0	DAFWA	Managing variable or constrained soils
5. Eyre Peninsula Agricultural Research Foundation (EPARF)	Minnipa, SA	2004	300	2.0	SARDI, CSIRO	Managing variable or constrained soils, managing in-season water use
6. Lower Eyre Agricultural Development Association (LEADA), http://agex.org.au/groups/lower-eyre-agricultural-development-association/	Port Lincoln, SA	2005	80	2.0	SARDI	Managing variable or constrained soils, managing in-season water use
7. Upper North Farming Systems, https://www.facebook.com/pages/Upper-North-Farming-Systems/342964929066490	Jamestown, SA	2000	80	2.0	CSIRO	Summer fallow management, managing in-season water use
8. Hart Field Site Group, www.hartfieldsite.org.au	Hart, SA	1982	548	3.7	SARDI	Summer fallow management
9. Mallee Sustainable Farming (MSFS), www.msfp.org.au	Balranald (NSW) to Murray Bridge (SA)	1997	1000	4.0	CSIRO	Managing variable or constrained soils, break crops and crop sequences
10. MacKillop Farm Management Group (MFMG), www.mackillopgroup.com.au	Naracoorte, SA	1998	120	1.2	SARDI	Managing variable or constrained soils, managing in-season water use
11. BCG (formerly Birchip Cropping Group), www.bcg.org.au	Birchip, Vic.	1992	400	2.0	CSIRO	Summer fallow management, break crops and crop sequences
12. Southern Farming Systems (SFS), www.sfs.org.au	Inverleigh, Vic.	1995	600	1.0	Vic. DEPI/La Trobe University	Managing variable or constrained soils, managing in-season water use
13. Riverine Plains Inc. (RPI), www.riverineplains.com.au	Yarrawonga, Vic.	1999	315	3.5	Foundation for Arable Research (NZ)	Managing variable or constrained soils, managing in-season water use
14. University of Tasmania (TIAR)	Cressy, Tas.	–	–	–	–	Managing in-season water use
15. Central West Farming Systems (CWFS), www.cwfs.org.au	Condobolin, NSW	1998	400	14.0	NSW DPI	Summer fallow management
16. FarmLink Research, www.farmlink.com.au	Junee, NSW	2003	335	2.0	CSIRO	Summer fallow management

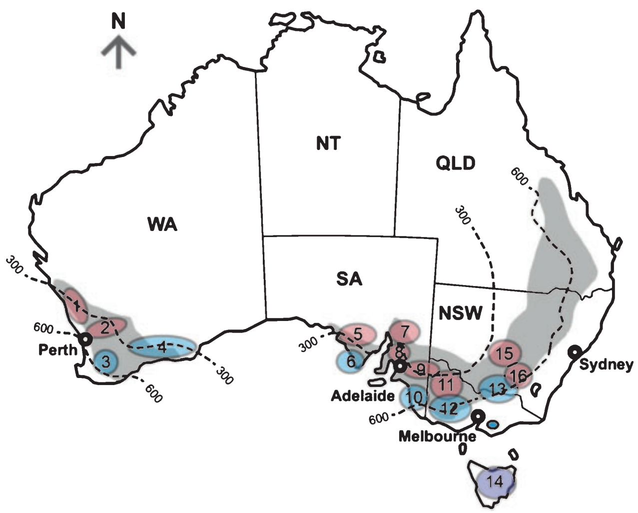

Fig. 2. Map showing the general location of the 16 individual projects within the grain-growing regions (shaded) led by regional grower groups and science agencies as part of the GRDC National Water Use Efficiency Initiative (2008–13). Details of the various projects and groups are shown in Table 1.

was pivotal to the successful engagement of the groups, and to building a sense of belonging to the wider Initiative.

Development of research themes

A critical initial task for the coordination team was to organise the many interventions proposed by the 16 regional projects into themes of research that provided a framework that tied the diversity of potential practice change into something people could relate to and discuss. This was necessary to allow each group to understand how their proposed interventions fitted into the broader farming system. This framework (Fig. 3), and an initial review and simulation study that considered how various approaches to improve WUE interact within farming systems, were subsequently published by Kirkegaard and Hunt (2010).

The framework was designed to accommodate the various interventions proposed for investigation by the regional groups, and to demonstrate the way in which combinations of pre- and in-crop management strategies, rather than individual interventions in isolation, were required to increase productivity and WUE. This was a critical aspect of the approach, given that most groups could afford to conduct specific experiments on only one or two components of the system. The four research themes developed, and the number of different groups pursuing aspects within those themes, were: (*i*) break crops and crop sequences (2 groups); (*ii*) summer fallow management (weeds, stubble and livestock) (6 groups); (*iii*) managing in-season water use (9 groups); (*iv*) managing variable or constrained soils (7 groups).

The themes allowed groups from different regions working on the same theme to see how the interventions affected WUE in different regions, and to understand how interventions from different themes interacted at the whole-farm scale. The themes also provided focus for the coordination team to target experiments and simulation along with additional sampling and analysis to ensure co-ordination and consistency in experimental design and measurement across regions. Early engagement between groups and scientists provided opportunities to develop sound approaches to longer term experiments, such as crop-sequence effects and impacts of livestock on soil structure, which require good planning and experimental design. As part of this process, pre-experimental modelling also provided initial insights to generate discussion and in some cases re-design of experiments. Annual initiative meetings (held in a different state each year) provided an opportunity to review the experimental and simulation outcomes, to reinforce the need for consistent approaches, and for the regional teams to discuss the effects of interventions in different regions and the impacts of interventions not under investigation in their region.

In each theme, we used literature review and pre-experimental modelling scenarios to assist in experimental design, assisted teams to gather the necessary data to interpret results and parameterise APSIM, and where possible extrapolated and scaled up the experimental outcomes to consider season and site interactions and whole-farm impacts. Throughout the initiative, growers and advisors were also testing emerging ideas on their own farms and with clients, refining ideas and providing a direct pathway for adoption.

We highlight selected examples of the outcomes from different themes, and some important interactions between interventions across themes required for impact at the whole-farm scale.

Selected outcomes from theme activities

Theme 1. Break crops and crop sequence

The benefits of *Brassica* and legume break crops to cereals have been studied extensively, and the increases to subsequent wheat yield of 0.6–0.8 t/ha arise from combinations of reduced disease and weed incidence, improved N fertility, residual water and improvements in soil structure (Kirkegaard *et al*. 2008; Peoples *et al*. 2009; Angus *et al*. 2011; Seymour *et al*. 2012). Despite this, the area of break crops declined dramatically in southern Australia between 1999 and 2009 because of declining autumn rainfall during that period (Pook *et al*. 2009; Cai *et al*. 2012) and the perceived riskiness or low profitability of break crops compared with cereals. In the drier areas of the Victorian and South Australian Mallee, high-input break crops such as canola are considered risky, and low-value grain legumes used for animal feed, such as pea and lupin, generally have lower gross margins than cereals grown in the same year. Nonetheless, the value of break crops in maintaining low weed and disease levels and providing non-fertiliser N are clear, and several studies point to longer term benefits of including them in the rotation (Robertson *et al*. 2010). Intensive cereal rotations have increased the requirement for fertiliser and weed control, and revived interest in the introduction of an alternative crop or pasture species (breaks) in crop sequences. Within the Initiative, the Birchip Cropping Group (BCG) and Mallee Sustainable Farming (MSF) in collaboration with CSIRO sought to investigate the impacts of a range of break crops, including those used for hay or brown manure, on WUE and profitability of the cropping system. Experiments were established in Mallee environments in both South Australia

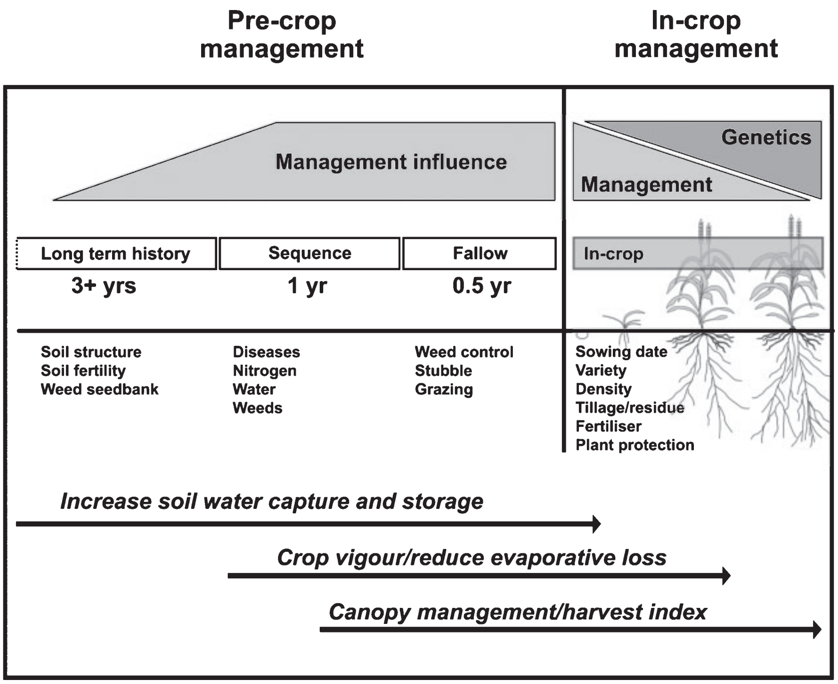

Fig. 3. A diagram summarising the range of pre-crop and in-crop management strategies that can influence the productivity and water-use efficiency of dryland crops (reproduced with permission from Kirkegaard and Hunt 2010). The diagram emphasises the continuum of overlapping influences that various management strategies have on aspects of water use and the important interactions.

(Karoonda) and Victoria (Hopetoun) to explore the effect of the inclusion of break crops in sequence with cereals. The novel features of both of these studies were (*i*) to follow the effects of break crops over several years to account fully for the economic benefits of the break crops in the system; and (*ii*) to consider lower cost, lower risk end-uses of the break crops, such as for hay or brown manure.

In both environments, the inclusion of legume break crops resulted in considerable increases in the yield of subsequent crops, with benefits measured for up to 3 years. These yield benefits were the drivers of WUE gains in the order of 16–83% (Browne *et al*. 2012; McBeath *et al*. 2014). At Hopetoun, in Victoria, identical field experiments were established on clay and sandy soil sites in nearby fields (2.3 km apart). Various break crops and wheat were grown in replicated plots over four seasons from 2009 to 2012 and the yield, and the profitability of each sequence was compared with continuous wheat. Grain, hay and brown-manure end-uses were compared, and a fallow was included. The experiment demonstrated that most of the break-crop options were at least as profitable over the 4-year crop sequence as continuous wheat (Fig. 4; Browne *et al*. 2012). Legume hay was often not as profitable as wheat or canola in the year it was grown, but the higher levels of residual soil water and N, which often persisted for several years, along with effective weed control lifted the overall profitability of the crop sequences. Crop sequences involving canola were also more profitable than continuous wheat, but this was due to the profitability of canola itself in the year that it was grown (Fig. 4*b*) rather than a marked break-crop effect on subsequent wheat yield (Fig. 5).

At Karoonda, the experiments also showed break-crop benefits on four distinct Mallee soil types across several seasons (McBeath *et al*. 2014). There were consistent cumulative benefits to subsequent cereals of 1 t/ha for up to 3 years after break crops. The study suggested that the benefits were largely due to positive impacts on the cycling and supply of nutrients. There was no conclusive effect on the supply of water to subsequent crops. The yield benefit of canola and legume break crops to a subsequent wheat crop compared with continuous wheat for both Hopetoun and Karoonda are summarised in Fig. 5. The results emphasise that the economic benefit from the legumes derives predominately from the yield increases to subsequent wheat. For canola, the yield benefits were small (Fig. 5), but the profitability of canola generated economic benefit within the sequence (Fig. 4).

The coincidence of the demonstration of yield benefits to cereal crops following break crops and the profitability of these systems over the medium term with average to above-average growing-season rainfall has resulted in rapid adoption of break crops, in particular legume breaks in the region, following the decline during the Millennium drought (Fig. 6). In particular, vetch for grazing, hay or brown manure has been rapidly adopted across the Victorian Mallee.

Some resistance remains to use of break crops because of the perceived riskiness of either a failed break crop or missing the profitability of a cereal crop in a season of above-average rainfall. Stochastic modelling using the Land Use Sequence Optimiser (Lawes and Renton 2010) has demonstrated that the inclusion of break crops could be profitable and manage risk if weed burden or disease is restricting cereal yields.

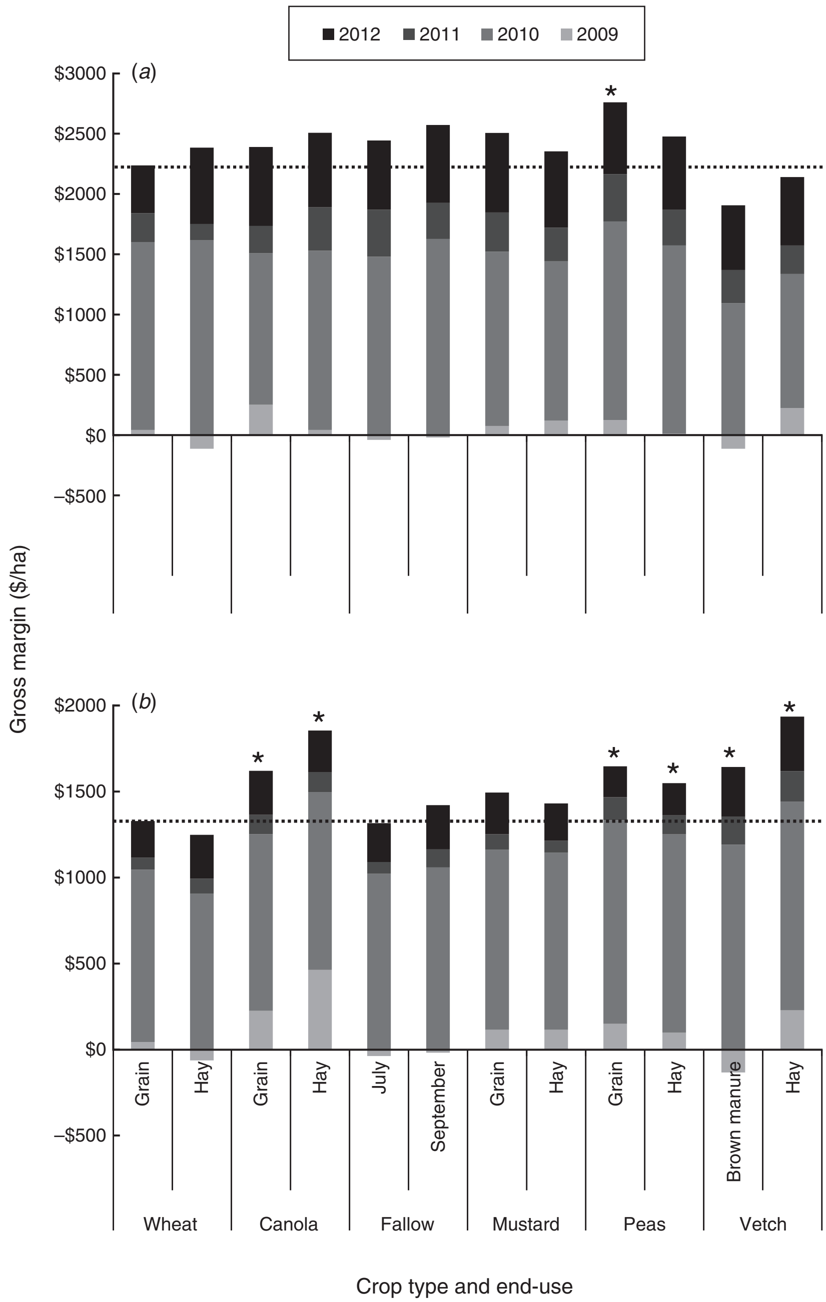

Fig. 4. Cumulative 4-year gross margin (AU$/ha) for various 4-year sequences commencing with a range of fallow or break-crop options grown for grain or hay on either (*a*) sand or (*b*) clay at Hopetoun in the Victorian Mallee (2009–12). The dotted line indicates profit returned by continuous wheat harvested for grain, and treatments with an asterisk are significantly different from this treatment (sand $P = 0.032$, clay $P < 0.001$).

Theme 2. Summer fallow management

Six groups across the regions nominated various aspects of summer-fallow management (weed control, stubble management and livestock grazing) as targets for improving the capture and storage of water. In southern Australia, summer-fallow rainfall had not traditionally been valued for winter crop production because the majority of rain falls during the cropping season, and weedy summer fallows were often considered valuable as summer feed for livestock. At the site considered in the simulation study by Kirkegaard and Hunt (2010), summer weed control and stubble retention were predicted to increase productivity and water-use, but the value across a broader range of sites was not known. A pre-experimental modelling study by Hunt and Kirkegaard (2011) used simulation to re-evaluate the contribution of summer-fallow rainfall across 37 locations in southern Australia and Western Australia. The study predicted that the potential contribution to yield was high (mean 1 t/ha, or 33%) but varied with location and soil type (from 0.1 to 2.0 t/ha). The benefits simulated related solely to water and no effects of N were considered. This suggested that targeting improved capture of summer rainfall was worthwhile and prompted a focused effort on ways to achieve it.

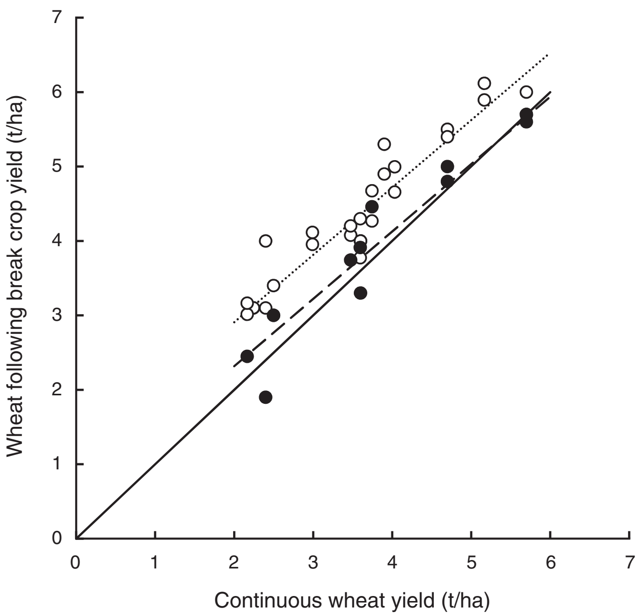

Fig. 5. Relationship between yield of wheat following break crops and yield of wheat after wheat (WW) at Karoonda (South Australian Mallee) and Hopetoun (Victorian Mallee). The relationships presented are parallel lines ($P < 0.001$, $R^2 = 0.90$) where wheat yield following a *Brassica* break crop (●) was BW = 0.51 + 0.91 WW yield (- - -), and following a legume break crop (○) was LW = 1.10 + 0.91 WW yield (. . .).

Prior to the Initiative, there was little agreement across the industry about the importance of summer weed control for improved fallow efficiency, a widely held view that stubble retention was central to good fallow management (and higher stubble levels were more effective), and increasing concerns that livestock grazing crops and stubbles were damaging soil structure in no-till, controlled-traffic farming systems. Six of the regional groups established various experiments across a range of soil types and environments to investigate the effects of summer weed control and stubble retention on soil water and N dynamics and subsequent crop growth. Two of the groups established experiments specifically designed to investigate the effects of sheep grazing on soil structure, water and N dynamics, and subsequent crop growth.

Summer weed control

The 20 replicated experiments on summer weed control conducted across the initiative clearly demonstrated the soil water and N accumulation and yield advantages of controlling summer weeds (Table 2). The return on investment was calculated from the costs of spraying and the additional yield, quality, and subsequent seasonal price of the crops. A wet summer fallow period during 2010–11 followed by a dry growing season in 2011 emphasised the benefits of summer weed control, but the effects were consistent across several sites and seasons. The effect of weed control on both water and N underpinned the reliability of the yield responses (Hunt *et al*. 2013*a*). In seasons with high growing-season rainfall (e.g.

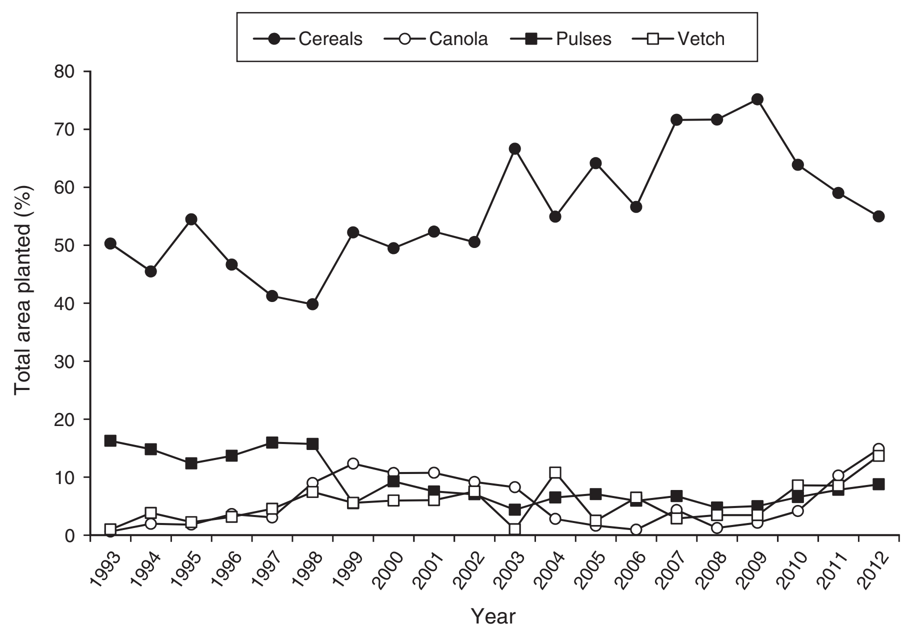

Fig. 6. Area of cereals (wheat and barley), canola, pulses (lentils, field peas, chickpeas, lupins) and vetch in the Birchip region of Victoria since 1993. Although cereals remain dominant, the area of all break crops has recovered since 2009, but the area of vetch in particular is now similar to that of canola (data courtesy Simon Craig, Birchip Cropping Group).

Table 2. Summary of field experiments in the National Water Use Efficiency Initiative reporting the impact of summer weed control on pre-sowing plant-available water and nitrogen, crop yield and return on investment

Values in bold are statistically significant ($P < 0.05$), values in plain text are not significant ($P > 0.05$), and values in italics were unreplicated paddock-scale demonstrations. Return on investment assumes chemical and grain prices in the year of the experiment

Site (soil type)	Year	Summer fallow rain (mm)	Additional PAW pre-sowing (mm)	Additional mineral N pre-sowing (kg/ha)	Sown crop	Additional yield (t/ha)	Yield with weed control (t/ha)	Return on investment in weed control
				New South Wales				
				NSW Department of Primary Industry and CWFS				
Waroo	2008	358	*56*	*25*	Wheat	*1.0*	*2.6*	*$12.00*
Gunningbland	2010	270	**53**	**57**	Wheat	**1.7**	**3.7**	**$5.67**
Gunningbland	2011	488	**98**	**85**	Canola	**1.0**	**2.2**	**$17.67**
Tottenham	2010	417	**21**	**32**	Wheat	**1.4**	**2.4**	**$4.67**
Rankins Springs	2010	304	0	**57**	Wheat	**1.0**	**3.7**	**$3.18**
Rankins Springs	2011	384	–	–	Wheat	**0.7**	**1.7**	**$9.91**
Rankins Springs	2012	476	62	88	Wheat	**1.2**	**3.5**	**$4.58**
Condobolin	2011	290	NA	**36**	Wheat	**1.1**	**2.2**	**$3.33**
Condobolin	2012	461	55	**62**	Wheat	**0.5**	**1.7**	**$2.61**
				Victoria				
				Birchip Cropping Group and CSIRO				
Curyo, Vic.	2008	76	24	**14**	Wheat	**1.3**	**2.5**	**$5.00**
Hopetoun (sand)	2009	90	11	–3	Barley	0.2	3.4	$1.20
Hopetoun (clay)	2009	90	3	10	Barley	0.3	2.8	$1.80
Hopetoun (sand)	2010	224	**40**	**45**	Canola	**0.4**	**3.1**	**$4.76**
Hopetoun (clay)	2010	254	**52**	**43**	Canola	**0.6**	**2.7**	**$7.16**
Hopetoun (sand)	2011	387	**29**	**41**	Wheat	**1.6**	**3.7**	**$7.62**
Hopetoun (clay)	2011	387	**36**	**53**	Wheat	**1.4**	**2.8**	**$10.09**
Hopetoun (sand)	2012	156	**42**	**44**	Lentils	**0.3**	**0.9**	**$3.19**
Hopetoun (clay)	2012	156	41	**55**	Lentils	**0.5**	**1.1**	**$3.97**
				South Australia				
				Upper North farming Systems and CSIRO				
Quorn (heavy)	2009	175	10	–	Wheat	**0.2**	**1.3**	**$0.98**
Pt Germein (light)	2009	89	**30**	**–**	Field peas	**0.4**	**1.5**	**$2.09**
Mean	–	–	**37**	**44**	–	**0.8**	**–**	**$5.57**

2010), the yield increase was driven primarily by N availability; in seasons with low growing-season rainfall, by water availability; and in average seasons, by both water and N because of co-limitation of those resources on yield (Sadras *et al*. 2012). Across all experiments in the initiative from 2008 to 2011, the average increase in water stored was 37 mm, the additional mineral-N accumulated was 44 kg N/ha, and complete control of summer weeds returned an average of AU$5.57/ha for every dollar per ha invested.

Experiments in South Australia (Sadras *et al*. 2012) and in the northern sand-plain region of Western Australia applied irrigation during the summer fallow to evaluate the benefit of increased water availability (Table 3). On loam soils at Hart in South Australia, Sadras *et al*. (2012) found that the yield gain from additional water declined from 0.6 t/ha to zero when yield of controls increased from 2.1 to 5.8 t/ha, and that additional N was required to capture the benefit of increased water availability in better years (Table 3). Modelling by Hunt and Kirkegaard (2011) predicted that sites with limited summer rainfall, reliable winter rainfall, and soils of low water-holding capacity such as the sand-plains of Western Australia would show smaller yield benefits from stored summer rainfall. In the experiments conducted in that region, the equivalent of 30 mm of extra water applied 1 month before sowing increased yield in three of six site–year combinations, whereas 60 mm of extra water gave a further yield increase on one occasion only (Table 3). The benefits of additional water were better captured on the sandy soil in the drier year of 2012, presumably because of better fallow efficiency (as predicted by Hunt and Kirkegaard 2011), but on the loam soil in the higher rainfall year of 2013, possibly a result of lower water-holding capacity and/or N leaching on the sand. The average yield increase over all site–year combinations for 30 mm extra water was 0.5 t/ha, showing that even in this region, summer weed control in response to summer rainfall can provide substantial benefits in both production and economic returns.

Although the economics of complete summer weed control were compelling, further experiments conducted by NSW Department of Primary Industries (DPI) and Central West Farming Systems (CWFS) clearly demonstrated that controlling weeds late is better than not controlling them at all (Haskins and McMaster 2012). This is illustrated by results from Gunningbland, NSW, in 2010 (Table 4), which are representative of results from other sites and seasons. Complete weed control (spraying 10 days after each significant rain event) yielded the most, but 'delayed' weed control (spraying 3 weeks after each significant rain event) and a treatment in which the first summer spray was missed

Table 3. Summary of experiments investigating effect of supplementary summer fallow irrigation on wheat yield at sites in South Australia and Western Australia

Treatments significantly different from control are shown in bold and treatments with the same letter within a row are not significantly different ($P > 0.05$). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

Site–soil	Year	Rainfall (mm)		Irrigation treatments			*P*-value
		Fallow	In-crop	Control	+50 mm	+100 mm	
			South Australia (*Sadras et al.* 2012)				
Hart	2009	10	266	2.6a	**3.2b**	**3.2b**	***
	2010	74	310	4.9	–	5.2	n.s.
	2010 (low N)	74	310	5.8	–	5.7	n.s.
	2010 (high N)	74	310	5.6a	–	**7.2b**	**
			Western Australia (*CSIRO, Liebe, Mingenew–Irwin, and North-East Farming Futures*)				
		Fallow	In-crop	Control	+30 mm	+60 mm	
Buntine[A]	2011	70	264	3.9	3.9	3.7	n.s.
Morawa	2012	38	179	2.3	2.4	2.3	n.s.
Dalwallinu sand	2012	94	141	2.1a	**3.3b**	**3.4b**	*
Dalwallinu loam	2012	94	141	2.1	2.0	2.0	n.s.
Dalwallinu sand	2013	123	180	3.4a	**4.0b**	**3.8b**	*
Dalwallinu loam	2013	123	180	2.8a	**4.0b**	**5.0c**	*

[A]Irrigation applied at Buntine in 2011 was 40 and 80 mm.

Table 4. Plant-available water and mineral nitrogen before sowing and wheat grain yield under different summer fallow treatments at NSW DPI and CWFS trial site at Gunningbland in 2010 (from Haskins and McMaster 2012)

Within a column, values followed by the same letter are not significantly different

Weed control	PAW (mm)	Mineral N (kg/ha)	Grain yield (t/ha)
Nil (no weed control at all)	81a	55a	2.2a
Miss first (as for complete but first spray missed)	114b	98c	3.7b
Delayed (sprayed 21 days after significant rain)	118bc	82b	3.0c
Complete (sprayed 10 days after significant rain)	130c	103c	3.6b
P-value	<0.001	<0.001	<0.001

(indicated as 'miss first' in Table 4) both yielded more than the nil control treatment. Typically, the return on investment was ~$3.50 for each dollar spent in these intermediate treatments, compared with ~$5.60 for complete control (Haskins and McMaster 2012).

The most commonly cited reason for not controlling summer weeds is provision of forage during summer months. However, whole-farm simulation using the AusFarm model (Moore and Hunt 2012) clearly demonstrated that this is a false economy (Table 5). In the system where weeds are allowed to grow for forage, a small increase in meat and wool production and a decrease in supplementary feeding is offset by a very large decrease in crop yields. Weeds growing during the hot, dry summer months do not convert water efficiently to dry matter, and grazing does not reduce the amount of water or nutrients that they use. Farmers with mixed enterprises are better off controlling summer weeds and using the water and N they save to grow more grain and fodder, which they can carry over for summer feeding.

The outcomes of this summer fallow weed control work were unequivocal and widely communicated and have been rapidly adopted by growers and consultants across southern Australia.

Stubble management

Retention and management (e.g. standing, mulched, slashed) of crop stubbles was selected by many regional groups as a strategy to increase WUE. The pre-experimental modelling study by Kirkegaard and Hunt (2010), along with much previous literature (Scott *et al*. 2010; Scott *et al*. 2013*a*), suggested that the impacts of stubble retention would be minor, but the perception among grower groups was that increased stubble and better management could increase water storage by reducing evaporation. Many of the experiments investigating weed management (e.g. Haskins and McMaster 2012; Hunt *et al*. 2013*a*) also considered stubble retention, and across the Initiative, the effects of stubble retention and different amounts of stubble were investigated in 29 experiments over four seasons at 13 sites (Table 6). In contrast to the large and reliable yield increases due to control of summer weeds, yield responses from stubble management were small and variable. The majority of replicated experiments in the initiative (17) found no significant effect of either retaining or removing (burning, grazing, cultivating, slashing and raking) stubble on crop yield. Ten experiments showed a significant yield effect of retaining stubble: three were positive (mean effect equivalent to 9% of stubble retained yield), and seven were negative (mean effect –12% of stubble retained yield, Table 6). Negative effects of residues are thought to be related to N immobilisation by surface-retained stubble, leading to N deficiency in the crop (Scott *et al*. 2010), and often occur in years with high yield potential and/or at N-limited sites.

The explanation for the limited positive impact of retained stubble is that although stubble slows evaporation it does not eliminate it, and surface soil will dry over extended periods without rain. Verburg *et al*. (2012) explained this using a 'pulse paradigm', which showed that the level of water stored

Table 5. Effect of strict weed control in grazed summer cereal stubble on crop and livestock production and area-weighted frequency of low ground cover in two AusFarm-simulated mixed farms at Temora (NSW) and Hopetoun (Vic.) from 1960 to 2010 (from Moore and Hunt 2012)

Site	Temora		Hopetoun	
	Weed control	No control	Weed control	No control
Mean wheat yield (t/ha)	3.6	2.8	1.9	1.5
Mean canola yield (t/ha)	2.3	1.8	1.5	1.1
Mean barley yield (t/ha)	3.5	2.5	2.3	1.2
Clean wool (kg/farm ha.year)	12.9	12.9	2.3	2.2
Lamb liveweight sold (kg/farm ha.year)	45.2	46.1	8.7	7.0
Supplementary feed (kg/ewe unit.year)	25	23	23	44
Deep drainage (mm/year)	65	50	20	6
Frequency cover <70%	0.18	0.14	0.01	0.06

from rainfall events during summer depends upon the size of the soil water pulses generated and the interval between them. Heavy and/or overlapping pulses of soil water will tend to lead to soil water storage as water moves below the evaporative zone. During the conditions of high evaporative demand in summer, infrequent or light rain evaporates from both covered and uncovered soils, so that any differences in water in surface soils diminish over time. As the evaporative demand declines in autumn, high stubble loads can prolong the levels of surface moisture conservation and allow earlier sowing in some circumstances (Fischer *et al*. 1990; Scott *et al*. 2010). The results from across the Initiative suggest that the major benefits of stubble are in preventing wind and water erosion, and improving the infiltration of rainfall by protecting the soil surface during summer rainfall and increasing surface roughness, rather than as a mulch to reduce evaporation (Foley and Silburn 2002; Hunt *et al*. 2011). Research at two sites in Western Australia (Ward *et al*. 2012) showed similar results, with no impact of residue retention on soil-water storage over summer and autumn, and no impact on subsequent crop yield.

Effects of livestock

As the adoption of no-till, controlled-traffic cropping systems increased during the 2000s (GRDC 2012), there was concern regarding the impact of grazing livestock on the anticipated improvements to soil structure, water capture and crop yield thought to be provided by these systems. Despite the concern, few published experiments examined this issue in contemporary, mixed farming systems, although the review of literature and a simulation study by Bell *et al*. (2011) suggested that grazing effects were shallow and transient, and unlikely to have significant impacts on crop yield. Two regional groups in the mixed farming area of southern NSW (FarmLink/CSIRO and CWFS/NSW DPI) conducted field experiments to investigate the impacts of grazing on soil structure, water and N accumulation, and subsequent crop growth. An experiment at Temora, NSW (Hunt *et al*. 2011), measured a series of crops managed under no-till, controlled-traffic systems in which plots were either ungrazed, or had stubble alone (summer) or stubble and vegetative biomass grazed (winter). Crop yields were largely unaffected by the grazing treatments throughout the experiment (Table 7). Detailed water-balance measurements showed that although infiltration rates were often reduced by surface compaction, the rates remained high enough in grazed treatments for the rainfall to infiltrate. Subsequent rainfall diminished differences in water storage when they did occur. Interestingly, in some years, crops grown after grazed stubbles yielded more than ungrazed treatments, because of extra N accumulation before sowing. The mechanism remains uncertain, but is likely to involve a combination of reduced N uptake in grazed crops, the return of N in grazed crops and stubbles to plots through urine, and enhanced solubilisation of organic N at high pH under heavy urine deposition (Unkovich *et al*. 1998). The outcomes from Temora and Condobolin suggest that most damage done by sheep is through removal of crop residues rather than by soil compaction through trampling. Together with the results from the stubble-retention experiments, this reinforces the need to maintain a stubble threshold to protect the soil, reduce erosion and increase infiltration. Increasing stubble above that level appears to add little value in terms of water storage, N nutrition and crop yield. This was clearly demonstrated at the Condobolin site in 2011, where there was no difference in the yield response to stubble removal by heavy grazing or by hand. Crop yield increased with increased stubble up to 3.5 t/ha, above which increasing stubble further did not increase crop yield (Fig. 7; Hunt *et al*. 2013*b*).

Collectively, the work within the Initiative revealed the importance of using summer-fallow rainfall in southern Australia, and the strategies for weed, stubble and stock management to do so have had the most rapid and potentially significant impact on improving WUE. The impact is direct but also, as predicted by Kirkegaard and Hunt (2010), indirect by facilitating synergies with modified in-crop management such as early sowing. The impact was summarised by a senior agricultural advisor and member of the GRDC Southern Regional Panel (which advises on research priorities), Mr Bill Long (pers. comm., 2013): 'The uptake of many of the aspects of this research program have been outstanding. Farmers no longer debate the benefits and costs of summer weed control.'

Theme 3. Managing in-crop water use

Figure 3 shows a range of in-crop agronomic management strategies that can be manipulated to improve the productivity and WUE of crops; many of these options were selected by the regional groups for investigation. Overall, these are designed to establish a healthy crop canopy and root system and to manage the trajectory of canopy growth according to resource availability

Table 6. Effect of a range of stubble treatments on crop yield in replicated experiments conducted as part of the National Water Use Efficiency Initiative across four states in Australia from 2009 to 2012

Site at Wubin involved large unreplicated blocks. n.a, Not available; n.s., not significant; UR, unreplicated

Site–soil type	Year	Crop	Crop yield (t/ha)					l.s.d.	Effect
			Standing	Slashed	Removed	Cultivate	Burnt	(P = 0.05)	size (%)
			Victoria						
			Birchip Cropping Group and CSIRO (Hunt *et al.* 2013*a*)						
Hopetoun, sand	2009	Barley	3.7	3.5	3.4	3.3	n.a.	n.s.	
Hopetoun, sand	2010	Canola	3.3	2.9	3.0	3.2	n.a.	n.s.	
Hopetoun, sand	2011	Wheat	3.7	3.8	3.7	3.4	n.a.	n.s.	
Hopetoun, sand	2012	Lentils	1.0	1.0	0.9	1.0	n.a.	n.s.	
Hopetoun, clay	2009	Barley	2.9	2.7	2.8	2.7	n.a.	n.s.	
Hopetoun, clay	2010	Canola	2.8	2.8	2.8	2.6	n.a.	n.s.	
Hopetoun, clay	2011	Wheat	2.6	2.8	2.9	3.0	n.a.	0.2	–12
Hopetoun, clay	2012	Lentils	1.2	1.2	1.0	1.1	n.a.	n.s.	
			New South Wales						
			New South Wales DPI and Central West Farming Systems (Haskins and McMaster 2012)						
Tottenham	2010	Wheat	2.4	2.3	n.a.	2.5	n.a.	n.s.	
Gunningbland	2010	Wheat	3.6	3.4	n.a.	3.9	n.a.	Sig.	–8
Rankins Springs	2011	Wheat	1.5	1.1	n.a.	1.6	n.a.	0.4	–7
Condobolin	2011	Wheat	2.3	2.3	n.a.	2.2	n.a.	n.s.	
Condobolin	2012	Wheat	2.5	2.5	n.a.	2.3	n.a.	0.2	8
			NSW DPI (Hunt *et al.* 2013*b*)						
Condobolin	2010	Wheat	4.7	n.a.	4.5	n.a.	n.a.	0.2	4
Condobolin	2011	Barley	2.5	n.a.	2.1	n.a.	n.a.	0.2	16
Condobolin	2012	Wheat	1.7	n.a.	1.8	n.a.	n.a.	0.2	–11
			FarmLink and CSIRO (Hunt *et al.* 2013*b*)						
Temora	2010	Canola	4.2	n.a.	n.a.	n.a.	4	n.s.	
Temora	2011	Wheat	4.1	n.a.	n.a.	n.a.	4.1	n.s.	
Temora	2011	Canola	3.4	n.a.	n.a.	n.a.	3.4	n.s.	
Temora	2012	Wheat	4.4	n.a.	n.a.	n.a.	5	0.3	–14
Temora	2012	Canola	4.7	n.a.	n.a.	n.a.	4.9	n.s.	
			South Australia						
			Upper North and CSIRO (Mudge and Whitbread 2010)						
Port Germein	2009	Peas	1.5	n.a.	n.a.	1.3	n.a.	n.s.	
Quorn	2009	Wheat	1.3	n.a.	n.a.	1.4	n.a.	n.s.	
			SARDI and Hart Group (Sadras *et al.* 2012)						
Hart	2009	Wheat	Compared bare ground with 5 t/ha stubble in 2009 and 2.4 t/ha stubble in 2010 but no significant differences and thus treatment yields in either year						
Hart	2010	Wheat							
			Western Australia (Liebe Group and CSIRO)						
Buntine, sand	2011	Wheat	3.1	3.3	n.a.	n.a.	3.4	0.2	–9
Buntine, sand	2012	Canola	0.8	0.7	n.a.	n.a.	0.9	0.1	–22
Wubin, sand/gravel	2011	Wheat	2.3	3.0	2.9	n.a.	n.a.	UR	
Wubin, loam	2011	Wheat	3.5	3.6	3.6	n.a.	n.a.	UR	

Table 7. Grazing vegetative crops in winter and/or stubble in summer had little impact on crop yield under continuous, no-till controlled traffic cropping sequence at Temora, NSW (from Hunt *et al.* 2013*b*)

Treatment	2009 (wheat)	2010 (canola)	2011 (wheat)	2012 (wheat)
Nil graze	1.6	4.1	4.6	4.7
Stubble graze	1.6	4.2	4.6	4.8
Winter and stubble graze	1.2	4.0	5.2	4.7
P-value	<0.001	0.62	<0.001	0.768
l.s.d. (P = 0.05)	0.2	n.s.	0.2	n.s.

(water and N) through the season. The study by Kirkegaard and Hunt (2010) predicted a significant synergy between the use of break crops, good fallow management and early sowing, whereby the value of the stored water and N from good pre-crop management could only be optimised with timely sowing of subsequent crops. Often, adjustments to other aspects of in-crop management may also be required to optimise the pattern of water and N use and productivity of early-sown crops. These include sowing density and row spacing, N management, fungicide application and grazing. We highlight a selection of examples investigated within the Initiative with a focus on those that interact strongly with pre-crop management strategies.

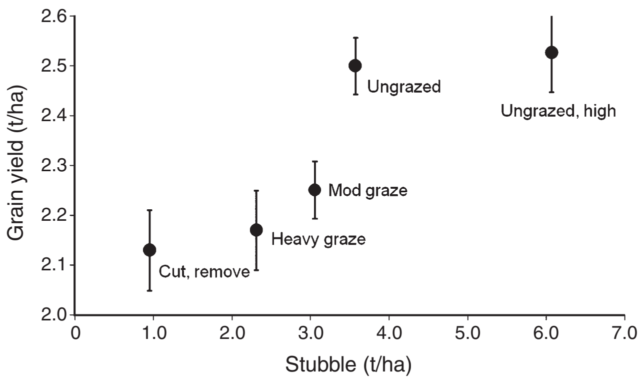

Fig. 7. Effect of stubble removal and grazing on residual stubble load and yield of wheat at Condobolin in central west New South Wales (data courtesy Neil Fettell, NSW DPI). Yield was similar for removal or grazed stubble and did not respond to increased stubble load from 3.5 to 6 t/ha.

Early sowing with slower maturing wheat

A benefit of good summer fallow management that has not been addressed in previous experiments is that it allows crops to be planted earlier and on more marginal rainfall events without risk of crop failure (Fischer and Armstrong 1990; Fischer *et al.* 1990). Storing soil water through better fallow management and early sowing are practices that complement each other to increase yield and WUE more than when either is practised alone (Kirkegaard and Hunt 2010). The potential to increase yield and WUE using earlier sown wheat following good fallow management was investigated in a series of experiments with three regional groups within the Initiative (FarmLink, CWFS and Southern Farming Systems (SFS)) (Hunt *et al.* 2012). Optimising yield of early-sown crops relies on first achieving an optimum flowering date to minimise frost and heat risk, because the development pattern under earlier sowing will be altered. This requires wheats of slower maturity as sowing date moves earlier. An attendant risk of early-sown, slower maturing wheat is excessive pre-anthesis biomass accumulation leading to rapid water depletion and low harvest index. Consequently, modified agronomic management including reduced plant density and deferred N application is necessary, along with attention to different disease and weed risks. The results in Table 8 show the success of this approach at Temora, in southern NSW. Grain yield of the early-sown, later maturing wheat managed for high harvest index was increased by 0.9 t/ha compared with current practice. Detailed measurements at the site revealed that a combination of deeper roots and increased subsoil water extraction, reduced evaporation, higher transpiration efficiencies and a longer spike development phase combined to generate the yield increase (Hunt *et al.* 2012). Across the three experimental sites, increases in WUE of 21–33% were achieved using this strategy.

At the whole-farm scale, introducing slow-maturing wheat into the sowing program, which allows earlier sowing, further increases whole-farm wheat yield, because an earlier opening to the sowing window means that all paddocks can be sown earlier, optimising flowering time. A simulation study comparing a sowing program that includes an earlier start to sowing (from early-April) using a slow-maturing variety with the current practice of sowing only mid–fast-maturing spring wheat cultivars from early-May suggests that whole-farm wheat yield can be increased by 9–17% depending on the region considered (Table 9). This study, along with others, suggested that significant sowing opportunities occur in most seasons for slow-maturing types in most areas (Moore 2009; van Rees *et al.* 2014). The combination of break crops, good summer fallow management and early-sown, slow-maturing wheat appears to hold great promise for substantial improvements in productivity and WUE across much of southern Australia.

Table 8. Increase in yield achieved with early-sown, slower maturing wheat varieties (e.g. Eaglehawk) compared with district practice of later sown, faster maturing spring varieties (e.g. Lincoln) (from Hunt *et al.* 2012)

Grain yield (t/ha)	40 plants/m^2	100 plants/m^2
EGA Eaglehawk (15 April)	6.5	6.1
Bolac (27 April)	6.0	5.8
EGA Gregory (9 May)	5.2	5.6
Lincoln (19 May)	5.0	5.6
P-value	0.007	
l.s.d. ($P = 0.05$)	0.5	

In high-rainfall zones where very slow-maturing winter wheat has a high yield potential (Acuña *et al.* 2011) and can also be grazed during the winter, early sowing increases the risk of viral diseases such as barley yellow dwarf virus (BYDV) as a consequence of higher aphid vector activity during the warm late summer and early autumn. Protecting early-sown crops from such disease is a critical part of the agronomy required for early sowing, and was investigated at several high-rainfall sites by the MacKillop Farm Management Group. The results demonstrated the significant yield improvements that can be achieved with aphid control using seed-dressing or foliar spray in susceptible varieties (Table 10). Yield loss was related to summer rainfall, with <5% yield loss when December–May rainfall was <100 mm but with losses increasing by 10% for every 50 mm of summer rainfall >100 mm.

The potential for on-farm adoption of early sowing of slow-maturing varieties is high, and modelling with ADOPT (Kuehne *et al.* 2013) indicates that 74% adoption within 8 years is reasonable given low investment costs and reversibility (Pannell *et al.* 2006). Adoption of early-sown, slow-maturing varieties has been rapid in southern NSW where suitable, slow-maturing varieties are available, and leading farmers who have adopted the practice have reported yield increases of up to 1.0 t/ha (Mr C Kingston, Mr B Haskins, Mr T Lehmann, Mr S Day, Ms H Gooden, Mr C Clemson, Mr P Gardoll, Mr W Nightingale, pers. comms 2012–13), consistent with those achieved experimentally and through simulation.

Row spacing

There was significant interest among groups in the effects of the trend towards wider row spacing as growers seek operational advantages of speed and stubble handing in no-till, stubble-retained systems. A preliminary review on the effects of row spacing during the initial stages of the Initiative (recently updated and published by Scott *et al.* 2013*b*) suggested yield decreases as

Table 9. Summary of APSIM whole-farm analysis showing the average change in whole-farm wheat yield (1956–2012) by adopting a strategy of using slower maturing wheat varieties in an earlier sowing window relative to mid–fast varieties sown in a conventional sowing window

The farm consisted of 20 fields sown one day apart in each year. Early sowing window opened 1 April, with the slow variety sown where sowing opportunity arises based on seedbed moisture, changing to mid–fast variety on the day shown. Percentage of slow variety sown across the farm and average anthesis dates is also shown. Values are reported for three locations where experiments were conducted during the Initiative

Location	Av. yield conventional start (mid–fast variety only) (t/ha)	Av. yield early start (slow variety followed by mid–fast variety) (t/ha)	Av. yield benefit (t/ha)	% Yield benefit	% Years slow variety sown	% Crops sown with slow variety	Av. anthesis date conventional start	Av. anthesis date of early start	Date of change from slow to mid–fast variety
Condobolin	2.2	2.4	0.2	9%	88%	78%	24 Sept.	28 Sept.	5 May
Temora	3.6	4.3	0.7	17%	91%	84%	6 Oct.	5 Oct.	5 May
Lake Bolac	4.3	5.2	0.9	17%	100%	100%	21 Oct.	9 Oct.	20 May

Table 10. Effect of reduced *Barley yellow dwarf virus* (BYDV) infection achieved by aphid control in a susceptible (cv. Brennan) and a BYDV-resistant wheat cultivar (cv. Mackellar) on the grain yield (t/ha) of early-sown wheat at Conmurra in South Australia (data courtesy MacKillop Farm Management Group 2010 and 2011 Trial Results Books)

Yield benefits in susceptible varieties averaged around 1 t/ha, but could be up to 2.5 t/ha

Variety	2010		2011	
	No control	BYDV control	No control	BYDV control
Brennan	6.3	7.2	6.5	7.3
Mackellar	7.3	7.6	7.9	8.1

rows were widened from 180 mm at yield levels >3 t/ha. A 3-year study by the Riverine Plains group in southern NSW and northern Victoria measured yield at row spacings of 225, 300 and 375 mm in a canola–wheat–wheat crop sequence from 2009 to 2011. The results showed a 3–6% yield penalty moving from 225-mm to 300-mm rows and 10–13% yield penalty moving from 225-mm to 375-mm rows. Yield suffered at wider row spacing because of lower WUE, with an increase of 14% in unproductive water loss (presumably evaporation between rows). This was consistent with the findings of Sprigg *et al*. (2014, this issue) in the eastern wheatbelt of WA. The yield penalties from wide rows need to be balanced against the operational benefits of faster sowing, decreased fuel use, greater herbicide safety, stubble clearance, inter-row sowing and reduced capital costs through fewer opener assemblies.

Theme 4. Managing constrained and variable soils

The Australian grain-growing region comprises large areas with variable or constrained soils where numerous physical and chemical constraints can limit the depth of rooting and the availability of water and nutrients to crops (Adcock *et al*. 2007). Some soil constraints such as surface sodicity, acidity or soil compaction can be ameliorated (lime, gypsum, ripping), and the cost-effectiveness of this drives wider adoption. In other cases, intractable soil constraints such as shallow soils, or subsoil salinity, sodicity or boron toxicity, cannot be easily treated and management involves adjusting inputs according to the lower yield potential of these soils to optimise profitability. In the Mallee of Victoria and South Australia, where these constraints are variable across the dune–swale landscape, the application of precision agriculture (PA) principles in zone management can be appropriate. Several groups within the Initiative investigated the impacts of amelioration and management of constrained or variable soils as a strategy to improve WUE, and selected outcomes are presented here.

Subsoil amelioration

Deep manuring. In the high-rainfall zone of southern Australia, subsoil constraints have been identified as a major limitation to crop production. The heavy clay Sodosols in the area have dense sodic subsoils that limit water and root penetration, generating significant yield loss through winter waterlogging. The SFS group, based in southern Victoria, pioneered the use of raised-bed cropping in the region, which transformed areas of low-value, waterlogged pastures to highly productive cropland during the 1990s (MacEwan *et al*. 1992). However, yields remain well below the water-limited potential, and there is much land unsuitable for beds because of insufficient slope. Collaborative studies with Department of Primary Industries Victoria and La Trobe University in 2006 and 2007 demonstrated significant yield increases from subsoil manuring (the placement of organic amendments such as animal manure or lucerne pellets into the subsoil) (Gill *et al*. 2012). Yield increases of >50% were achieved in wheat and canola crops as a result of improved capture, storage and access of subsoil water and nutrients by crop roots, and an apparent deepening of the soil profile explored by roots as a result of deep organic placement. SFS decided to pursue this technique further within the WUE Initiative to test it at a wider range of sites, and to record the persistence of the responses, which was important to cover the high cost of the amendment (~$1000/ha). At three sites in 2009, similarly high yield increases in cereals were achieved (65–100% yield increases; from ~5 to 10 t/ha); subsequent studies in 2011 and 2012 provided reduced responses and similar effects were achieved with incorporation of nutrients and stubble using a mouldboard plough. Consistent yield benefits remain to be verified in larger plot studies, and the practicalities of sourcing and deep placement of the amendments at commercial rates and scales remain a challenge. However, the GRDC has invested in the further development of commercial machinery capable of achieving that goal.

Gypsum. In Western Australia's South Coast region, surface and subsurface sodicity is prevalent, resulting in poor drainage, surface sealing and transient waterlogging (Lu *et al*. 2004). Researchers from Department of Agriculture and Food WA and Precision Agronomics Australia joined with South East Premium Wheat Growers Association (SEPWA) to investigate the potential for gypsum application on responsive soils to improve productivity and WUE. Gypsum reduces clay dispersion, which improves soil structure and drainage, reduces waterlogging, and can assist to leach salinity and boron deeper into the soil profile. Increased soil-water storage and deeper roots can generate significant improvements in yield and WUE. Yield maps were used to identify underperforming paddocks and electromagnetic (EM) surveys and soil testing were used to identify soils likely to be responsive to gypsum due to high levels of sodicity (Lemon *et al*. 2012). The team found that at responsive sites (e.g. Ravensthorpe and N Stirlings, Table 11), yield improvements of 38–133% were achievable and yield improvements could persist for several years after gypsum application. WUE was improved from 11 to 16 kg/ha.mm, representing an increase from 56% of yield potential to ~80%. At other sites (e.g. Scaddan and Jacup), the crops were not responsive to gypsum, but were often yielding closer to water-limited potential (Lemon *et al*. 2012). Accounting for the cost of gypsum, the highest return on investment was achieved on responsive soils at ~5 t/ha applied gypsum.

N management on variable soils—matching N supply to soil type

The Mallee region of southern Australia is characterised by a dune–swale system, comprising deep sandy dunes of low organic matter and N fertility, mid-slopes of low fertility sand over clay, and swales comprising higher organic matter and fertility but with shallow subsoil constraints (e.g. impenetrable layers, high salt and/or boron levels). The plant-available water capacity of soils on a dune–swale system in the Mallee can vary from 30 to 120 mm, reflecting variation in soil texture and constraints to crop water extraction over relatively short distances. Variable-rate fertiliser applications can be used to manage this variation, although it was not common practice when the Initiative commenced. Highly variable soils coupled with variable rainfall has generated a cautious approach to cropping in the area because the risk of losing money invested in inputs such as N fertiliser is high. As a result, fixed, low rates of N applied to cereals across all soil types (~15 kg N/ha) was district practice at the commencement of the Initiative. However, N deficiency on the sandy dune soils generates major yield gaps in wet seasons, and poor crop performance in swale soils in dry seasons causes N to accumulate beyond

Table 11. Yield responses in crop sequences following a single application of gypsum (5 t/ha) at gypsum-responsive and unresponsive sites on the south coast of Western Australia (from Lemon *et al*. 2012)
Significant responses to gypsum are shown in bold

Sites	Responsive sites		Unresponsive sites	
	Ravensthorpe	N Stirlings	Scaddan	Jacup
Gypsum application year:	2008	2009	2007	2010
2011 Control yield (t/ha) + gypsum response (%)	Wheat 2.4 n.s.	Barley 2.8 n.s.	Wheat 4.4 n.s.	Wheat 2.2 n.s.
2010 Control yield (t/ha) + gypsum response (%)	**Wheat** **1.3** **72%**	**Barley** **0.6** **40%**	**Canola** **1.2** **–12%**	Wheat 2.3 n.s.
2009 Control yield (t/ha) + gypsum response (%)	**Field peas** **0.4** **133%**	**Barley** **1.8** **38%**	Barley 3.6 n.s.	
2008 Control yield (t/ha) + gypsum response (%)	Barley 2.3 n.s.	– – –	Wheat 3.6 n.s.	

crop needs (Sadras 2002; Sadras and Roget 2004). In collaboration with CSIRO, the Mallee Sustainable Farming (MSF) group investigated the effect of matching N inputs to soil type by shifting N inputs from the heavier soils to the sandy dunes. Three years of field experiments were combined with bio-economic modelling to investigate the impacts of tailored management on productivity, WUE, profitability and risk (McBeath *et al*. 2012; Monjardino *et al*. 2013). The results suggested that district practice of 15 kg N/ha applied across the field generated a $30/ha loss on dune, a $7/ha net return on mid-slope, and a higher $66/ha net return on the swale (Table 12). However, the net return from dunes could be maximised at $136/ha by increasing N to 60 kg/ha, and the mid-slope at 30 kg N/ha, whereas current practice of 15 kg/ha gave best returns on the swale. Accounting for the risk aversion of growers, and assuming an N budget of 15 kg/ha, growers would be better off applying more N to the dune and less to the swale to optimise outcomes. The potential cost associated with this change in management was an increase in the standard deviation by $85/ha and the mean of losses in the worst 10% of years increasing by $16/ha.

The WUE on the dune soils could be increased by up to 91% by increasing the level of N applied (Fig. 8). In addition, the research provides avenues for improvement in resource use efficiency, as the results demonstrate that district practice fertiliser application can result in parts of the paddock (clay loam swale soils) being over-fertilised with no WUE gain. Reduced fertiliser input in these parts of the paddock can in part offset the increased costs of increased N inputs in the sandy parts of the paddock.

Surveys conducted as part of the Initiative showed that adoption of zone-specific N management rose by 32% and 40% between 2008 and 2012 in the South Australian and Victorian Mallee and that 56% and 75% of growers in the South Australian and Victorian Mallee, respectively, were using the technology in 2012 (GRDC 2010, 2012). This was similar to the Upper Eyre Peninsula (67% adoption) but was around double that in other areas in the Initiative with less variable soils (Wimmera and central NSW, 33% and 42% adoption in 2012).

Table 12. Pairwise comparisons of yield differences (t/ha) and standard error of difference (SED) between district practice (15 kg N/ha) and high fertiliser at sowing (40 kg N/ha) (2010–12) along a 150-m swale (clay loam) to dune (sand) system covering a transition of four soil types

Treatments where yield was significantly increased with the higher N are shaded grey. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

Soil	2010	2011	2012
Clay loam	–0.37 (0.21)	0.00 (0.16)	–0.08 (0.13)
Clay loam	0.36 (0.32)	0.27 (0.22)	0.13 (0.29)
Clay loam	0.25 (0.24)	0.01 (0.21)	0.27 (0.19)
Sand over clay	0.26 (0.27)	0.10 (0.16)	0.33 (0.15)*
Sand over clay	0.12 (0.24)	0.77 (0.18)***	0.66 (0.16)***
Deep sand over clay	0.59 (0.20)**	1.02 (0.12)***	0.37 (0.14)**
Sand	0.62 (0.16)**	1.15 (0.14)***	0.53 (0.12)***
Sand	0.55 (0.20)*	1.03 (0.25)***	0.66 (0.16)***
Sand	0.42 (0.12)**	0.83 (0.26)**	0.45 (0.11)***

Managing paddock variability across a whole-farm

Soil characteristics vary between as well as within paddocks, providing scope to target inputs and better management to those paddocks likely to be most responsive to amelioration or increased inputs. CSIRO worked with case-study farms in Western Australia to characterise the yield potential of all paddocks across a 4000-ha, low-rainfall cropping enterprise (Oliver and Robertson 2013). Soil-testing records, farm rainfall and yield data, combined with knowledge of specific paddock history, were combined to determine which soils were underperforming in terms of potential yield and the reasons why. The yield, rainfall and positional data from 32 paddocks were collected during harvest from 2004 to 2009, and the actual yields were compared with potential yield calculated from soil, climate and management data. This benchmarking approach revealed that across normal seasons, only 10–30% of the farm was performing near potential, whereas 40–50% was performing at <50% of potential. Soil maps prepared by the growers, combined with additional soil testing, revealed that the low-performing areas had gravel, loamy earth and shallow sandy duplex soils, which comprised 20% (900 ha) of the farm. Many had intractable soil constraints, whereas some with acid sandy soils were responsive to lime. The work concluded that there was significant potential to realistically and reliably improve grain yield on around one-quarter (1000 ha) of the farm.

Summary and conclusions

At its commencement, the WUE Initiative was set a clear objective of achieving a 10% increase in the WUE of grain-cropping systems. We have outlined how the diverse set of

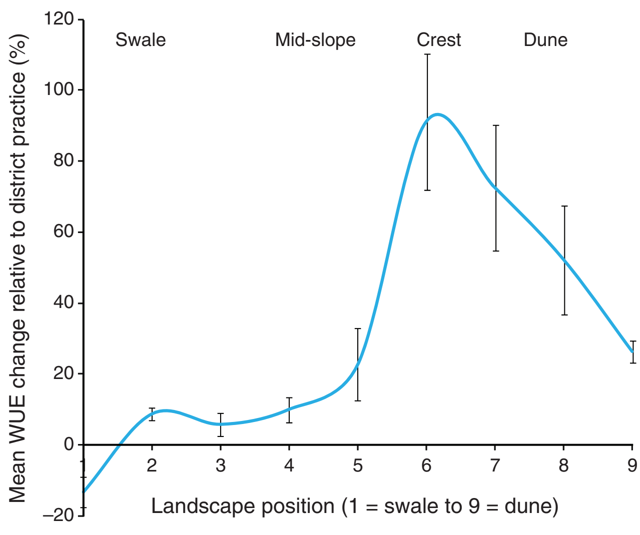

Fig. 8. Increase in water-use efficiency (WUE) resulting from addition of 40 kg N/ha at sowing as percentage change from district practice of 15 kg N/ha at sowing across variable soils in a dune–swale landscape at Karoonda in the South Australian Mallee. The largest response occurred on sandy dune soils where additional nitrogen increased yield and WUE by up to 90%, whereas in the swale, the yield was unresponsive to additional N. Data have been smoothed statistically using a moving average to transition the response across the landscape (adapted from McBeath *et al*. 2012)

interventions across 16 projects was organised into integrated themes and have outlined specific outcomes within each theme to achieve that goal. A summary of the measured impacts of the interventions on WUE, and available evidence at the time of writing for immediate adoption, are compiled as an overview in Table 13. In most cases, the improvement in WUE demonstrated experimentally for several management interventions significantly exceeded the 10% level sought, and in some cases adoption had commenced during the Initiative. An independent, *ex post* economic analysis by Agtrans Research commissioned by the GRDC encompassing 13 of the 16 projects has estimated a benefit : cost ratio of 3.7 : 1 (over 30 years using a 5% discount rate) and an internal rate of return of 18.5% (Chudleigh 2014). The scientific legacy of the Initiative is found in the numerous peer-reviewed publications from the work (>10 at time of writing) and the large set of ideas for further improvement to cropping systems that have attracted ongoing funding for Research, Development and Extension (Table 13).

Finally, several aspects of the Initiative were important in achieving more than could have been done by separately funded projects operating individually; for the benefit of those considering similar future initiatives these include:

(1) *Targeting the outcome rather than the discipline.* Use of increases in WUE as the goal allowed those tendering to the Initiative to consider the broadest possible range of interventions without pre-empting what regional growers and researchers considered important for productivity improvements. Unlike a 'Subsoil Constraint Initiative' or a 'Soil Biology Initiative', where the problem is defined in the title, targeting WUE opened the possibility for participants to nominate a range of different approaches considered most likely to have impact.
(2) *Using regional grower groups as a vehicle*. The GRDC deliberately used the existing network of regional grower groups as targets for the investment but encouraged collaboration with science agencies to develop the research ideas as part of the initial tender conditions. These collaborations built on networks of existing relationships, to ensure that relevant research with rapid pathways to adoption through the group networks were combined with scientific rigour.
(3) *The national coordination role*. A coordinating team of scientists embedded within several of the regional projects in most states provided a direct communication pathway both within and across the Initiative. The farming systems agronomy, crop simulation and modelling capability within the team proved of enormous value during the initiative to extrapolate across sites and seasons and to assist in scaling up to the farm level. The farming systems agronomist 'champion' appointed to the Initiative provided a constant

Table 13. Summary of the increases in water-use efficiency (WUE) achieved experimentally using a range of management interventions within four Theme areas, evidence for impact and adoption of the interventions, and new research within the grains industry arising from the Initiative

Theme	Innovation	Group/s	WUE increase	Evidence for adoption and impact	New research
1	Break crops	MSFS, BCG	16 to 83%	Increase in break-crop area since 2009	GRDC Crop Sequencing Initiative (2011–16)
2	Summer weed control	CWFS, BCG, Upper North	60%	Widespread consultant adoption and promotion	GRDC Stubble Initiative (2013–18)
3	Early sowing	CWFS, FarmLink, SFS	21–33%	Increasing consultant promotion, on-farm adoption and breeding company varietal development	GRDC Early Sowing project (2013–16)
	Wider rows	RPI	–6 to 13%	Increased grower awareness of yield impacts of wider rows	GRDC Stubble Initiative (2013–18)
	Irrigation timing	TIAR	12–23%		GRDC HRZ and Irrigated Cropping Initiatives
	Disease control	SFS, MFMG	20–25%	Adoption of insecticidal seed dressings	GRDC Early Sowing project (2013–16)
4	Variable rate N	MSFS	Up to 91%	Consultants in the Mallee using N recommendations 56 to 75% increase in PA adoption since 2009	GRDC Stubble Initiative (2013–18)
	Responsive systems	EP	22%		
	Gypsum application	SEPWA	15–54%	Gypsum extraction and sales increased from 2010 -2012 contrary to lower farm returns.	GRDC Subsoil constraints – understanding and management (2014–19)
	Subsoil manuring	SFS	28%	Construction of equipment for paddock scale application by local farmers	GRDC Deep-manuring equipment design GRDC HRZ Initiative
	Mouldboard/spade	MFMG, SFS, WA Sandplains	20–80%		GRDC HRZ Initiative GRDC Subsoil constraints—understanding and management (2014–19)

point of contact, accessible and visible by frequent visits to the regional areas.

(4) *The conceptual framework and consistent approach to WUE*. Organising the 16 diverse projects into the four themes and using a consistent WUE-benchmarking approach (Hunt and Kirkegaard 2012) were important initial steps to encourage engagement across the Initiative. The themes and the interactions between them provided the 'mental map' for the individual groups to feel part of the wider Initiative while remaining focused on the specific piece of the story that they selected for investigation. The pre-Initiative simulation predicting the important interactions of pre- and in-crop management was validated with experimental data during the course of the initiative, providing powerful, consistent and reinforced messages that were locally relevant.

(5) *Five-year duration*. The 5-year duration of the Initiative allowed for the thorough testing of farming systems issues across a wide range of sites and seasons (e.g. summer fallow weed and stubble management) to provide consensus regarding the recommendations that emerged. Longer term responses to management, such as inclusion of break-crops or the impact of sheep grazing on soils, could also be investigated for sufficient time to adequately resolve the issues scientifically and provide convincing paddock-scale validation through grower and advisor networks associated with the Initiative.

(6) *Annual workshops*. The annual workshops provided a regular forum that moved around the regions. They encouraged a sense of belonging and involvement, created an expectation that progress would be reviewed by participant's peers, and created opportunities for genuine interaction, collaboration and debate. Although different groups were able to focus on specific interventions, they were exposed to a much broader range of other approaches from across the initiative, which deepened the mutual understanding among scientists and growers of the important interactions outlined in Fig. 3.

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