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Ground cover, erosion risk and production implications of targeted management practices in Australian mixed farming systems: Lessons from the Grain and Graze program

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ABSTRACT

Maintaining the productive capacity of the agricultural soils of Australia's broadacre cropping zone requires careful management, given a highly variable climate and soils that are susceptible to degradation. Mixed crop-livestock farming systems are the predominant land use across these regions and managers must operate farms for long-term sustainability as well as shorter-term profitability. Achieving profitable and sustainable businesses has required ongoing innovation and productivity gains, of which the integration of crop and livestock enterprises has been an important part. Production-soil erosion trade-offs associated with enterprise integration is critical information that has not been investigated to date at a whole-farm level. The objective of this study was to systematically evaluate management options developed in Grain and Graze (an integrated program of research, development and extension targeting mixed farms) to identify farm systems responses to soil erosion risks across seven regions spanning the mixed-farming area of Australia. To evaluate production-soil erosion trade-offs, we linked the APSIM soil water, soil nutrient cycling, annual crop and surface residue simulation models to the GRAZPLAN pasture and ruminant simulation models, using the AusFarm modelling software. Our results demonstrate that the management options tested in Grain and Graze support the principles of conservation agriculture and inform the sustainable intensification of mixed farming systems. Across the regions considered we found that: (1) Increasing pasture legume content and soil fertility can consistently benefit farm production and environmental indicators, (2) management interventions that target direct management of ground cover have the greatest potential to reduce soil erosion rates, (3) management during critical periods of naturally high soil erodibility and wind/water erosivity can substantially increase or decrease erosion risk; the timing of management interventions is therefore critical, and (4) grazing management to balance use of crop residues and pasture biomass is required to avoid developing hot spots of erosion and soil degradation.

1. Introduction

Managing soil erosion is critical to meet the demands of agricultural production and ensure long-term global food security (Lal, 2001; Webb et al., 2017). The need to maintain healthy and productive soils is superimposed on the challenges of adapting agriculture to climate change and meeting consumer demands for food and fibre in systems that have often experienced some level of historical soil degradation (Moore and Ghahramani, 2013; Peterson and Snapp, 2015). Solutions require land management practices and systems that carefully balance soil conservation and agricultural production outcomes (Rockström et al., 2017). However, balancing production goals with efforts to conserve soils and maintain or improve soil health is often challenging for land managers. Social and economic barriers can slow adoption rates of soil conservation practices, leaving producers highly exposed to climate variability and market forces (Pannell et al., 2006; Marshall et al., 2014). While the basic tenants of sustainable agriculture have been known for many years, integrating this knowledge into the management of mixed (crop-livestock) farming systems remains a major obstacle to resilience building in agricultural systems (Hansen, 1996; Giller et al., 1997; Franzluebbers et al., 2014). Analysing the production and soil conservation trade-offs in integrated farming systems is critical to understand the possible barriers for adoption of soil conservation practices and potential for integrated crop-livestock practices to

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sustainably intensify agriculture (Sanderson et al., 2013; Cowie et al., 2018).

Wind and water erosion are key causes of soil degradation in agricultural lands (Van Pelt et al., 2017). The processes result in soil nutrient decline and impact carbon cycling, affecting land productivity (UNEP-IRP, 2016) and production vulnerability to climate variability and change (Reed and Stringer, 2016). Farm land use and management practices typically affect the disturbance and surface cover of soils and hence their resistance to wind and water erosion (Koch et al., 2015; Pierre et al., 2017). In mixed farming systems where both crop and livestock production are important, current management factors that influence provision of surface cover and potential soil erosion are the selection of crop and pasture types, soil fertility, crop residue management (e.g. grazing, harvesting practice), cultivation practices and grazing management (Ewing and Flugge, 2004; Freebairn and Silburn, 2004; Kirkegaard et al., 2014). Enterprise diversification and increasing land use intensity has enabled productivity gains, however the design and evolution of modern farming systems has also contributed to soil erosion (Chappell and Baldock, 2016) and changes in soil fertility (Liebig et al., 2017). The costs to farming systems have been significant (Robertson et al., 2009; ELD Initiative, 2015). Diversified rotations that include break crops (secondary crops used to break disease cycles and increase diversity within crop rotations, e.g. legumes or oilseeds) often produce lower and more readily degradable biomass in these paddocks compared with cereal crops. As a result, soils of break crop paddocks can be more susceptible to wind and water erosion during the dry season (McPhee and Muehlbauer, 1999; Krupinsky et al., 2007). Similarly, grazing livestock on crop residues over summer may further reduce vegetation cover and break up the soil surface, increasing soil susceptibility to wind erosion (van Gool et al., 2008). Management options that effectively balance the production benefits of mixed farming systems with negative trade-offs to ecosystem services must be identified and tested (e.g., Bonaudo et al., 2014; Lemaire et al., 2014).

In Australia, a series of research, development and extension programs have been examining the opportunity to improve both production and soil management in crop-livestock systems (Hacker et al., 2009; Bell et al., 2014). In particular, 'Grain and Graze' has been a national program spanning Australia's crop-livestock regions which has involved participatory evaluation of farming systems innovations aimed at improving the profitability and resilience of mixed farming businesses. Issues that have been targeted have included grazing immature or dual-purpose crops (Dove and McMullen, 2009; Bell et al., 2015), pasture cropping (Millar and Badgery, 2009; Lawes et al., 2014; Thomas et al., 2014), ground cover management (Lilley and Moore, 2009), and changes to the combination and integration of enterprises (Robertson et al., 2009; Bell and Moore, 2012). Similarly, the potential to sustainably intensify crop-livestock systems has been increasingly examined in North and South America (e.g., Liebig et al., 2012; Kunrath et al., 2014), Europe (e.g., Peyraud et al., 2014) and Africa (e.g., Thornton and Herrero, 2015). However, the impacts of changes in crop-livestock systems on soil erosion, ground cover, and other ecosystem services in agricultural landscapes over the long-term have been rarely examined. This is a challenging problem as there are a range of interactions between the crop and livestock enterprises that occur at the whole farm level and these are greatly influenced by the climatic and edaphic conditions. Climatic variability is particularly important in Australia where risks for erosion are likely to be exacerbated under drier than normal conditions; hence evaluating the resilience of systems to these climate shocks is critical for sustainable intensification of Australian agriculture (Revell et al., 2012; Allan et al., 2016; Hochman et al., 2017), but requires long-term analyses.

The objective of this study was to identify key trends, responses and thresholds in agricultural production and soil erosion metrics in response to a range of changes to crop-livestock systems that were investigated in the Grain and Graze program across Australia. The agricultural system processes of interest in this study – especially soil erosion – depend on the frequency and magnitude of episodic events that are best evaluated over the long term. To evaluate these processes we used biophysical simulation models, parameterised for representative locations and management systems across Australia's mixed crop-livestock farming zone. Scenarios involving proposed management interventions were then simulated in each location to explore the impacts on ground cover, erosion, productivity and other system functions over the whole farm. The modelling approach allowed us to examine to what extent enterprise management can counter episodic erosion events and identify joint environmental and production benefits. As a result, the study has enabled a novel understanding of outcomes for soil conservation in relation to recent opportunities in land management through applying a substantive biophysical modelling framework to farming systems innovations that are currently being developed and applied. The extension of our biophysical analysis to the economic interactions between mixed farming management and erosion risks is a necessary step that is beyond the scope of this paper.

2. Materials and methods

2.1. Integrated farming systems analysis

We have used AusFarm modelling software, linking the Agricultural Production Systems sIMulator (APSIM; McCown et al., 1996) and GRAZPLAN (Donnelly et al., 1997), to investigate the long-term impacts of changes in management practices in the mixed farming agricultural region of southern Australia. The modelling framework has been developed and used extensively to examine mixed farming scenarios of southern Australia, and was the most suitable option to examine a range of biophysical outputs over a long sequence of historical seasons (based on meteorological input data). The biophysical modelling framework is described in detail below, it is run on a daily time step using input weather data files over a period of 50 years. Summary data is generally aggregated and presented as annual mean values. Holzworth et al. (2014) provide a comprehensive review of the model and performance analysis. Here, we parameterised the model to represent mixed farming systems and management practices for regional case studies across southern Australia and informed by local producer knowledge. Lessons learned were expected to be consistent with existing knowledge of the effectiveness of soil conservation practices in crop-livestock systems (e.g., Valbuena et al., 2012; Lemaire et al., 2014), with our simulation approach enabling analysis of regional production and soil erosion responses to farm management practices over the long term.

2.2. Regional case studies

One representative location was selected in each of the 7 Grain and Graze regions across Australia to serve as a case study to examine the outcomes for soil management resulting from various interventions in agricultural practice (Fig. 1). Semi-structured interviews with experienced land managers from each region were used, together with land use and production statistics from the Australian Bureau of Statistics' 2011 Agricultural Census (ABS, 2011), to identify management practices typical of a well-run mixed farm at each location (Table 1). At each location, 1 to 4 soil types typical of the region were included in the description of the physical resources on the farm. At 6 of the 7 locations, patterns of land use were described as a set of fixed land use sequences (or rotations), with a substantial proportion of land (ranging from 36% at Hamilton to 100% at Waikerie) rotated between grain crops and pastures. A seed pool reset for annual pastures was included at the end of cropping sequences to ensure the productivity of pastures was maintained. Reset values were selected to maintain a pasture composition consistent with best practice in mixed farming in each region. This modelling approach substituted for the real-world requirement to renovate ley pastures occasionally to ensure their ongoing productivity, particularly at the conclusion of long cropping sequences

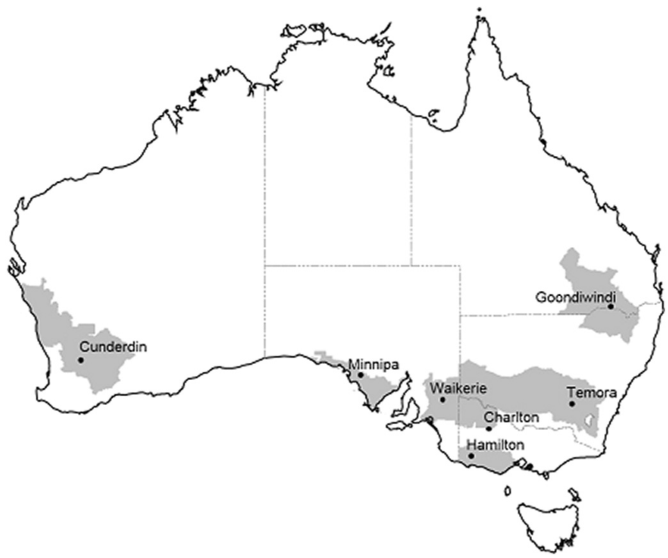

Fig. 1. Map showing the seven regions (greyed area) and main location associated with the Grain and Graze study sites.

or after unfavourable climatic conditions (Revell et al., 2012). For the study locations, the livestock enterprise was modelled as a breeding ewe flock. The exception was the Northern location (Goondiwindi, Queensland), where the simulated farm had separated grain crop and beef cattle enterprises and the cropping paddocks were managed according to an opportunity-cropping system. More detailed information about the soils, land use allocations, crops and crop management, pastures and livestock enterprises in the systems simulated for each region is provided in Table 1.

2.3. Model configuration

For each location, a mixed farming systems model was constructed by linking the APSIM soil water, soil nutrient cycling, annual crop and surface residue simulation models (Keating et al., 2003) to the GRAZPLAN pasture and ruminant simulation models (Donnelly et al., 1997), using the AusFarm modelling software (Moore et al., 2007). APSIM soils were selected from the associated APSoil database based on the regional case studies (https://www.apsim.info/Products/APSoil.aspx). The farm system structure for the Cunderdin location is provided as an example (Fig. 2). In addition to production of crops, pastures and livestock, these models are able to capture the effects of ground cover management on the water balance (including runoff and hence water erosion) and inputs of carbon to the soil. Groundcover is linked to production in the model routines via its effect on water available for germination and transpiration in the soil water balance (simulated by suppression of soil evaporation and reduction in runoff) and via provision of N for plant growth via decomposition of plant residues. Changes in soil organic carbon have no direct impact on processes influenced by soil structure in the model, such as water infiltration.

Patched Point daily weather data (date, maximum and minimum air temperature (°C), rain (mm), solar radiation ($MJ\,m^{-2}$) and vapour pressure (hPa)) for each location were acquired from the SILO database as input to the simulations (www.longpaddock.qld.gov.au/silo). The representative Grain and Graze management systems were described in AusFarm using a module that implements a rule-based language for specifying the management events (Moore et al., 2014). Rules were written to govern the sequence of land uses in each field; crop and pasture management (sowing, fertilisation and harvest); reducing heavy crop residues through burning or tillage; livestock husbandry; and grazing management, including grazing of pastures, growing crops and crop residues. Where fixed rotations were specified, sufficient fields were included in the simulation to ensure that each phase of each rotation was present each year (Fig. 2). The soil humus and soil biomass pools (decomposer organisms) were reset at the start of each pasture or cropping phase to keep soil organic matter near its starting value, so that each modelled year was directly comparable; otherwise the soil water and biomass dynamics in each phase were allowed to determine resource availability in the next phase of each crop-pasture-fallow sequence. All simulations were run at a daily time step over the period 1957–2011; results are reported for the 50 years 1962–2011 in order to remove any effect of the initial conditions of the simulation.

2.4. Key practice changes that influence ground cover

In addition to the “base” scenario derived from local expertise and statistical data, a set of alternative farming systems were modelled in which single changes to management were implemented. Changes to the base scenario with each intervention were the set of practice changes (or “interventions”; Table 2) was drawn from the activities and practice change targets across the regional Grain & Graze projects. Except the changes associated with each intervention, all other aspects of the scenario remained the same.

Because results will be presented in terms of change from the base scenario, it is important to note that for most of the interventions in Table 2, the management practice in the base scenario varies from location to location. For example, the simulations that vary the grazing of stubbles at Goondiwindi introduce this practice, while at Temora or Charlton, they reduce or eliminate the grazing of stubbles.

2.5. Indices of ground cover and erosion risk

Because the loss of ground cover affects erosion in a non-linear fashion, the frequency of days with predicted projective biomass cover below $0.50\,m^2\,m^{-2}$ has been selected as the statistic by which the effects of the various management interventions on ground cover have been evaluated. While it is not ideal to use a single ground cover value to represent erosion risk as a range of other factors need to be considered (e.g. soil texture and the structure [height and spatial distribution] of the ground cover), the 0.50 threshold (50% ground area covered with vegetation and 50% bare soil) is a value commonly used as a guide to cover management and falls within the range of fractional ground cover values that are advisable (e.g. Felton et al., 1987; Leys et al., 2009). As values of the frequency of ground cover below 0.50 are combined for simulations containing multiple paddocks, area-weighted averages are reported.

An index of water erosion risk was computed by evaluating the Modified Universal Soil Loss Equation (MUSLE) estimates produced in APSIM for each paddock and day of each simulation (Littleboy et al., 1992). Slope and slope length factors (S and L) for each location were taken from the spatial data sets of Gallant (2001), and the erodibility constant (K) for each soil type was estimated from the particle size distribution, surface organic carbon content and saturated drainage rate using the equation given by Loch et al. (1998).

An index of wind erosion risk was computed based on the Australian Land Erodibility Model (AUSLEM) of Webb et al. (2009a, 2009b), with the addition of a term accounting for the probability of erosive winds:

$$ER_{wind} = e_{texture} \cdot \exp\left(-\frac{\text{COVER}}{0.107}\right) \bullet \exp\left(-\frac{\theta_1}{0.042}\right) \bullet \int_{\nu=6}^{\infty} f(\nu) \bullet (\nu - 6)^3 \, d\nu$$

where the texture scalar $e_{texture}$ equals 3.0 where surface clay content is < 0.07 and 1.0 otherwise; $COVER$ is the ground cover in $m^2\,m^{-2}$; θ_1 is volumetric water content of the surface soil; and $f(\nu)$ is the probability density function of instantaneous wind speed over the course of the day, fitted as a Weibull distribution with a non-zero probability of zero wind. The inclusion of $f(\nu)$ in AUSLEM is made on the assumption that the empirical ground cover and soil moisture terms of the model

Table 1
Description of the base mixed farming scenarios at 7 locations in the cereal-livestock zone for which various farm management interventions have been modelled.

	Southern NSW Temora	Southern Victoria Hamilton	Queensland Goondiwindi	Western Australia Cunderdin	East SA Waikerie	Eyre Peninsula Minnipa	Northern Victoria Charlton
State	NSW	Vic	Qld	WA	SA	SA	Vic
Location	147°52′E, 34°42′S	142°04′E, 37°39′S	150°20′E, 28°31′S	117°14′E, 31°39′S	139°59′E, 34°11′S	135°09′E, 32°50′S	143°24′E, 36°18′S
Average annual rainfall (mm)	527	647	605	362	268	322	434
Farm area (ha)	1500	1250	2500	4000	2400	2400	1600
Soils							
1	Shallow red Chromosol	Brown Sodosol	Black Vertosol	Gravelly sand	Light loamy sand	Gravelly sandy loam	Sandy clay loam
2	Light red Chromosol	Black Vertosol		Deep sandy duplex	Red Sodosol	Sandy clay loam	Clay loam
3	Heavy red Chromosol	Brown Sodosol		Deep loamy duplex		Sandy loam	
4				Acid yellow sand			
Land use	Sequence Soil %	Sequence Soil %	Sequence Soil %	Sequence Soil %	Sequence Soil %	Sequence Soil %	Sequence Soil %
P = perennial pasture	P 1 10	P 1,2 64	W/S/K/ ∅ 1 30	A 1 20	AWBW 1,2 50	A 1 33	V(C/O)WB 1 30
A = annual pasture †	3AW$_d$CW$_d$BW 2,3 53	3UCW$_d$BCW$_d$B 3 36	O 1 10	AWWW 2 30	AWW 1,2 50	AWB 2 34	2AWBW 1 50
U = lucerne							
∅ = fallow	4UW$_d$CW$_d$BW 3 37		P 1 60	AWB 3 10		AWWB 3 33	3UWBLCW 2 20
(crops below in table)				AWLC 4 40			
	W B C P U A	W B C P U	W S K O P	W B C L A	W B A	W B A	W B O C L U V A
Percentage of land allocated (%)	32 11 11 10 16 20	8 8 8 64 12	–– 30 –– 10 60	36 3 10 10 41	55 15 30	28 19 53	33 20 –8– 3 8 8 20
Frequency of opportunity crops (%)			45 32 31				21 79
Crops							
Cultivars: W Wheat (grain -only)	Gladius		Hartog	Wyalkatchem	Mace	Wyalkatchem	Scout
W$_d$ Wheat (dual-pur.)	Wedgetail	Mackellar		Spear			
B Barley	Hamelin	Gairdner		Gairdner	Hindmarsh	Keel	Hindmarsh
S Sorghum			Buster				
O Oats		Hyola 42	Algerian				Echidna
C Canola	Oscar			Karoo			Clancy
L Lupins				Belara			Belara
K Chickpea			Amethyst				
V Vetch							Paraggio[#]
Sowing windows: Cereal (grain)	W: 1 May-15 Jun W$_d$: 1 Apr-15 May	16 Apr-15 Jun	W:1 May-1 Jul S:16 Sep-16 Dec	W:11 Apr-16 Jul B: 25 Apr-16 Jul	25 Apr-30 Jun	25 Apr-31 Aug	W: 25 Apr-21 May B: 1 May-21 May
Cereal (forage)			16 Mar-1 Jul				1 Jun-30 Jun
Canola	15 Apr-31 May	16 Apr-15 Jun		16 Apr-16 Jul			1 May-31 May
Grain legume			1 May-1 Jul	2 May-16 Jul			16 Apr-30 Jun
Sowing rainfall (mm)	15 - 25	15	15	10	15	20	10
Minimum sowing rainfall days	3	5	5	5	3	3	3
Dry sowing at end of sowing window?	Yes	Yes	Forage oats only	Yes	Yes	Yes	Yes
Sowing fertiliser	Urea	Nitrate	Urea	Urea	Ammonium+urea	Ammonium+urea	Urea
In-crop fertiliser	Urea	Urea	Urea	Urea	Ammonium+urea	Urea	Urea
Fertilizer rates (kg N ha^{-1}):	W W$_d$ B C	W B C	W S O K	W B C L	W B	W B	W B O C L
Sowing	20 20 20 25	50 50 50	50 100 0 0	30 20 40 0	40 30	10-30 30	20 30 30 20 0
In-crop	40-70 55-70 40 90	50 50 70		30 20 40 0		0 or 20 0 or 20	0-60 0-60 0-35 0-60
Pastures							
Species 1	Phalaris	Perennial ryegrass	Gatton panic	Annual ryegrass	Annual medic	Annual medic	Vetch
Species 2	Lucerne	Phalaris	Annual medic	Subterranean clover	Barley grass	Barley grass	Lucerne
Species 3	Subterranean clover	Subterranean clover			Capeweed	Capeweed	Subterranean clover
Species 4	Annual ryegrass	Lucerne					Annual ryegrass
Species 5		Annual ryegrass					
Livestock							
Livestock enterprise	Dual-purpose ewe flock	Ewes for 2[nd]-cross lamb production	Breeding cows	Self-replacing ewe flock	Dual-purpose ewe flock	Dual-purpose ewe flock	Dual-purpose ewe flock
Maternal breed	Medium Merino	Border Leicester x Merino	British x Brahman	Medium Merino	Large Merino	Large Merino	Large Merino
Terminal sire breed	Border Leicester	Dorset	Charolais		Suffolk	Suffolk	Dorset
Stocking rate (DSE winter-grazed ha^{-1})†	9.1	10.2	9.4	4.5	2.0	3.0	5.7
Joining period	1 Feb-14 Mar	8 Feb-21 Mar	16 Dec-15 Mar	1 Feb-14 Mar	16 Nov-14 Jan	1 Dec-11 Jan	1 Mar-11 Apr
Weaning day	19 Oct	26 Oct	21 Jun	19 Oct	15 Aug	25 Aug	15 Nov
Cull age (years)	6	6	9	6	6	6	6
Cull stock sale day	31 Jan	31 Jan	1 Sep	31 Jan	11 Nov	26 Sep	31 Jan
Offspring born per ewe/ cow mated	1.22	1.55	0.92	0.95	0.89	0.83	1.30
Offspring weaned per ewe/ cow mated	0.95	1.23	0.92	0.77	0.81	0.74	0.99
Body condition score for maintenance: Adults	2	2-2½	1½-2	2-2½	2	1½-2	2-2½
Replacements	2-2½	2-2½	1½	2-2½	2	1-1½	2-2½
feeding: Young stock	1½	2	1½	1½	1-1½	1	1½
Maintenance feed	Wheat	Wheat	80:20 sorghum+hay	Barley	70:30 barley+hay	70:30 barley+hay	70:30 barley+lupin
Young stock sale day	1 Dec-1 Apr	1 Dec-25 Apr	3 Aug-31 Jul	1 Dec-30 Jun	2 Sep-31 Dec	1 Nov-25 Apr	1 Dec-1 Mar
Young stock target weight (kg LW)	45-50	n/a	450-500	45	50	50-55	50-55
Grazing of stubbles							
Stubble grazing start	Harvest	Harvest	None	Harvest	Harvest	Harvest	Harvest
Minimum stubble cover	0.70	0.70		0.60	0.65	0.60	0.70
Maximum days on stubble	42	42		150 30	90	90	42
Grazing of wheat crops							
Wheat crops grazed	DP cultivar	All wheat crops	None	None	None	None	None
Threshold mass to start (kg ha^{-1})	1500	1500					
Threshold mass to end *(kg ha^{-1})	500	800					
Cumulative grazing threshold to end	1200 DSE-days	1200 DSE-days					

*Grazing of dual purpose crops is also ended when Zadoks stage 30 is reached. † Winter-grazed areas include grazed crops at Temora & Hamilton.
#Forage medic (Medicago truncatula) model used to represent Vetch.
†Number of years of consecutive annual pasture in the rotation.

hold across the range of measured wind speeds.

Synoptic wind speed data for each location (or a nearby weather station in the case of Waikerie) were obtained from the Bureau of Meteorology and used to estimate the parameters of $f(\nu)$ for each day as a function of the mean daily wind speed. Where necessary, wind speeds at 2 m height were estimated from 10 m height data using the equation of Allen et al. (1998). Composite mean daily wind speed data sets for each location were then assembled from (i) the synoptic data, where at least 6 measurements per day were available; (ii) a regression estimate from 09:00 and 15:00 wind speeds where these were available; and (iii) by quantile-matching to the gridded wind speed data set of McVicar et al. (2008). Owing to limited data availability, at some locations, daily mean wind speed estimates were only available for the years 1974–2011.

Both the wind and water erosion risk indices were aggregated to the farm scale by computing area-weighted averages over all paddocks for each day, and were then normalized so that the total value of the index over all days in the base scenario for each location summed to 1.0 (i.e. they are intended for comparisons within locations only). Proportional changes in wind and water erosion risk from the base scenario are reported.

2.6. Other indices of system function

In addition to soil erosion risk, several other measures of the performance of the agro-ecosystems are also reported as metrics of farm production efficiency and natural resource management. Net farm crude protein production (i.e. grain protein + meat protein + wool protein − supplementary feeding protein) per mm of rain per hectare was calculated as a measure of farm water use efficiency (Thomas et al., 2010). Changes in the relative use of feedbase components (i.e. pastures, crop stubbles, dual-purpose or forage crops and supplementary feed) were determined by calculating annual totals of metabolizable energy intake for each feed component.

3. Results

3.1. Risk of low ground cover

Predicted ground cover levels and the frequency of ground cover falling below 0.50 were influenced by location, land use, season and management. The long-term simulated data suggest that ground cover would regularly fall below the 0.50 threshold in the farming systems we have described. On average, ground cover (farm paddock weighted average) was below 0.50 for > 30 days per year at all locations except Hamilton (Table 3), but highly variable between seasons at all locations (Fig. 3). Levels of ground cover for comparable phases and rotation sequences varied widely by location. At Cunderdin cereal cropping dominant rotations protected soils from low ground cover, compared with annual pastures, with an average number of days each year below 0.50 ground cover of 19 for the AWWW rotation and 69 for continuous annual pasture (A). This was in contrast to little difference between crops and annual pasture at Minnipa, with 87 days per year below 0.50 ground cover for the AWWB rotation and 80 for continuous annual pasture (A). Rotations with break crop (lupins, canola) had more days each year below 0.50 ground cover, while perennial pastures maintained the highest ground cover levels. In the opportunity cropping system at Goondiwindi, which involved long periods of fallow, ground cover levels frequently fell below the 0.50 threshold.

Differences from the baseline scenario in the number of days each year where average farm ground cover fell below 0.50 resulting from each intervention are reported in Table 3. A number of the interventions had a clear effect on year-round ground cover across multiple land use systems and locations. Modification of pasture management by increasing pasture fertility generally reduced days that ground cover was < 0.50, particularly in farming systems with continuous annual pasture paddocks (land use sequence = A). Conversely, the removal of pasture legumes or lowering pasture soil fertility resulted in a marked increase in the number of days where ground cover was < 0.50 across locations, however the size of this effect was quite variable among locations. Increasing stocking rate by 10% from the base scenario resulted in a small increase (several days per year) in the number of days each year when ground cover was < 0.50. Lesson learned 1: That improving the productivity of annual pastures through improved management protected soils through increased ground cover.

Replacing annual crops or pastures on the least productive land with a perennial pasture (pasture modification) had only a small impact on farm cover levels, at the majority of locations. However, at Cunderdin the inclusion of a C4 perennial grass (Gatton panic) on the least productive land type – used for continuous annual pasture – had a major effect, reducing the number of days below the 0.50 ground cover threshold by 53 (from 69 to 16 days per year) for these paddocks and by 10 days year^{-1} on average across the farm (Table 3).

Changing confinement feeding thresholds had consistently large effects on ground cover. Stopping the use of confinement feeding during periods of low paddock biomass and low ground cover increased the number of days per year with low ground cover by as much as 50%, but effects were variable for different regions. For example, excluding any confinement feeding increased the frequency when ground cover was < 0.50 by 25 days per year at Minnipa but only 7 days per year at Waikerie. Increasing confinement feeding at Minnipa reduced the days per year where ground cover was < 0.50 by 15 days, and reductions in the period of low ground cover were also observed at other locations (Table 3).

Burning of stubbles greatly increased the occurrence of low ground cover on farms. This increased days per year where ground cover was < 0.50 by as much as 23 days at Waikerie and Goondiwindi compared with 9 days at Minnipa (note that this represents a reversal, compared with the magnitude of the change from the confinement feeding intervention for Waikerie and Minnipa). Lesson learned 2: Notwithstanding differences between regions, management interventions that directly target ground cover management, such as stubble grazing and burning, will have the largest effects on farm ground cover levels relative to other interventions.

3.2. Wind and water erosion risk

Table 4 shows the modelled relative changes in erosion risk from implementing the ground cover-related management interventions described in Table 2. The largest responses in erosion risk were due to omitting confinement feeding at Temora, Minnipa and to a lesser extent at Hamilton (although it should be noted that the absolute levels of water erosion at Minnipa and wind erosion at Hamilton are predicted to be small). The most consistently large effects on erosion risk were found for changes to stubble burning: not burning stubbles reduced water erosion risk by 16–41% and wind erosion risk (apart from Minnipa) by 16–86%, even though only a small proportion (16–41%) of cropping land was burnt in these simulations and only in the paddocks and years where residue masses were highest. Reducing the area of stubbles grazed by livestock decreased erosion risk at Cunderdin and Minnipa but increased it at Temora. Goondiwindi was exceptional amongst the case study locations, in that the only practice change that substantially altered erosion risks was the burning of stubbles.

The introduction of a C4 perennial grass (Gatton panic) on marginal land at the four lower-rainfall locations had only a modest impact on erosion rates at the farm scale. This result is partly due to dilution in space, since only 20% of farm area was modelled as undergoing land use change; it is also likely to be partly due to production-focussed grazing management rules ensuring high utilization of the perennial grass-based pastures over summer-autumn, especially at Cunderdin and Waikerie. The introduction of dual-purpose cropping at Minnipa resulted in a substantial reduction in the risk of both wind and water erosion. This is a somewhat unexpected result, given the relatively small contribution of dual-purpose crops to the feedbase and farm average ground cover; it suggests that deferment of pastures while wheat crops are grazed can be important in those seasons when there is a high risk of erosion.

Even though this analysis was carried out over 50 years, the erosion risk values are dominated by a relatively small proportion of days. For example, at Minnipa over the 50-year simulation, 50% of the total wind erosion risk occurs within just 6 months of this period, and 90% of the total water erosion risk accrues in only 13 (different) months. This result is not unexpected, since the conditions required for wind and water erosion (in particular the source of erosive energy) differ for these events. This also helps to explain why there are instances where an intervention has increased the estimated wind erosion risk while reducing water erosion risk, or *vice versa* (Table 4). Lesson learned 3: Management interventions coinciding with periods of naturally high soil erodibility and wind/water erosivity may substantially increase or decrease erosion risk.

Table 5 presents estimates of the marginal rates of change of (relative) erosion risks to these practice changes. On average across the sites, the marginal effect of increasing stubble grazing area on both wind and water risk was determined to be 10 times lower, compared with increasing the area of stubble burning (Table 5).

3.3. Farm production

In general, effects of the interventions on crop yields were relatively small (mostly < 5%) (see Supplementary Table S1). However, both the removal of legumes from pastures (negative) and improvement of pastures through increased soil fertility (positive) in the model had carry-over effects on crop yields, presumably due to changes in the production of pasture legumes altering soil nitrogen supply. Consistently, the yield of lupins was not affected in the same way and there was either no change or a small increase in lupin yield when legumes were removed from pastures.

Stubble burning generally resulted in a small decrease in wheat and canola yield, but effects on barley and lupin yields were variable. "Best practice" farm management produced wheat yield increases from 0.5 to 8.0% across the locations, but grazing dual-purpose wheat resulted in a yield penalty ranging from 8% to 25%. Since crop grazing was considered a component of best practice, there was a decrease in the yield of dual-purpose crops for this intervention. The 10% higher stocking rate scenarios also produced a small negative effect on the yield for locations where dual-purpose crops were grown (See Supplementary Table S1). Note that dual-purpose crop grazing was a standard component of the base model for Temora and Hamilton, so the dual-purpose cropping intervention shows results of the exclusion of crops from grazing at these locations.

Interventions that resulted in the largest changes in water use efficiency (WUE), as defined by the percentage change in net farm protein production per unit of rain, were associated with pasture productivity (Table 6). Across all locations the removal of pasture legumes reduced WUE while increased fertility of pastures increased WUE. At Waikerie and Charlton perennial grass modification resulted in a 15% reduction in WUE, which was related to an associated grain yield penalty due to the reduction of area cropped. The decrease in WUE with the dual purpose cropping intervention at Temora and Hamilton was associated with a reduced crop yield.

The metabolisable energy intake by livestock of each of the available feedbase components for each farming system and location is reported in Supplementary Table S2. At the higher rainfall locations, continuous pastures and pastures in rotation phases accounted for > 80% of energy intake by livestock; for the lower rainfall areas crop stubbles, supplementary feeding and dual purpose or forage crops (at Goondiwindi) made up a larger part of the feed supply. The targeted diversification of the feedbase from the Grain and Graze interventions generally improved overall productivity of the farming system, although this was variable across the sites. For the Cunderdin site, implementing the 'best practice' range of interventions resulted in a replacement of 17 percentage units of supplementary feeding with annual and perennial pasture, a clear win-win scenario for erosion risk management and reduced farm costs.

4. Discussion and conclusions

The Australian Grain and Graze program, supported by our farming systems simulation experiments, has provided valuable insights to the potential for balancing agricultural production with soil conservation, while revealing the complexity of meeting the challenge across mixed farming landscapes. Despite this complexity, there was some predictability in the outcomes from interventions in farm practice under consideration. This is highlighted by the consistent improvement in farm ground cover (albeit small in some regions), that could be achieved when the "best practice" combination of interventions was applied. Our results provide four important lessons that inform how production and soil conservation may be achieved. These lessons support established knowledge of soil conservation practices and include: (1) Management interventions that target direct management of cover have the greatest potential to affect soil erosion rates, (2) increasing pasture legume content and adequate soil fertility can consistently benefit farm production and environmental indicators, (3) management interventions coinciding with periods of naturally high soil erodibility and wind/water erosivity can substantially increase or decrease erosion risk; so the timing of management interventions is critical, and (4) careful management of rotational grazing in mixed farming systems is needed to maintain crop stubble and pasture biomass to avoid developing hot spots of erosion and soil degradation.

First, interventions that were associated with both improved pasture productivity and the direct management of cover (e.g. stubble burning and confinement feeding) had the largest effects on the frequency of low ground cover and high erosion risk. This was a consistent result across locations, although the magnitude differed. Location x land use system x intervention interactions were apparent in our study, suggesting that farming systems will have unique challenges in managing ground cover associated with their location (i.e., soil type and fertility, slope, crop/forage species) and climate. Effects of location are expected to intensify under future climate scenarios for southern Australia, with a relatively larger reduction in net primary productivity predicted for lower rainfall agricultural regions (Moore and Ghahramani, 2013). Similar highly variable responses may be expected in rangelands (Webb et al., 2012). For locations with a strongly Mediterranean-like climate (such as Cunderdin) the benefits of carrying ground cover from cereal crops into the summer and autumn had an important role in reducing soil erosion risk. The risk of low ground cover following an annual pasture relative to cereal cropping was high at sites with a Mediterranean-like climate, compared with sites that had more evenly distributed annual rainfall. Changes to stubble grazing management, stocking rates and use of dual-purpose crops had smaller effects on farm ground cover and other indicators of system performance. Our findings suggest that improving net primary production during pasture and break crop phases, and the tactical conservation of ground cover, provide the best opportunities of those considered to reduce erosion risk in mixed

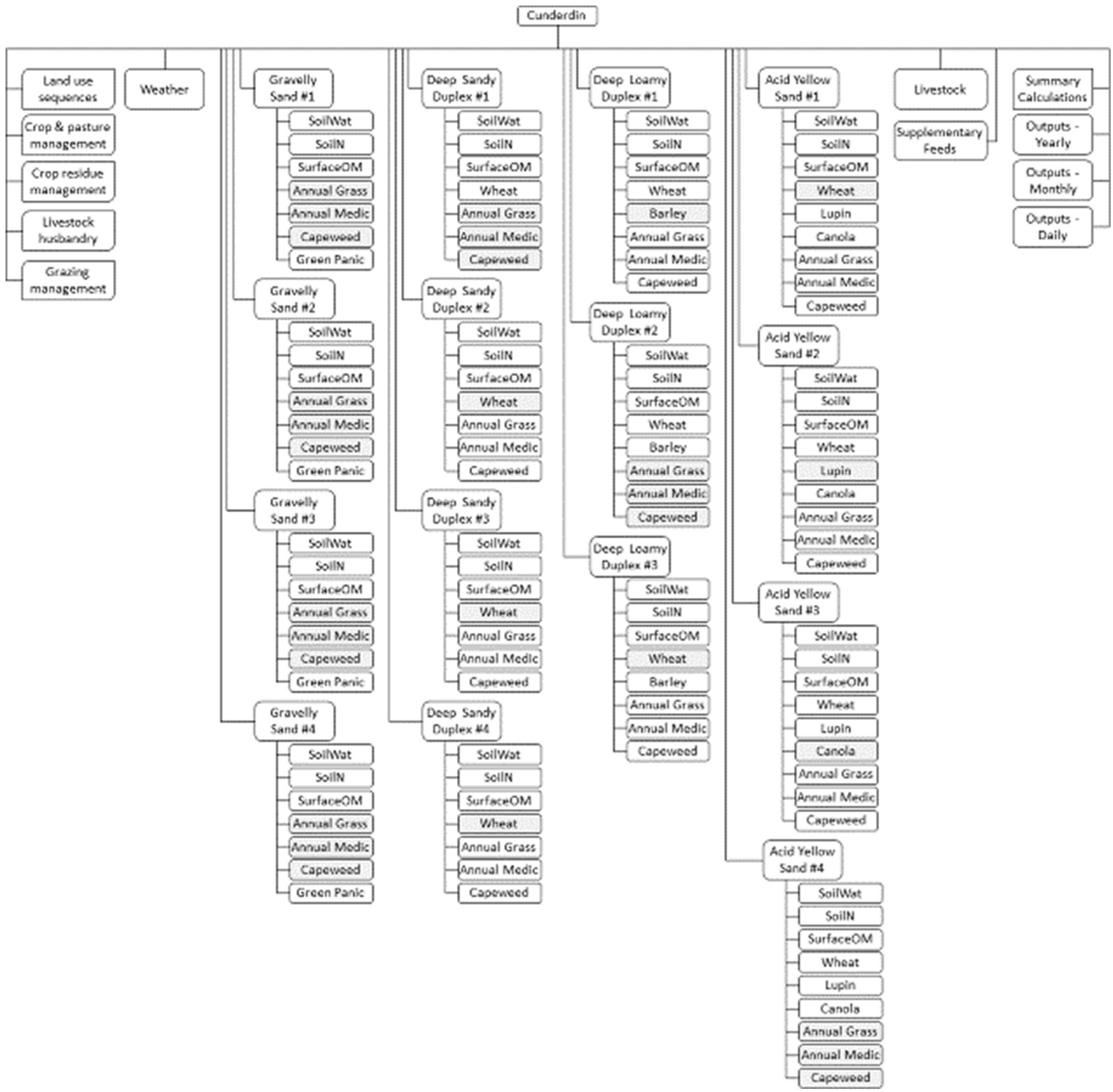

Fig. 2. Farm system structure used in the simulation of one of the Grain and Graze sites (Cunderdin, Western Australia). Modules represented with half-rounded rectangles are rule scripts (Moore et al., 2014). To demonstrate the use of the modules during a simulation, the shaded modules in the diagram show plants that are actively growing at one specific point in time, being immediately after weed control in cropping paddocks.

farming businesses. Conversely, strategic rotations that lower net primary production (such as winter fallowing, where winter pastures are sprayed out to manage crop weeds) would be expected to substantially increase erosion risk, although this scenario was not included in our modelling scenarios.

Second, increasing the productivity of pastures through increased legume content and soil nutrient fertility resulted in clear and consistent benefits to farm production and environmental indicators across the study sites. On a percentage change basis, crop yields were 3% higher and overall farm water use efficiency increased by between 2 and 13 percentage units at the 6 sites under high-intensity pasture management. Wind and water erosion risk indicators were improved for 5 sites, and were mixed at the remaining 2 sites, for high-intensity pasture management. The effects of pasture management on ground cover were due to increased cover in continuous pastures, but also for ley pastures in the cropping rotations. This is consistent with the benefits to crop growth that would have contributed to higher levels of ground cover, thereby reducing erosion risk. It is likely that in this study we have underestimated the scope for improvement in farm productivity associated with pasture improvement because of the relatively high pasture productivity assumed in the base scenarios; in reality, the performance of ley pastures on many farms will be poorer than that simulated. Across southern Australia, pastures in cropping rotations in many regions have become unproductive over time due to an increased focus on crop production with intensive weed management and low fertiliser inputs decreasing the density and quality of

Table 2
Interventions (changes to farm management) that were analysed for their long-term effect on ground cover and erosion risk. For each location, practices used in the base scenario are indicated with an 'X'.

			Location						
Intervention area	Description	Change in practice	Temora	Hamilton	Goondiwindi	Cunderdin	Waikerie	Minnipa	Charlton
Grazing of stubbles	Stock are grazed on crop stubbles beginning immediately after harvest, moving off paddocks according to feed, cover and stock condition thresholds	All stubbles	X	X		X	X	X	X
		Cereal stubbles only							
		No stubble grazing			X				
Changed intensity of pasture management	Low-intensity pastures: annual legumes are removed. Intensive pastures: soil nutrient fertility[*] and the proportion of annual legumes is increased	Low-intensity pastures							
		Standard pastures	X	X	X	X	X	X	X
		High-intensity pastures							
Perennial grasses on marginal land	10–20% of land on the least-productive soil type is sown with a locally-relevant perennial grass, grown in mixture with other species	No perennial grass				X	X	X	X
		C3 perennial grass	X	X					
		C4 perennial grass			X				
Dual-purpose wheat crops	Some or all of the wheat crops are grazed during the winter. A different wheat cultivar with a longer growing season may be employed	No dual purpose crops			X	X	X	X	X
		Dual purpose crops	X	X					
Confinement feeding	Paddocks are closed to grazing when ground cover falls below a threshold. If no paddock remains available for grazing, confine all livestock to a feedlot and feed them to maintain live weight. For the base scenario, the cover threshold is 0.70 at Temora, Hamilton and Charlton; 0.65 at Goondiwindi and Waikerie; and 0.60 at Cunderdin & Minnipa. For less confinement feeding, these thresholds are reduced by 0.10; for more confinement feeding, they are increased by 0.10.	No confinement feeding							
		Less confinement feeding							
		Base scenario	X	X	X	X	X	X	X
		More confinement feeding							
Burning of stubbles	Shortly before the next crop sowing period, stubbles are burnt (80% removal) if their mass exceeds a threshold. Thresholds masses are set so that the long term frequency of burning is approximately 20%	No stubble burning	X	X	X	X	X	X	
		Stubble burning							X
Increased stocking rate	Number of ewes or cows is increased by 10%	Standard stocking rate	X	X	X	X	X	X	X
		Increased stocking rate							
"Best practice"	Combination of all stubbles grazed + intensive pasture management + C3 or C4 perennial grass on marginal land + dual purpose crops + no stubble burning + standard stocking rate	Best practice							

[*] Management of soil nutrient fertility is described by Mokany et al. (2010).

Table 3
Effect of farm management interventions on the frequency of low ground cover (whole-farm weighted average of days below 0.50 $m^2 m^{-2}$ ground cover) in mixed farming systems at 7 locations. The values in the first row are the number of days per year that ground cover falls below 0.50 under the base management scenario. Subsequent rows show changes from the base scenario in the number of days per year that ground cover falls below 0.50.

		Southern NSW	Southern Victoria	Northern	Western Australia	East SA	Eyre Peninsula	Northern Victoria
Intervention area	*Change in practice*	Temora	Hamilton	Goondiwindi	Cunderdin	Waikerie	Minnipa	Charlton
Base scenario		**34**	**3**	**89**	**56**	**66**	**77**	**31**
Stubble grazing	All stubbles			+1				
	Cereal stubbles only	+4	-1	+1	-2	+1	-5	+1
	No stubble grazing	+4	0		+3	-1	-3	0
Pasture management	Lower-intensity pastures	-1	0	+2	+14	+5	+13	+5
	Higher-intensity pastures	-4	0	-2	-7	+1	-16	-3
Perennial pastures on marginal land	No perennial grass	+5	+1	na				
	C_3 perennial grass			na	na	na	na	na
	C_4 perennial grass	na	na		-10	0	+5	-1
DP cropping	No dual purpose crops	+2	0					
	Dual purpose crops			+1	+1	+1	-7	+2
Confinement feeding	No confinement feeding	+16	+2	+11	+16	+7	+25	+8
	Less confinement feeding	+9	0	+5	+8	+4	+3	+5
	More confinement feeding	-6	0	-4	-8	-4	-15	-3
Stubble burning	No stubble burning							-15
	Stubble burning	+19	+5	+23	+11	+23	+9	
Stocking rate	Increased stocking rate	+2	+1	+3	+1	+3	+1	+1
"Best practice"		-10	0	-6	-12	-5	-17	-20

Note: Grey shading of cells indicates the intervention setting selected in the base scenario. na = the intervention is not applicable for this location.

pasture swards (Reeve et al., 2000). The effects on crop and pasture yields are likely to have been exacerbated by degradation due to past wind and water erosion (e.g., Turner et al., 2016). In a recent feedbase audit in Australia, the proportion of pastures considered to be in decline, by state, was as high as 60% (Donald et al., 2012). Increasing pasture productivity and legume content should be carefully considered in mixed farms of Australia to increase productivity and to assist in erosion risk mitigation.

Third, we found that the timing of management interventions is critical to their impact on wind and water erosion. Through the long-term simulation of various farming systems, we were able to quantify the episodic nature of soil erosion events. A majority of estimated wind and water erosion occurred during a relatively small number of 'events' over the course of the 50-year simulation. The episodic nature of erosion processes is generally associated with periods of below-average rainfall and low ground cover (Aubault et al., 2015). A management change in the period immediately before a high-erosion-risk period could therefore substantially affect the overall outcome; the timing of management interventions is critical for their effects on wind and water erosion. This also provides encouragement that management interventions to reduce the rate of soil erosion can avoid a large ongoing financial burden. Strategic destocking has been found to reduce erosion risk by half for a mixed farm on the south-coast of Western Australia, but this practice may be financially unsustainable (Salmon et al., 2002). Increasing perennial species on farm land that is susceptible to erosion can be an effective erosion control measure (e.g. Salmon et al., 2002; Moraine et al., 2016), but farmers may be reluctant to implement this change in dryland farming systems if it reduces the area available for cropping and results in a large decrease in farm water use efficiency (as shown here in our study). Further, in lower rainfall climates with little rain outside the annual growing season, swards of productive perennial grasses may not persist well. For example, the persistence and productivity of Gatton panic grass at Cunderdin is likely over-estimated in our modelling compared with what has been achieved in practice. For farmers seeking to retain existing farm rotations, the opportunity to manage ground cover tactically after a season of below-average rainfall should be considered. Tactical management systems, used for a targeted, small proportion of seasons, have less effect on farm profit. Over time, farmers have adopted new agricultural practices (such as no-till cropping) to mitigate soil erosion (Llewellyn et al., 2012), which have been found to be effective in other cropping systems globally (e.g. Thorne et al., 2003). The irregular and periodic nature of high erosion risk conditions is therefore more likely to catch land managers off guard, so we would suggest a greater focus to identify and implement strategies that will alert managers to risks early and provide effective and economical options to mitigate erosion. There is good potential to develop strategies to prevent wind and water erosion in the study regions because a majority of predicted erosion events occur during a small number of short events over the 50 years that the farming systems were simulated. More generally, our results suggest that management strategies for the sustainable intensification of agriculture should explicitly consider the temporal characteristics of erosion events as influenced by the timing of erosive wind/water events, and the timing of changes in ground cover.

Fourth, our results demonstrated that careful management of rotational grazing in mixed farming systems is needed to maintain crop stubble and pasture biomass to avoid developing hot spots of erosion and soil degradation. By modelling paddock rotation sequences, we compared levels of ground cover under the various cropping and pasture scenarios to be evaluated, and identified strengths and weaknesses of various rotations across the study sites. At Cunderdin, ground cover in annual pastures fell below 0.50 for about 70 days per year longer than for cereal cropping rotations. However, associated higher soil erosion in annual pastures should not necessarily be assumed. Some field studies have found soil loss measured from pastures consistently lower than in cropping rotations, although some of these effects may have been mitigated more recently by changes in cultivation practices (Edwards, 1987; Erskine and Saynor, 1996; Freebairn and Silburn, 2004). It should be noted that the variation in soil disturbance due to the different cultivation practices of land managers, and associated differences in erosion risk, were not included in this study (D'Emden et al., 2008). Lilley and Moore (2009) also found that ground cover levels remained higher in pastures in comparison to crops for a range of farming systems and locations in the Murrumbidgee catchment in New South Wales. The contrary results at the Cunderdin location may be explained by two biological processes unique to the strongly

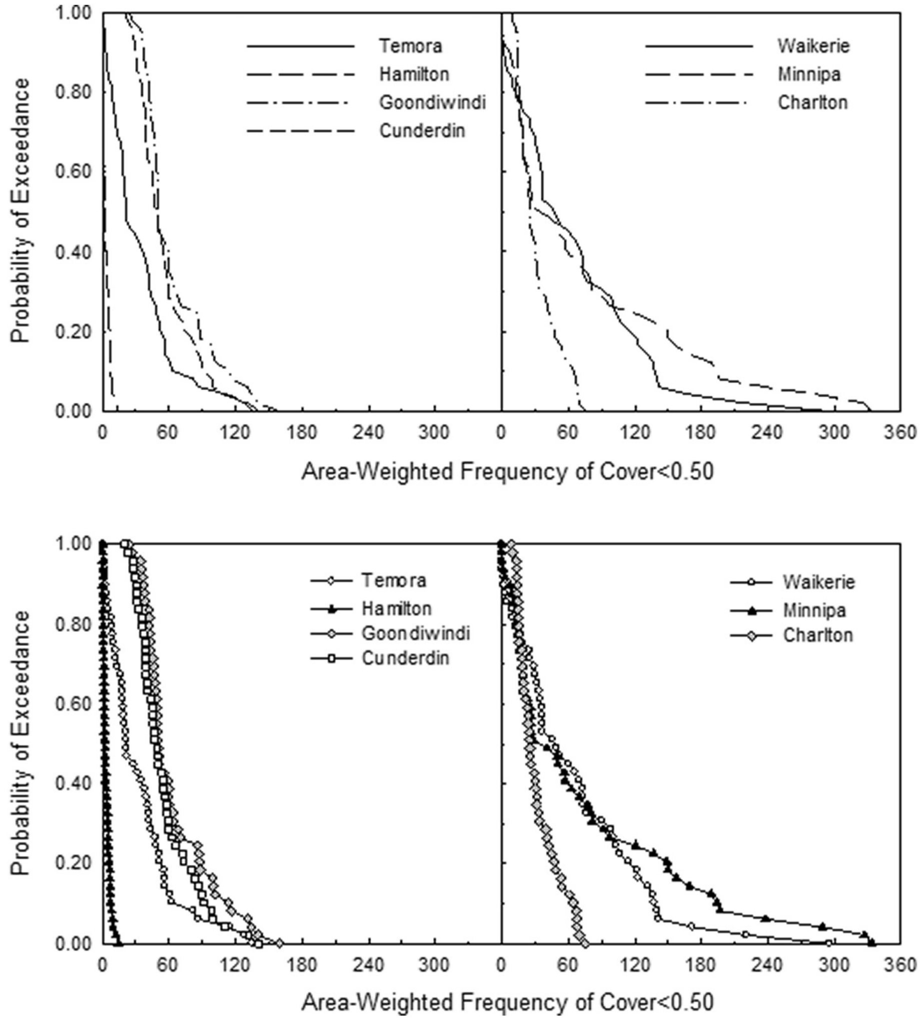

Fig. 3. Probability distributions (given as probabilities of exceedance) of the annual number of days that the fractional ground cover of the farm simulation (as a weighted paddock average) is below 0.50 for each of the 7 Grain and Graze sites. Each curve is composed of 50 years.

Table 4
Effect of farm management interventions on the risks of water and wind erosion relative to that in the base scenario at each of 7 locations. Values are changes (in percent) from the water or wind erosion risk index under the base scenario.

		Southern NSW		Southern Victoria		Northern		Western Australia		East SA		Eyre Peninsula		Northern Victoria	
Intervention area	Change in practice	Temora		Hamilton		Goondiwindi		Cunderdin		Waikerie		Minnipa		Charlton	
		Water	Wind	Water	Wind	Water	Wind	Water	Wind	Water	Wind	Water	Wind	Water	Wind
Stubble grazing	All stubbles					0	-1								
	Cereal stubbles only	+13	+29	-7	-13	0	0	-13	-18	-1	+2	-16	-28	+10	-7
	No stubble grazing	+12	+9	-7	-6			-13	-11	-13	-4	-25	-27	+4	-7
Pasture management	Lower-intensity pastures	+12	+17	-4	+9	+1	-2	-3	+16	0	-7	+16	-21	+47	+3
	Higher-intensity pastures	-2	-5	-9	-16	-1	-1	-6	-7	-4	+6	-24	-3	-9	+22
Perennial pastures on marginal land	No perennial grass	+11	+19	+14	+10	na	na								
	C_3 perennial grass					na	na	na	na	na	na	na	na	na	na
	C_4 perennial grass	na	na	na	na			-6	-10	-2	-7	-20	-3	-7	0
Dual purpose cropping	No dual purpose crops	+13	+12	-10	+3										
	Dual purpose crops					-1	0	-1	-1	-1	+6	-17	-36	+9	+2
Confinement feeding	No confinement feeding	+45	+530	+6	+39	0	+8	+7	+18	-10	+20	+1400	+110	+18	0
	Less confinement feeding	+18	+54	+5	+16	-1	+1	0	+1	-2	+1	-9	-23	+12	-55
	More confinement feeding	+1	-29	-11	-17	-1	-1	-7	-12	-1	-5	-27	-44	-8	+37
Stubble burning	No stubble burning													-41	-86
	Stubble burning	+30	+76	+29	+52	+36	+29	+16	+15	+28	+32	-10	+43		
Stocking rate	Increased stocking rate	+11	+15	+2	+37	0	+2	-1	+1	+4	+4	-10	-12	+11	-14
"Best practice"		-8	-26	-16	-24	-1	-2	-7	-15	-5	-4	-34	-42	-51	-87

Note: Grey shading of cells indicates the intervention setting selected in the base scenario. na = the intervention is not applicable for this location.

Table 5
Marginal rates of change (sensitivity coefficients) in the risk of water and wind erosion as selected management practices or land uses are changed, derived from long-term simulations at representative locations in each Grain & Graze region. Values are in units of (proportional change in erosion risk) per unit of change in the quantity given in each row.

Change in practice	Southern NSW		Southern Victoria		Northern		Western Australia		East SA		Eyre Peninsula		Northern Victoria	
	Temora		Hamilton		Goondiwindi		Cunderdin		Waikerie		Minnipa		Charlton	
	Water	Wind	Water	Wind	Water	Wind	Water	Wind	Water	Wind	Water	Wind	Water	Wind
Increase in the area of stubbles grazed (ha grazed ha cropped land^{-1})	−0.2	−0.2	+0.3	+0.3	+0.0	−0.0	+0.2	+0.2	+0.2	+0.1	+0.5	+0.6	−0.1	+0.1
Increase in the area of stubbles burnt (ha burnt ha cropped land^{-1})	+1.4	+3.5	+1.1	+2.0	+0.9	+0.7	+0.8	+0.8	+1.5	+1.8	−0.7	+2.8	+2.0	+4.1
Conversion of marginal land to perennial forages (ha converted ha farm^{-1})	−1.1	−1.9	−0.2	−0.1	na	na	−0.3	−0.5	−0.1	−0.3	−1.0	−0.2	−0.3	−0.0
Adoption of dual-purpose cropping (ha grazed ha crop^{-1})	−0.4	−0.4	+0.3	−0.1	−0.0	+0.0	−0.0	−0.0	−0.1	+0.5	−0.5	−1.0	+0.6	+0.2
Adoption of confinement feeding for cover (ha farm ha farm^{-1})	−0.5	−5.3	−0.1	−0.4	−0.0	−0.1	−0.1	−0.2	+0.1	−0.2	−13.6	−1.1	−0.2	−0.0
Increase in stocking rate (proportion of base SR)	+1.1	+1.5	+0.2	+3.7	+0.1	+0.3	−0.1	+0.1	+0.4	+0.4	−1.0	−1.2	+1.1	−1.4

na = the intervention is not applicable for this location.

Mediterranean-like climate of Cunderdin, in the central wheatbelt of Western Australia. First, the amount and duration of green biomass produced from pastures is likely to be smaller at Cunderdin, relative to crops, since pastures have a shorter growing season (similar to crops) in this climate compared with other regions of southern Australia (Moore et al., 2009). Second, the lack of rainfall over summer will slow the decomposition rate of residues (Roper, 1985), thereby extending the time that ground cover from crop residues remains above 0.50 following a cropping phase.

Location-specific responses to changes in access to stubble grazing are expected, since if livestock are not grazed on crop residues then the grazing pressure on other parts of the farm will increase. At Temora, this increased grazing pressure over summer is likely to have fallen on lucerne paddocks, which tended to have lower ground cover. While stubble burning occurred at approximately the same frequency across locations, effects of stubble burning on the number of days each year where ground cover was below 0.50 were not consistent. At locations where there were multiple crop/pasture rotations the frequency of ground cover falling below 0.50 increased similarly due to stubble burning. The estimated erosion risk benefits to rotation components, or even to farm averages, should be viewed with some caution, as these sometimes result through the transfer of grazing pressure to other paddocks on the farm. The use of feed-lotting systems, rather than 'sacrifice' paddocks to manage low farm ground cover may be an economically effective strategy (Lilley and Moore, 2009), but may incur other environmental trade-offs, such as the concentration of nutrients and possible nutrient leaching or run-off that affect future restoration potential (Dowling and Crossley, 2004).

The Grain and Graze program identified and evaluated mixed farm integration technologies that have implications for ground cover and soil management, in addition to farm productivity. Here, we have shown that there is consistency in the benefits of a range of management interventions with positive soil management outcomes. Some messages, such as maintaining adequate ground cover by destocking and avoiding burning stubbles during periods of erosion risk are commonly extended in the industry. However, the value of retaining productive, legume-based, annual pastures in rotations for improved ground-cover management may need greater emphasis. In much of the

Table 6
Farm water use efficiency (net farm kg protein produced mm^{-1} ha^{-1}) for the base management scenario and effects of farm management interventions on water use efficiency (% change) at 7 locations in southern Australia.

Intervention area	*Change in practice*	Southern NSW Temora	Southern Victoria Hamilton	Northern Goondiwindi	Western Australia Cunderdin	East SA Waikerie	Eyre Peninsula Minnipa	Northern Victoria Charlton
Base scenario		**0.56**	**0.28**	**0.32**	**0.47**	**0.43**	**0.28**	**0.43**
Stubble grazing	All stubbles			0				
	Cereal stubbles only	-1	0	0	-2	0	0	-1
	No stubble grazing	-1	0		-2	-2	-1	+1
Pasture management	Lower-intensity pastures	-4	-1	0	-10	-8	-24	-9
	Higher-intensity pastures	+8	+2	0	+5	+5	+13	+6
Perennial pastures on marginal land	No perennial grass	-1	-3	na				
	C_3 perennial grass			na	na	na	na	na
	C_4 perennial grass	na	na		+4	-15	-1	-15
DP cropping	No dual purpose crops	+2	+5					
	Dual purpose crops			0	0	0	-1	0
Confinement feeding	No confinement feeding	0	0	0	1	0	-2	-1
	Less confinement feeding	0	-1	0	0	0	-1	0
	More confinement feeding	-1	0	-1	0	-1	-1	+1
Stubble burning	No stubble burning							-2
	Stubble burning	-1	+1	0	-1	+2	0	
Stocking rate	Increased stocking rate	-1	+1	-1	-2	-2	-2	-1
"Best practice"		+8	+2	0	+7	-12	+14	-11

Note: Grey shading of cells indicates the intervention setting selected in the base scenario. na = the intervention is not applicable for this location.

mixed farming region, farmers have been disbanding sheep enterprises and relying on continuous cropping with intermittent spray-fallowing phases. While this scenario was not specifically modelled, we would expect based on our other simulations that a decline in Net Primary Production from pastures during a fallow phase is likely to increase the number of days with < 50% ground cover, and increase erosion risk in these paddocks. Without the development of alternative profitable options to stabilise bare fallows, it will be important that profitable options are available to ensure the production of plant biomass, and subsequently ground cover, when paddocks are rested and/or renovated (e.g. for weed seed reduction) between cropping sequences.

Managing mixed farming systems to meet production goals while conserving soil resources will be critical for agricultural sustainability in a changing world (Montgomery, 2007). Improved flexibility and responsiveness in farm management through mixed enterprise farming is a key standpoint of the Grain and Graze program. The importance of exploiting farming systems synergies through integrating multiple business enterprises have been demonstrated for a range of agricultural systems (e.g. Revell et al., 2012; Bell et al., 2014; Thomas et al., 2015). The long-term benefits (or costs) to soil conservation associated with mixed farming systems will be influenced by regional climate variability and soils, and moderated strongly by local management decisions and land use rotations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.02.001.

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