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Assessing the Potential for Zone-Specific Management of Cereals in Low-Rainfall South-Eastern Australia: Combining On-Farm Results and Simulation Analysis

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Abstract

In the low-rainfall region of south-eastern Australia, distinctive soil types reflecting the typical landscape of higher elevated dunes and swale zones at the bottom can be found within one field. Different soil characteristics cause consequently large variability in cropping productivity between soils and across seasons. To assess the possibilities for zone-specific management, five farmer fields were zoned into a dune, mid-slope and swale zone. For each site, zone yields were mapped over 2 years and soil properties were surveyed. This information was used to parameterize and validate the APSIM model for each zone. Field-measured PAWC increased from the dune to the swale zone. On-farm results and simulation analysis showed distinctive yield performance of the three designed zones. However, yield is not related to PAWC, it is rather a complex relationship between soil type, fertility and rainfall. While in high-rainfall years, the swale zones yielded higher due to higher soil organic carbon content and less drainage losses, the dune zones performed better in the low-rainfall years due to lower evaporation losses. This study emphasizes that in this specific environment where soil variation in texture and subsoil constraints strongly influence crop performance, mechanistic crop models and long-term field observations are necessary for better understanding of zone-specific performance, and simple linear relationships across years or sites are not useful.

Introduction

The Mallee of south-eastern Australia is a major grain-growing region of Australia. Grain production is, however, constrained by several challenges which may be exacerbated under climate change; low and erratic rainfall (annual average rainfall 250–350 mm) and highly variable and often constrained soils found within large fields (>100 ha) and depending on the season, highly variable crop growth. Such variability in soil reflects the typical dune–swale landscape with light sandy soils on the higher elevated dunes and heavier loam or clay soils in the swale resulting in variation in soil fertility, subsoil constraints and consequently plant available water capacity (PAWC) (Connor 2004). The attainable yield, that is the yield achieved using optimum management, can differ strongly within a field and also from season to season. In certain years, low water supply can result in terminal drought, which may be accelerated by large crop biomass due to high early nitrogen (N) supply (‘haying off’) (van Herwaarden et al. 1998, Sadras 2002) or in higher rainfall years a lack of N-supply limiting cereal yield and profit (Monjardino et al. 2013). In risky environments, farmers most often respond to these limitations by adapting a risk averse strategy with inputs well below yield maximizing rates (Sadras et al. 2003b, Sadras and Rodriguez 2010, Monjardino et al. 2013). High N use efficiency (NUE) is achieved at the expense of low water use efficiency, as attainable yield levels in good rainfall years are not reached (Sadras and Rodriguez 2010). However, water supply is not only determined by rainfall, but also by the capacity of the soil to store available water which is available for plants (i.e. the PAWC), which is related to texture, subsoil constraints and the organic matter content. The large heterogeneity in PAWC due to texture and subsoil constraints across one field causes large variability in the attainable yield of a certain season. In particular, dividing the field into different zones according to PAWC, soil fertility and texture and matching input to the attainable yield of that zone appears to be a promising strategy to increase the resource use efficiency and profitability of farming (Rab et al. 2009, Oliver and Robertson 2013). Several methods to define attainable yield have been developed. In southern Australia, the attainable yield is often estimated using the French & Schultz (1984) boundary function, where yield is the result of in-season rainfall minus a fixed evaporation of 110 mm, which is multiplied by a transpiration efficiency factor of 20 kg mm^{-1} ha^{-1}. Sadras and Angus (2006) modified this equation suggesting an evaporation term of 60 mm and a transpiration efficiency of 22 kg mm^{-1} ha^{-1}. However, such simple linear rainfall–yield relationships will ignore yield differences caused by soil variability. Zoning the field into high-performing and low-performing areas is challenging, as usually such information is based on limited harvest yield monitoring, so that patterns in seasonal variability in yield are not captured. Closely linked to this point, zoning based on yield mapping does not explain the complex interaction between water supply nutrient availability and yield. Therefore, decisions on fertilizer application based only yield mapping to zone areas of like performance are difficult to make (Lawes et al. 2009a,b). Long-term field experiments, which would help determine spatial and temporal dynamics in yield are rarely conducted due to labour and financial constraints.

Another method, which has developed into a commercially offered service over the past decade, is electromagnetic soil mapping (EM38). EM38 measures the apparent electrical conductivity (ECa), which is correlated to soil water, texture and salt concentrations. Although found to be effective in the Mallee landscape (Llewellyn et al. 2008), such soil properties can be difficult to relate to yield performance in many situations (Rab et al. 2009).

Conducting simulation experiments with validated process-based crop models can help to address many of the above limitations by analysing yield variability and its driving factors over multiple seasons for such zones. Monjardino et al. (2013) combined crop simulation knowledge of the variation in PAWC and economic analysis for one site in the Mallee (Karoonda), and suggested that a higher economic return is possible using higher N-fertilizer rates for sandy soils than what are typically used by farmers. However, they assumed that other abiotic and biotic stresses were minimized. Wong and Asseng (2006) also used crop modelling to analyse the long-term agronomic performance of EM38 soil zones in Western Australia. They concluded that on non-constrained soils the PAWC is positively correlated to yield. Rainfall (annual average 327 mm) in their study site at the edge of the wheat cropping belt of West Australia is concentrated (75–86 %) in the growing period from April to October. While total rainfall in the Mallee is similar, the share of precipitation in the April to October period is less pronounced (60–65 %).

While mechanistic crop models have been shown to usefully define site-specific attainable yields, it is necessary to test these models for such constrained soils in the low-rainfall Mallee. In this environment, a high sensitivity of APSIM to the characterization of the soil water parameter, namely first- and second-stage evaporation can be expected (Hunt and Kirkegaard 2011).

A range of simple vs. more complex zoning methods are used in the Mallee environment that usually result in zones largely based on dune, mid-slope and swale soils (Robertson et al. 2012). It is not the intended purpose of this study to test zoning methods but instead examine the approach to better understanding differences in zone behaviour and their management. Against this background, we used crop simulation modelling to analyse the seasonal–spatial dynamic nature of the attainable yield at five farmer fields characterized by the swale–dune system in the Mallee. We explore whether it is possible to identify simple linear yield relationship (such as PAWC-yield or In-season rainfall-Yield) for establishing zones in the region or whether more sophisticated soil considerations such as those included in the crop simulation models are of value. To achieve this, we went through following steps:

(i) describe the chemical and physical soil properties of the swale, mid-slope and dunes at five sites and how they define PAWC; (ii) set up the crop model APSIM for these zones, (iii) evaluate simulated crop yield against observed; and (iv) finally using a simulation experiment with historical weather data to explore the factors determining the yield variability and potential zoning.

Material and Methods

Sites

Four fields from commercial farming operations, in the Victorian and South Australian Mallee were selected in 2006: these included Bimbie (34°27′S, 142°58′E), Carwarp (34°27′S, 142°12′E), Pinnaroo (35°20′S, 140°54′E) and Loxton (34°29′S, 140°34′E). In 2007, an additional site at

Cowangie (35°13′S, 141°23′E) was also surveyed and included in the study. Annual average rainfall is 311 (Bimbie), 290 (Carwarp), 319 (Cowangie), 274 (Loxton) and 337 mm (Pinnaroo). The larger share of the rainfall is between April and October, which covers most of the growing season (Bimbie 189; Carwarp 175; Cowangie 206; Loxton 171; Pinnaroo 219 mm). Average daily temperature is similar at all sites and highest in January (24.3–22.7 °C) and lowest in July (9.6–9.9 °C).

Soil sampling and zoning

Based on an EM38 survey, Llewellyn et al. (2008) presented a zoning of one farmer field at each of the abovementioned sites. They showed that these EM38 defined zones are constant over seasons (measurements 2005–2007) and reflect the typical dune–swale landscape common in this region and resulted in differentiating the fields into three zones: dune, mid-slope and swale. For soil samples collected prior to sowing (April 2006) at Bimbie, Carwarp, Loxton and Pinnaroo, soil chemical and textural analysis was undertaken. Samples (n = 9) were collected using a stratified transect sampling pattern across each field to a depth of 110 cm (0–20, 20–40, 40–60, 60–80 and 80–110 cm horizons) and averaged according to the subsequent zoning based on the EM38 surveys. In 2007, only one sample was taken from the site in Cowangie to a depth of 110 cm for each zone. All samples were analysed as follows: organic carbon (OC) was analysed using the combustion method after a pre-treatment with dilute acid to remove inorganic carbon. Soil pH was measured in a 1 : 5 soil/0.01 M $CaCl_2$ suspension, and EC 1 : 5 was measured in a 1 : 5 soil/water suspension (Rayment and Higginson 1992). Boron (B) was determined using 0.01 M $CaCl_2$ extracting solution and immersion in a 98 °C water bath (Rayment and Higginson 1992). Chloride (Cl) was measured in a 1 : 5 soil : water extract. Exchangeable sodium percentage was calculated following measurement of cation exchange capacity using 0.1 M ammonium Cl with 0.1 M barium Cl extractant (method 15E1) outlined in Rayment and Lyons (2011). Soil samples were further analysed for Colwell extractable phosphorus (P) and extractable sulphur (S) using 0.25 M potassium Cl at 40 °C (Rayment and Lyons 2011). Soil textural analysis of proportions of sand, silt and clay were determined using the pipette method, after sieving to remove gravel as described in USDA (1982).

PAWC of each zone was characterized by drained upper limit (DUL), crop lower limit (CLL) and rooting depth. DUL was determined at a point within each zone using the techniques described by Dalgliesh and Foale (1998). CLL was determined for each zone using the lowest soil moisture values measured at the harvest of wheat crops in 2006 (nine cores across the three soil classes) and in 2007 (27 cores across the three soil classes). Soil OC, initial soil mineral N content and water content were measured prior to sowing in 2006 and 2007.

Management and harvest

As these experimental sites were all part of commercial farming operations, all sowing and management was undertaken by the farmer. Wheat (cvv. Janz and Yitpi) and barley (cv. Sloop) were sown in April/May along with the typical application of starter fertilizer (N 5–20 kg ha^{-1}; P 7–16 kg ha^{-1}). In 2006, soil mineral N at sowing was lower in the dune zones followed by the mid-slope in Bimbie (0–90 cm 15 kg ha^{-1} dune, 23 kg ha^{-1} mid-slope, 80 kg ha^{-1} swale), Carwarp (0–90 cm 45 kg ha^{-1} dune, 75 kg ha^{-1} mid-slope, 80 kg ha^{-1} swale), and Loxton (0–90 cm 34 kg ha^{-1} dune, 45 kg ha^{-1} mid-slope, 57 kg ha^{-1} swale) than in the swale systems. In Pinnaroo, the results were opposite (0–90 cm 64 kg ha^{-1} dune, 41 kg ha^{-1} mid-slope, 39 kg ha^{-1} swale). In 2007, the same pattern was found again: Bimbie (0–90 cm 18 kg ha^{-1} dune, 32 kg ha^{-1} mid-slope, 85 kg ha^{-1} swale), Carwarp (0–90 cm 57 kg ha^{-1} dune, 98 kg ha^{-1} mid-slope, 105 kg ha^{-1} swale) and Loxton (0–90 cm 35 kg ha^{-1} dune, 56 kg ha^{-1} mid-slope, 78 kg ha^{-1} swale). Similar results to Loxton were observed for Cowangie (0–90 cm 25 kg ha^{-1} dune, 57 kg ha^{-1} mid-slope, 55 kg ha^{-1} swale). In Pinnaroo, again it was different (0–90 cm 44 kg ha^{-1} dune, 43 kg ha^{-1} mid-slope, 38 kg ha^{-1} swale). The harvest was done for the entire field using a commercial combine header fitted with a yield monitor. Yield data were extracted from a 50- to 100-m sweep for the locations within the field where soil sampling had been undertaken. All yield data are represented as dry weight calculated from harvested grain weight and assuming 10 % moisture content.

APSIM parameterization and validation

APSIM is a widely used farming system model that simulates crop growth and development based on environmental variables (Holzworth et al. 2014). Management decisions such as sowing date, fertilizer application, etc. can be specified in a manager module. APSIM was widely tested in Australia and evaluation in the Mallee region evaluation can be found in Hochman et al. (2009), Hunt et al. (2013) and Yunusa et al. (2004). APSIM (version 7.5r3008) was configured with the wheat and barley module, the soil water module SOILWAT, and the soil N module SOILN, Surface OM and Manager.

Every site and soil zone was represented by an individual soil file to represent the soil chemical (Table 1) and physical characteristics (Fig. 2). Potential rooting depth

Table 1 Chemical soil properties of soil zones sampled 2006/2007 near sowing. Characterization of layers below based on 1–9 core samples. Standard error of the mean was calculated if possible and presented in brackets

		Zone (determined by EM38 measurements)											
		Dune				Mid-slope				Swale			
Site	Depth cm	ESP %	Conduc dS/m	Boron mg/kg	Cl mg/kg	ESP %	Conduc dS/m	Boron mg/kg	Cl mg/kg	ESP %	Conduc dS/m	Boron mg/kg	Cl mg/kg
Bimbie	20	1 (0)	0.0 (0.02)	0.7 (0.1)	11 (2)	2 (1)	0.1 (0.01)	0.6 (0.0)	6 (1)	21 (5)	0.7 (0.22)	1.7 (0.1)	793 (285)
	40	11 (5)	0.1 (0.01)	1.5 (0.0)	12 (2)	13 (3)	0.3 (0.07)	2.7 (0.7)	130 (90)	36 (1)	1.3 (0.17)	9.6 (0.4)	1441 (216)
	60	22 (5)	0.3 (0.05)	7.0 (1.8)	27 (7)	26 (5)	0.4 (0.08)	10.3 (2.6)	175 (75)	43 (1)	1.5 (0.09)	14.2 (1.8)	1405 (178)
	80	31 (3)	0.4 (0.04)	12.3 (2.2)	50 (15)	37 (3)	0.6 (0.04)	18.3 (2.6)	244 (61)	49 (1)	1.4 (0.11)	18.4 (1.9)	1508 (146)
	110	34 (0)	0.5 (0.01)	12.5 (0.5)	94 (2)	43 (4)	0.7 (0.06)	20.0 (1.4)	340 (58)	53 (0)	1.4 (0.12)	20.3 (1.6)	1645 (161)
Carwarp	20	0 (0)	0.1 (0.01)	0.7 (0.1)	7 (2)	1	0.1	1.0	16	9 (3)	0.5 (0.22)	1.8 (0.4)	440 (220)
	40	2 (1)	0.1 (0.00)	1.0 (0.1)	8 (1)	4	0.1	1.8	20	30 (1)	0.9 (0.05)	6.9 (0.8)	874 (58)
	60	6 (3)	0.2 (0.03)	3.0 (1.2)	17 (8)	19	0.4	6.6	66	37 (0)	1.1 (0.10)	10.7 (1.1)	1046 (131)
	80	14 (6)	0.2 (0.06)	5.5 (2.3)	31 (15)	31	0.5	13.3	63	41 (1)	1.1 (0.13)	13.8 (0.4)	1065 (108)
	110	20 (6)	0.3 (0.06)	6.3 (1.8)	26 (10)	36	0.5	16.7	75	43 (2)	1.2 (0.09)	14.6 (1.9)	1027 (108)
Cowangie	20	1	0.1	0.6	9	1	0.1	1.0	5	6	0.2	0.9	8
	40	1	0.1	0.7	4	1	0.1	1.3	19	11	0.2	1.1	10
	60	1	0.1	0.9	3	3	0.1	2.1	12	18	0.3	2.8	99
	80	1	0.1	0.8	3	12	0.2	8.7	46	29	0.8	13.1	790
	110	1	0.1	0.7	2	22	0.4	16.7	91	37	1.0	20.8	1456
Loxton	20	1 (0)	0.0 (0.02)	0.4 (0.0)	6 (1)	0 (0)	0.1 (0.01)	0.5 (0.1)	6 (0)	1 (0)	0.1 (0.00)	0.9 (0.0)	6 (0)
	40	1 (0)	0.1 (0.00)	0.6 (0.1)	5 (1)	1 (0)	0.1 (0.01)	0.9 (0.1)	5 (1)	8 (4)	0.2 (0.05)	2.1 (0.4)	34 (19)
	60	0 (0)	0.1 (0.00)	0.6 (0.0)	5 (0)	2 (1)	0.1 (0.01)	1.4 (0.3)	6 (1)	29 (7)	0.6 (0.21)	12.1 (4.9)	367 (115)
	80	1 (0)	0.1 (0.00)	0.6 (0.0)	4 (1)	5 (3)	0.1 (0.05)	3.4 (1.9)	9 (3)	39 (3)	1.0 (0.21)	13.6 (6.5)	785 (268)
	110	1 (0)	0.1 (0.00)	0.7 (0.1)	3 (0)	12 (6)	0.2 (0.08)	5.9 (4.1)	25 (18)	41 (3)	1.1 (0.21)	18.9 (0.8)	993 (295)
Pinnaroo	20	15 (4)	0.2 (0.01)	1.8 (0.3)	73 (0)	13 (4)	0.2 (0.05)	1.7 (0.6)	75 (31)	3 (1)	0.2 (0.03)	3.2 (0.8)	33 (8)
	40	25 (5)	0.4 (0.07)	12.0 (1.2)	69 (2)	23 (6)	0.5 (0.12)	10.9 (3.2)	207 (84)	17 (4)	0.5 (0.10)	13.2 (5.3)	240 (56)
	60	29 (5	0.5 (0.04)	16.1 (0.3)	83 (16)	30 (8)	0.7 (0.17)	20.2 (5.6)	259 (109)	32 (3)	0.7 (0.06)	23.6 (5.3)	375 (26)
	80	31 (2)	0.5 (0.06)	13.5 (0.1)	78 (21)	31 (6)	0.7 (0.18)	17.6 (3.8)	334 (140)	40 (1	0.8 (0.02)	28.6 (1.9)	456 (37)
	110	38 (0)	0.5 (0.00)	14.3 (0.0)	124 (49)	37 (5)	0.8 (0.14)	16.0 (1.0)	393 (170)	42 (1)	0.9 (0.02)	29.7 (1.7)	499 (29)

was assumed to be 140 cm across all sites and zones. Subsoil constraints were taken into account using the measured CLL value. Run-off is based on the USDA-Soil Conservation Service procedure known as the curve number technique and the values used reflected the effect of texture (sand and loam = 68; clay = 73). Potential evapotranspiration (Priestley and Taylor 1972) is calculated using an equilibrium evaporation concept: Soil evaporation is assumed to take place in two stages: the constant (U), or first stage and the falling rate (Cona) or second stage. Cona and U are considered to be soil specific (Ritchie et al. 2009), and therefore, the values were defined according to texture similar to Hunt and Kirkegaard (2011). If the top layer was clay, U was set to 6. For loamy and sandy top layers, this value was set to 4. If clay occurred in the next layer up to 40 cm, the value was set to 3.5, otherwise to 2 (Texture data not shown). Flow between adjacent layers under unsaturated conditions is defined by two parameters (diffusivity constant, diffusivity slope), which were parameterized following standard practice according to soil texture (diffusivity constant: sand 250; loam 88; clay 40; diffusivity slope: sand 22; loam: 40; clay 16).

When water content in any layer is below SAT but above DUL (saturated water flow), the fraction of the water, which drains to the next deepest layer each day, is described by the SWCON parameter and is set according to texture (Sand 0.7; Loam 0.5; Clay 0.3). Measured OC levels were used to parameterize the model. The amount of inert OC fraction (Finert) for each layer followed the convention set by Probert et al. (1998) where soil OC concentration in the deeper layers is assumed to be inactive and also represents the quantity of Finert in all layers.

Finally, for every sampled point simulation runs (n = 135) were carried out based on measured initial soil N and water content. Zone-specific soil OC and hydrological soil characterization was used for each simulation set-up (3 zones at each site) (Fig. 2). Sowing date, planting density and cultivar choice were the same for each simulation run within one site and year (see section 2.3).

Analysis

Observed yields and predicted yields for every core were grouped according to the zone (dune, mid-slope and swale) they were located. Averages of the cores located within these zones are presented. To assess the goodness of fit of these simulated – measured comparisons, the root mean square error (RMSE) between predicted and observed data was calculated as follows:

$$\mathrm{RMSE} = [(\sum (\mathrm{O} - \mathrm{P})^{2/n})]^{0.5}$$

where O and P are the paired observed and predicted data and *n* is the total number of observations. Additionally, for comparison, the traditional r^2 regression statistic (least-squares coefficient of determination) forced through the origin was calculated.

Simulation experiment

To explore the response of the different zones to N-fertilizer, a simulation experiment was conducted: For every site and soil zone (5 sites × 3 site-specific soil types), long-term simulations were devised using historical weather data (01/01/1959 to 31/12/2012) with different N-rates (0, 15, 30, 60, 120 kg ha^{-1}) applied at sowing. Wheat sowing was triggered by first rainfall within the time from 20th April to 10th July. The common wheat cultivar Yitpi was sown at a density of 150 plants m^{-2}. Surface organic matter and initial mineral N (25 kg ha^{-1}) were reset annually on April 1st. After initialization, soil water was not reset to allow fallow rainfall (November–April) to influence winter-grown crops. The first three simulated years (1959–1962) were discarded to avoid the influence of the initial water content in the first year of simulation. Historical climate data for the period were obtained from the Silo Patched Point Data Set (http://www.bom.gov.au/silo).

Results

Soil profiles

The landscape pattern of the Mallee was reflected in the physical (soil texture and CLL), and soil chemical properties (OC, S, ESP, electric conductivity, B, Cl) (Table 1, Figs 1 and 2) of the swale, mid-slope and dune soil types. There was a dominant trend that the dunes zones had a relatively high proportion of sand, while the swale zones had a higher clay proportion (Fig. 2). However, across zones and sites, available P concentration ranged from 22 to 41 mg kg^{-1}, indicating adequate to high P availability as a result of many years' fertilizer application, and high exchangeable K (208–409 mg kg^{-1}). For available S, differences between zones were observed; for the dunes, S was below 6 mg kg^{-1}, the critical concentration, at all sites and almost all soil horizons. At Bimbie and Pinnaroo, higher values of 10–12 mg kg^{-1} could be found in the soil layer below 60 cm. For the mid-slope zones, only Cowangie and Loxton had values below the critical threshold. The swale zones had a low S content of 4–6 mg kg^{-1} in the top soil, but in the layers below values of 96–233 mg kg^{-1} were measured. Only in Cowangie did the swale zone have low S

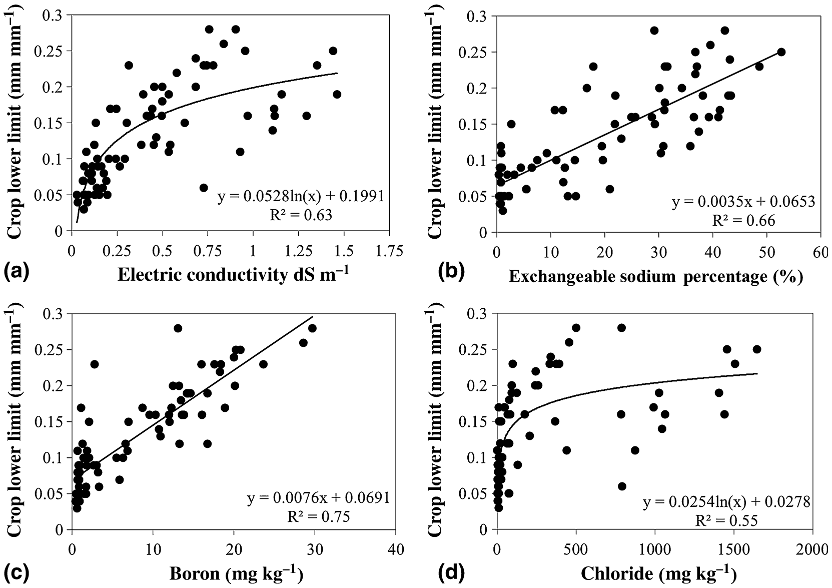

Fig. 1 Relationship between measured crop lower limit and soil chemical properties.

values of 4–12 mg kg^{-1} across soil layers. The lowest values for OC were found in the dunes (range 0.71 to 0.86 %, Fig. 2) while the mid-slope zones ranged from 0.82 to 1.15 % and the swale zones had the highest OC content from 1.08 to 1.3 %. Soil pH $CaCl_2$ was 7.5 to 8.6 across sites and zones. Soil pH measured in water was about 10–12 % higher than the pH measured in $CaCl_2$, but showed the same pattern. Cation exchange capacity (CEC) followed the trend of OC and S, being lowest in the dune (across sites and soil horizons: 13 meq/100 g), medium in the mid-slope (17 meq/100 g) and highest in the swale zone (24 meq/100 g). Sodicity of the soil, expressed here as exchangeable sodium percentage (ESP), showed again the trend that ESP was low in the dune zones, and highest in the swale zone. However, large differences between sites existed. The dune zone in Loxton, Cowangie and Carwarp could be classified as non-sodic soils, even in the subsoil. In Bimbie and Loxton, this zone was already moderately sodic in the upper layers, while very strongly sodic in the subsoil (Table 1). The mid-slope zone only in Bimbie (2–43 %), Carwarp (1–36 %) and Pinnaroo (13–37 %) could be classified as very strongly sodic, while the swale zone, at least in the subsoil, was very strongly sodic, across sites. EC 1 : 5, Cl and B were higher in the swale, fine textured soils. The highest B (3.2–29.7 mg kg^{-1}) and Cl (33–499 mg kg^{-1}) accumulations were found in the swale zone in Pinnaroo, while the highest EC (0.7–1.4 dS m^{-1}) was in Bimbie. Cowangie was affected to a lesser extent by these constraints in comparison with the other sites. For EC1 : 5 values above 0.4 dS m^{-1}, for B 10–14 mg kg^{-1} and for Cl 1000 mg kg^{-1}, constraints in terms of crop water uptake could be expected. A good relationship between these parameters and the crop lower limit had been found (Fig. 1a–d) indicating higher CLL with increasing subsoil constraints.

The overall and the top layer PAWC was largest at the five sites in the swale, followed by mid-slope and smallest in the dune zones (Fig. 2). Although CLL is higher in the swale zones in comparison with the mid-slope and the dune zones, the DUL of this zone type was also substantially higher, which led to the overall high PAWC. Despite this general pattern, the absolute PAWC for each zone type differs from site to site. For instance, the low constrained zone in Loxton had a PAWC of 72 mm, while the low constrained zone of Cowangie had a PAWC of 134 mm. To sum up, across sites soil sampling showed a pattern of increasing OC, PAWC and subsoil constraints from the dune zones to the swale.

Observed yield performance of the zones and APSIM validation

In-crop rainfall in 2006 ranged between 78 and 107 mm representing a season in the lowest deciles of historical seasonal rainfall and consequently resulting in grain yields of almost zero in the swale zone at Carwarp and 849 kg ha^{-1} in the dune zone at Pinnaroo (Fig. 3). In-crop rainfall in 2007 was relatively better ranging between 117–180 mm with yields ranging from 410 kg ha^{-1} (low constrained zone Loxton) to 1986 kg ha^{-1} (severely constrained zone Cowangie) (Fig. 3). Extractible soil water at sowing (esw-sowing) was lower in 2006 (range 15–61 mm) than in 2007 (range 42–160 mm). In 2006, the yield decreased at all sites from the dunes to swales. In 2007 for Bimbie and Carwarp, this trend was again observed; however, in Loxton and Pinnaroo the mid-slope

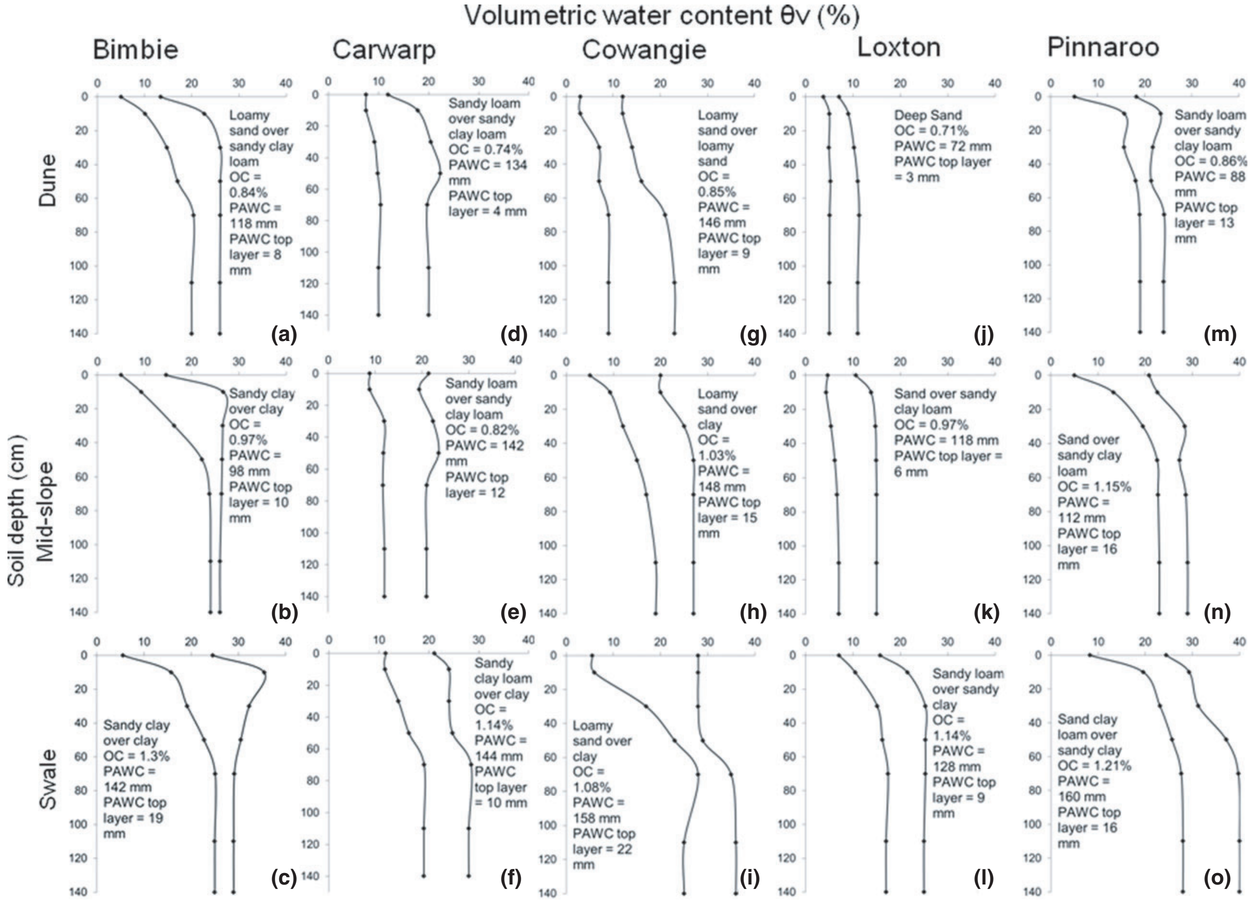

Fig. 2 Plant available water capacity as determined by crop lower limit and drained upper limit for the three designated soil zones at each location. In addition, soil texture and organic carbon in the top layer are shown.

zones and in Cowangie the swale zone were the highest yielding. A good relationship was found for observed yields and the corresponding water supply (which includes in-crop rainfall plus soil water at sowing) for the mid-slope and swale zone (r^2: 0.68 and 0.67) across sites (Fig. 4). As shown in Fig. 4 yields were higher for the dune zone under low water supply.

The relationship between simulated and observed grain yields (n = 26) is considered good with a RSME of 320 kg ha^{-1} against an observed mean of 820 kg ha^{-1} (Fig. 5). Observed yields ranged from 38 to 1986 kg ha^{-1}, which is reflected in the simulation results (Fig. 5; $r^2 = 0.71$). As expected with a model that does not account for other biological constraints such as weeds and disease, the model predicted slightly higher yield levels than those observed.

Simulation experiments

In the simulation experiment across all sites, mean yields when no N-fertilizers were applied were highest in the mid-slope zones, followed by the swale zone and lowest in the dune zone (Table 2). However, the swale zones had greater amplitude of possible yields indicating a higher production risk, followed by the mid-slope zones. In the dune zones, yields were relatively stable across seasons for low fertilizer application rates.

Overall, no relationship between PAWC and yield could be detected. In Loxton, for instance the dune zone had a low PAWC of 72 mm but still had a high average yield of 1916 kg ha^{-1} at 120 kg N ha^{-1}. In contrast, the swale zone in Pinnaroo with a PAWC of 160 mm yielded only 1612 kg ha^{-1} at the same N-rate (Table 2).

Generally, all dune zones showed the strongest mean response to the 30 kg ha^{-1} and higher N-application rates taking all years of simulation into account. The response to N was progressively lower at higher N-application rates. The coefficient of variance with higher N-rates increased as well, indicating a stronger variability in grain yield from season to season even for the dune zones. Yield at 120 kg ha^{-1} N-rate was generally the highest in the dune zones followed by the mid-slope and then by the swale zone

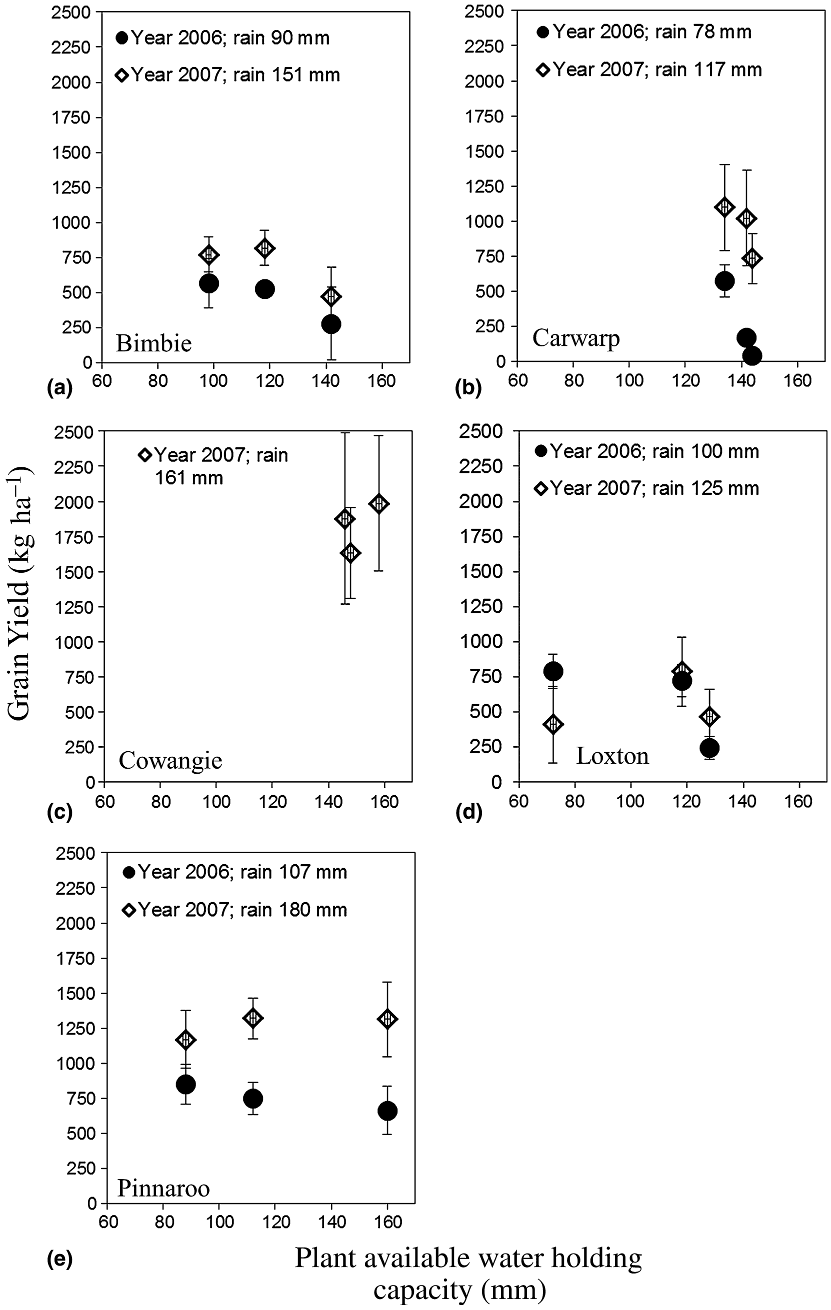

Fig. 3 Observed dry grain yield in relation to the PAWC. Rain is growing season rainfall.

(Table 2), while the mid-slope and the swale zones were less responsive to increasing N-supply.

Comparing the simulated yields at 30 kg N ha^{-1} vs. water supply (the sum of extractible soil water at sowing (esw-sowing) plus in-crop rainfall) showed a good relationship for the swale zone across sites (Fig. 6). Yields were lower than at the dune zone with water supply being <200 mm. For such a low water supply, the dune zone was generally superior in terms of yield performance than the other zone types. However, with higher water supply when N becomes more limiting, yield at the dune zone remained at around 1500 kg ha^{-1}. Only in Cowangie, yield reached 2000 kg ha^{-1} on the dune. Yields for the mid-slope and swale, where soil N-supply was higher, reached levels of 3000 kg ha^{-1} with a water supply above 300 mm.

Esw-sowing for the 30 kg N ha^{-1} rate increased with higher summer rainfall (Fig. 7b). It was highest in the dune zone followed by the mid-slope zone and lowest at the swale zone for in-fallow rainfall to 200 mm. In case of high summer rainfall (>200 mm), the mid-slope and the swale

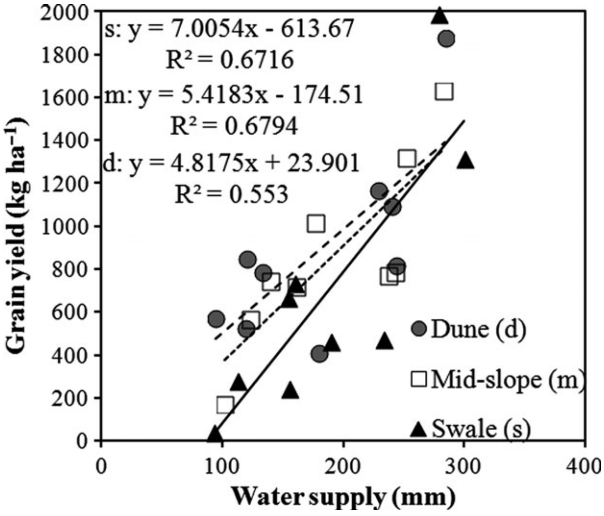

Fig. 4 Water supply (extractible soil water at sowing plus in-crop rainfall) vs. observed yield (years 2006/2007) for the zones across sites.

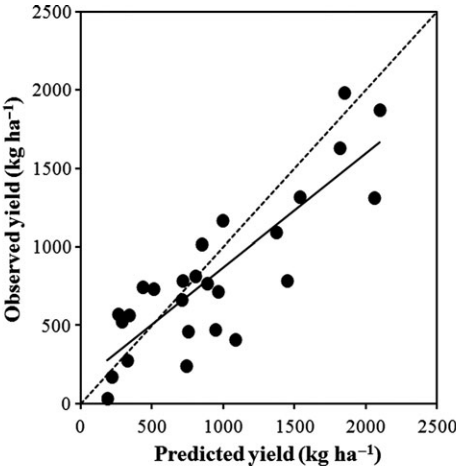

Fig. 5 Comparison between predicted and observed grain yield (years 2006/2007).The dotted line represents the 1 : 1 line. The RMSE is 320 kg ha^{-1} against an observed mean grain yield of 820 kg ha^{-1}. Regression analysis gave following result: Y = 0.7269x + 142.76 and R2 =0.71.

zones contain more water at sowing. In-fallow soil evaporation was by far the most important source of water loss from the system in low-rainfall seasons (<200 mm) (Fig. 7a). For instance, for 100 mm of rainfall there was a mean evaporation of 60–90 mm across sites and soil zones. Generally, in the dune zone, the evaporation was lower than in the other zone types. However, at high rainfall the importance of soil evaporation was reduced in relation to the remaining esw-sowing and drainage and run-off become more important (Fig. 8). In particular, in the dune zone the amount of rainfall could exceed the relatively low PAWC.

Mean evaporation during crop growth (in-crop-es) across soil zones was highest in Pinnaroo (140 mm), Bimbie (121 mm) and Cowangie (120 mm) followed by Carwarp (113 mm) and Loxton (109 mm) (Table 3). When in-crop-es was grouped according to in-season rainfall, the comparison of the means showed strong differences between seasons (Fig. 7c). Evaporation terms increased from roughly 60 mm across zones and sites when there was <100-mm in-season rain to more than 150 mm when there was more than 250-mm rain. However, the ratio between in-crop-es and in-crop rainfall declined with increasing rainfall (Fig. 7c). The zone-specific in-crop-es differs from site to site; while in Loxton and Carwarp, in-season-es was on average lowest in the dune zone, it was lowest in Bimbie, Cowangie and Pinnaroo for the mid-slope zone (Table 3). However, highest in-crop-es was simulated for the swale zone, which was also reflected in the relationship between in-crop rainfall and in-crop evaporation (Fig. 7c).

Water losses from the system other than evaporation, namely run-off and drainage were important only at higher rainfall levels (>300 mm) for the swale zone (Fig. 8). For the dune zones, run-off was of less importance, but drainage was a major pathway of water loss at high rainfall. For rainfall >300 mm, the mean drainage loss across sites was substantial (>50 mm).

Discussion

Soil properties

The three soil zones reflected the different soil properties in a typical Mallee dune–swale landscape. The swale zone was constrained by subsoil constraints (Table 1) across sites with high concentrations of ESP, B, Cl and EC reducing extraction of soil water by crop roots. A good relationship existed between these soil properties and the CLL (Fig. 1), which is supported by other studies (Rodriguez et al. 2006, Hochman and Dang 2007). Despite this limitation, the swale zones had the highest OC content related to clay content and the formation of stable clay-organic matter aggregates as reported by Tisdall and Oades (1982) for similar soils. Due to the finer soil texture, the swale zones had the highest overall PAWC across sites despite the high CLL. This was reflected in the evaporation sensitive topsoil layer, where the PAWC was again highest (with the exception of Carwarp) in the swale zones (Fig. 2). Contrary to this, the dune zones had sandy soils with very low OC content (all below 1 %) and low PAWC. In Pinnaroo, PAWC in the dune zone was around half that of the swale zone (Fig. 2). The K and P status in all soils was high due to regular fertilization and was assumed to be non-limiting. S is a highly mobile nutrient, and due to the low clay content of the course-textured soils, that is dunes, they are prone to S

Table 2 Simulated mean grain yield (kg ha^{-1}) and coefficient of variance (Standard deviation/mean) for different soil zones (D = dune; M = mid-slope; S = swale) in response to different N-rates based on APSIM (years 1963–2012)

		Fertilizer rates (kg N ha^{-1})				
Site	Zone	0	15	30	60	120
Bimbie	D	456 (0.19)	723 (0.27)	991 (0.37)	1349 (0.50)	1717 (0.66)
	M	938 (0.43)	1102 (0.49)	1238 (0.56)	1434 (0.64)	1655 (0.75)
	S	723 (0.64)	871 (0.71)	977 (0.75)	1082 (0.85)	1189 (0.96)
Carwarp	D	582 (0.11)	900 (0.19)	1182 (0.27)	1602 (0.40)	1979 (0.56)
	M	1417 (1.01)	1433 (1.01)	1441 (1.02)	1448 (1.01)	1443 (1.01)
	S	1041 (1.08)	1054 (1.08)	1064 (1.09)	1071 (1.09)	1071 (1.10)
Cowangie	D	997 (0.11)	1315 (0.13)	1621 (0.18)	2103 (0.29)	2652 (0.43)
	M	1839 (0.24)	2063 (0.30)	2163 (0.36)	2365 (0.42)	2664 (0.52)
	S	1332 (0.45)	1492 (0.52)	1551 (0.60)	1666 (0.69)	1949 (0.77)
Loxton	D	462 (0.19)	784 (0.22)	1097 (0.25)	1524 (0.35)	1916 (0.46)
	M	1052 (0.45)	1204 (0.51)	1301 (0.54)	1422 (0.60)	1528 (0.69)
	S	684 (0.59)	814 (0.66)	920 (0.72)	1032 (0.80)	1096 (0.92)
Pinaroo	D	516 (0.21)	791 (0.27)	1073 (0.34)	1471 (0.49)	1831 (0.62)
	M	1206 (0.47)	1420 (0.52)	1548 (0.57)	1719 (0.64)	1956 (0.72)
	S	958 (0.51)	1181 (0.56)	1288 (0.65)	1434 (0.76)	1612 (0.86)

leaching. Therefore in the dunes, S deficiency (<6 mg kg^{-1}) could occur for higher growth rates although such symptoms were not observed in the generally low-rainfall years of the field measurements (Peverill et al. 1999).

Use of APSIM on constrained soils in a low-rainfall environment

Setting APSIM up for the constraint soil zones with high salt and B concentrations is a challenge as it is difficult to quantify the effect of such constraints on water uptake by the plant. However, it is acknowledged that subsoil constraints affect the ability of the crop to take up water at low levels of soil moisture (Hochman and Dang 2007). Hochman and Dang (2007) tested an approach modifying the water-extraction coefficient (kl) in APSIM based on subsoil constraint indices for Vertisols. Rodriguez et al. (2006) discussed possible changes to the rooting depth in the simulation set-up due to soil constraints as sodium and Cl. However, they did not come to a final conclusion about the best representation of these processes in modelling frameworks. Whitbread et al. (2015) and Whitbread (unpublished data) showed that for two sites in the Mallee, determining the lower limit of PAWC by suction plate (usually then called permanent wilting point) overestimated actual CLL. They found the best match between observed and predicted yield and soil moisture using the CLL measured as described by Dalgleish and Foale (1998) using a rain-out shelter approach. Here, the subsoil constraints were assumed to directly influence CLL. This study supported such an approach as B, Cl, ESP and EC are well correlated with CLL at the research sites (Fig. 1). In line with this result, this study used the field-measured CLL as described in section 2.2 (Fig. 2). Based on the PAWC field characterization and the simple rule for the setting of Cona and U, the soil water balance model within APSIM was parameterized and produced reasonable predictions of yield (RMSE 311 kg ha^{-1}; Fig. 5). This level of error was comparable to other studies in this low yielding farming system (Hochman et al. 2009; 500 kg ha^{-1}). The slight overprediction by the model under higher rainfall conditions as in 2007 might be due nutrient limitations other than N or other biological constraints, as the model does not capture such limitations to growth. However, the validation exercise showed that the production for the different zones can be successfully simulated.

Long-term performance of the different zones based on crop modelling

In the simulation experiment, across all sites the yield was lower in the dune zones than in the mid-slope and swale zones when no N fertilizers were applied (Table 2). Yields were limited in many seasons by the availability of N, consequently yield variability was less in the dune zone than in other zones. This finding reflects the limited native N-supply associated with the low soil OC content (Fig. 2). Consequently, these dune zones showed the strongest response to fertilizer applications indicating the strong N-limitation of the sandy dune zones (Table 2). Despite the lower PAWC of the dune zones, maximum achievable yield at 120 kg ha^{-1} N-rate was higher than for the other two zone types. Nevertheless, production risk (indicated by the variance of the mean; Table 2) increased with N-rates of 120 kg ha^{-1} also for the dunes to high levels. Therefore,

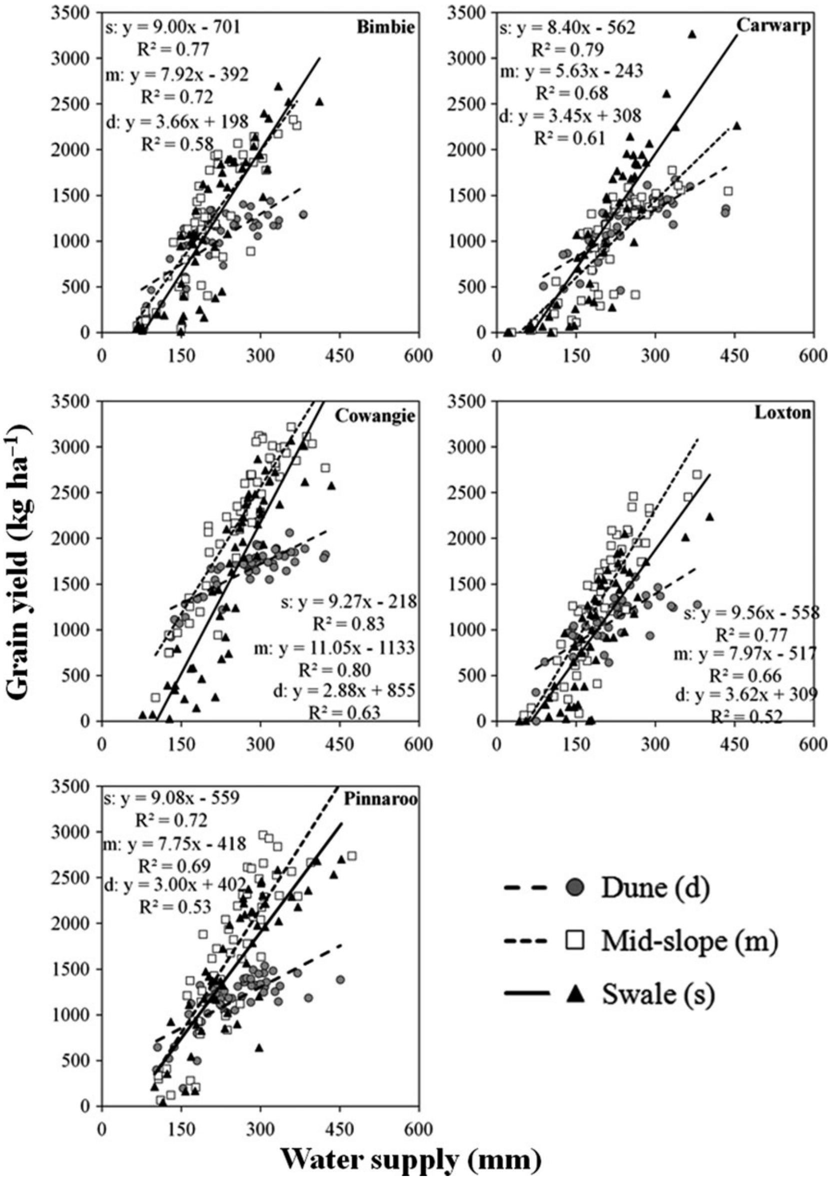

Fig. 6 Water supply (extractible soil water at sowing plus in-crop rainfall) vs. simulated mean grain yield (years 1963–2012). The crop was annually fertilized with 30 kg N ha^{-1}.

such maximum yield is rather a theoretical construct and not relevant as an economic yield target for a farmer (Monjardino et al. 2013).

In the region, farmers typically apply 30 kg N ha^{-1} or less. Simulated N response was high with a positive linear relationship found between water supply and yield for mid-slope and swale zones (Fig. 6). On the dune soils, the relationship between water supply and yield were weaker. In high-rainfall years, the mid-slope and swale zones perform well due to higher nutrient supply capacity of the soils, while in low-rainfall years the dune zones perform better. This finding is associated with the lower N-supply, which limits the crop growth rate on the dunes. In good rainfall years, this led to lower yields than for the other zones, but in the low-rainfall years, it prevented the crop from being affected by the haying off phenomena (van Herwaarden et al. 1998). A second reason was that in low-rainfall years evaporation is by far the major loss of water (Fig. 7). In-crop evaporation was lower on a sandy soil (dune zone) as it stored less water in the evaporation sensitive top layer than the fine textured soils of the mid-slope and the swale zones (Fig. 2 and Fig. 7c, Table 3). In years with low in-fallow rainfall, the sandy soils of the dunes had the advantage of lower evaporation as the rainfall drained to deeper layers where evaporation losses could not occur and thus, the esw-sowing is usually higher (Fig. 7a and 7b). However, with higher rainfall drainage becomes more important for the sandy soils as the PAWC is too low to store the water (Fig. 8) (Sadras et al. 2003a). Therefore, under these con-

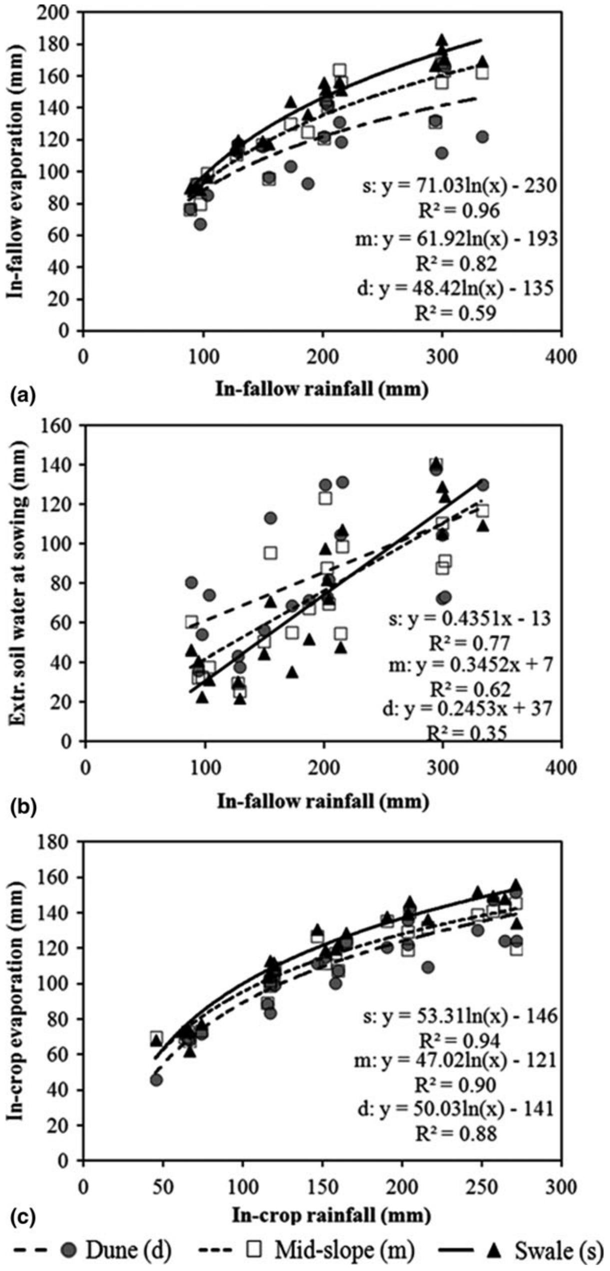

Fig. 7 Relationship between (a) in-fallow rainfall and simulated in-fallow evaporation, (b) in-fallow rainfall and simulated extractible soil water at sowing, and (c) in-crop rainfall and simulated in-crop evaporation for each zone averaged across sites. Simulation based on the years 1963–2012 and an annual fertilizer application of 30 kg N ha^{-1}. Simulated data is presented as mean average for in-fallow rainfall, respectively in-crop rainfall <100, <150, <200, >200 mm.

ditions esw-sowing was lower than in the other zones (Fig. 7b). The simulation analysis showed a complex interaction between soil type, evaporation, rainfall, overall PAWC, top layer PAWC and N-supply and its effect on growth and yield.

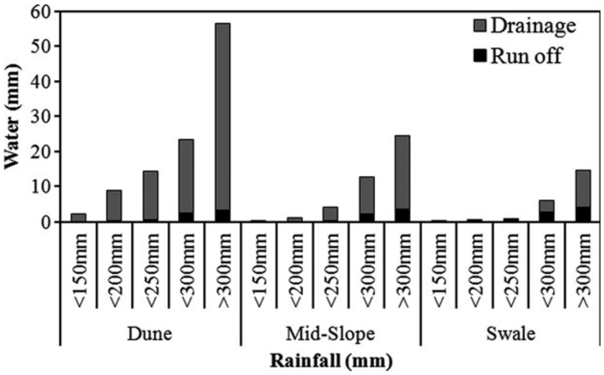

Fig. 8 Mean simulated in-crop drainage and runoff losses for different rainfall quantities averaged across sites for the three soil zones. Simulation based on the years 1963–2012 and an annual fertilizer application of 30 kg N ha^{-1}.

To sum up, crop production differs significantly spatially (site and zone) and seasonally (from year to year) in response to N-application. This finding suggests that defining linear relationships between rainfall and attainable yield is of little use. None of the three zones described in this study can be generally classified as low performing, rather the specific seasonal weather conditions define the suitability of the zone for cropping. Such results are contrary to the Western Australian situation reported by Wong and Asseng (2006), where simulated response to fertilizer was low on course-textured soils with low PAWC and therefore recommended such zones for land use change. In their study, the PAWC was positively related to yield. One reason for this is the very different rainfall patterns between the two regions of study. In the Western Australian cropping district of their study 75–86 % of rainfall typically falls between April and October compared to 60–65 % for the same period in a Mallee district. The peak in rainfall distribution in West Australia increases the importance of the storage capacity of a soil to prevent drainage, and reduces the risk of evaporation losses. Contrary, the more even distribution of rainfall in the Mallee cause higher evaporation rates, especially for those soils with high storage capacity (swale zones) in the evaporation sensitive top layers. This different rainfall pattern makes the extrapolation of findings from Western Australia (Lawes and Robertson 2011) for zone-specific management of limited use in the Mallee region of south-eastern Australia. Another method used in zone-specific management, yield maps, can be misleading in certain conditions. For example, the highest observed yield in this study was found in a wetter year in the zone at Cowangie with severe subsoil constraints. A further important point is as widely discussed in the literature and also here that N-availability influences attainable yield (van Heerwarden et al., 1998).

Table 3 Simulated in-crop evaporation and coefficient of variance for different soil zones (D = dune; M = mid-slope; S = swale) in response to in-crop rainfall based on APSIM runs (years 1963–2012). The crop was annually fertilized with 30 kg N ha^{-1}

		In-crop rainfall (mm)				
Site	Zone	<100	<150	<200	<250	>250
Bimbie	D	66 (0.29)	103 (0.14)	120 (0.14)	137 (0.14)	155 (0.15)
	M	64 (0.32)	102 (0.14)	116 (0.13)	131 (0.13)	147 (0.14)
	S	67 (0.33)	109 (0.14)	125 (0.13)	142 (0.14)	156 (0.14)
Carwarp	D	66 (0.15)	96 (0.14)	109 (0.11)	122 (0.14)	136 (0.11)
	M	61 (0.42)	103 (0.13)	126 (0.11)	138 (0.15)	154 (0.15)
	S	56 (0.50)	108 (0.13)	129 (0.11)	141 (0.14)	160 (0.14)
Cowangie	D	72 (0.09)	93 (0.13)	113 (0.11)	123 (0.12)	133 (0.12)
	M	73 (0.07)	94 (0.12)	112 (0.10)	121 (0.10)	129 (0.10)
	S	79 (0.09)	107 (0.12)	129 (0.11)	141 (0.10)	146 (0.12)
Loxton	D	52 (0.39)	83 (0.17)	101 (0.12)	110 (0.11)	124 (0.13)
	M	63 (0.36)	100 (0.14)	121 (0.13)	133 (0.11)	147 (0.10)
	S	59 (0.39)	104 (0.14)	126 (0.13)	142 (0.11)	153 (0.09)
Pinaroo	D	72 (0.04)	109 (0.14)	130 (0.13)	150 (0.12)	160 (0.14)
	M	74 (0.03)	108 (0.14)	129 (0.14)	148 (0.12)	152 (0.12)
	S	76 (0.02)	115 (0.12)	136 (0.13)	154 (0.11)	159 (0.15)

The fact that a higher N-supply can lead to lower yields in low-rainfall years makes clear that the concept of attainable yield has to take N-availability into account. Simple yield models as discussed above define attainable yield independently of N-supply. Therefore, we argue to further improve zone-specific management in this low-rainfall region, simulation modelling and long-term field trials/on-farm observation are important to help understand the soil–weather–management interactions. Finding ways to apply such information, for example to define trigger points for management decisions, (Hochman et al. 2009, Mudge and Whitbread 2010) are therefore future research topics. Based on the soil survey and the simulation analysis following recommendations can be given: (i) The dune zones are normally nutrient limited rather than water limited, especially by N (section 4.1 and Table 2). Here, additional fertilization (30–60 kg N ha^{-1}) would result in gains in almost all seasons. Similar results were found by Monjardino et al. (2013). (ii) The mid-slope zones are the most variable, and in some years, in-season fertilization will result in high yield response. Short-term and seasonal climate forecasts are of specific relevance for managing this zone (Asseng et al. 2012). (iii) The swale zones were poor yielding in dry years, but may perform well in wet years as they are rarely nutrient limited. Additional N-fertilization is often not required; however, in-season decisions can be made on end use, for example grain or, in very dry years, graze or hay.

Conclusions

The study showed the attainable yield in the low-rainfall region of south-eastern Australia is highly variable spatially (soil type) and temporally. Fine textured soils (swale) perform well in wet years, supported by the higher soil N-supply, but yield badly in dry years due to the high evaporation losses. Thus, PAWC alone is not a good predictor of crop performance across these soils. Sandy soils (dune) are generally more nutrient limited than water limited. Crop-soil models and long-term field observations are helpful to understand crop–soil–weather interactions and identify patterns for zone-specific management. Consequently, simpler methods, which ignore soil variability, differences in evaporation characteristics, and N- supply are consequently not recommended for zone-specific management support in this region.

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References

Asseng, S., P. C. McIntosh, G. Wang, and N. Khimashia, 2012: Optimal N fertiliser management based on a seasonal forecast. Eur. J. Agron. 38, 66–73.

Connor, D. J., 2004: Designing cropping systems for efficient use of limited water in southern Australia. Eur. J. Agron. 21, 419–431.

Dalgleish, N. P., and M. A. Foale, 1998: Soil Matters: Monitoring Soil Water and Nutrients in Dryland Farming Systems. Agricultural Production Systems Research Unit, Toowwomba, Qld, Australia.

French, R., and J. Schultz, 1984: Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. Aust. J. Agric. Res. 35, 743–764.

van Herwaarden, A., G. D. Farquhar, J. Angus, R. Richards, and G. N. Howe, 1998: "Haying-off", the negative grain yield response of dryland wheat to nitrogen fertiliser. I. Biomass, grain yield, and water use. Aust. J. Agric. Res. 49, 1067–1081.

Hochman, Z., and Y. Dang, 2007: Simulating the effects of saline and sodic subsoils on wheat crops growing on Vertosols. Aust. J. Agric. Res. 58, 802–810.

Hochman, Z., H. van Rees, P. S. Carberry, J. R. Hunt, R. L. McCown, A. Gartmann, D. Holzworth, S. van Rees, N. P. Dalgliesh, W. Long, A. S. Peake, P. L. Poulton, and T. McClelland, 2009: Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet helps farmers monitor and manage crops in a variable climate. Crop Pasture Sci. 60, 1057–1070.

Holzworth, D. P., N. I. Huth, P. G. deVoil, E. J. Zurcher, N. I. Herrmann, G. McLean, K. Chenu, E. van Oosterom, V. O. Snow, C. Murphy, A. D. Moore, H. E. Brown, J. P. M. Whish, S. Verrall, J. Fainges, L. W. Bell, A. S. Peake, P. L. Poulton, Z. Hochman, P. J. Thorburn, D. S. Gaydon, N. P. Dalgliesh, D. Rodriguez, H. Cox, S. Chapman, A. Doherty, E. Teixeira, J. Sharp, R. Cichota, I. Vogeler, F. Y. Li, E. Wang, G. L. Hammer, M. J. Robertson, J. Dimes, A. M. Whitbread, J. Hunt, H. van Rees, T. McClelland, P. S. Carberry, J. N. G. Hargreaves, N. MacLeod, C. McDonald, J. Harsdorf, S. Wedgwood, and B. A. Keating, 2014: APSIM - Evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350.

Hunt, J. R., and J. A. Kirkegaard, 2011: Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. Crop Pasture Sci. 62, 915–929.

Hunt, J. R., C. Browne, T. McBeath, K. Verburg, S. Craig, and A. M. Whitbread, 2013: Summer fallow weed control and residue management impacts on winter crop yield though soil water and N accumulation in a winter-dominant, low rainfall region of southern. Crop Pasture Sci. 64, 922–934.

Lawes, R., and M. J. Robertson, 2011: Whole farm implications on the application of variable rate technology to every cropped field. Field Crops Res. 124, 142–248.

Lawes, R. A., Y. M. Oliver, and M. J. Robertson, 2009a: Integrating the effects of climate and plant available soil water holding capacity on wheat yield. Field Crops Res. 113, 297–305.

Lawes, R. A., Y. M. Oliver, and M. J. Robertson, 2009b: Capturing the in-field spatial–temporal dynamic of yield variation. Crop Pasture Sci. 60, 834–843.

Llewellyn, R., B. Jones, A. M. Whitbread, and C. W. Davoren, 2008: The role for EM mapping in precision agriculture in the Mallee. Proceedings of the 14th Australian Agronomy Conference, Adelaide, Australian Society of Agronomy.

Monjardino, M., T. McBeath, L. Brennan, and R. S. Llewellyn, 2013: Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. Agric. Syst. 116, 37–51.

Mudge, B., A. M. Whitbread, 2010: Making better decisions about crop rotations in low rainfall environments: should stored moisture and the timing of the seeding opportunity influence this decision? In 'Food Security from Sustainable Agriculture'. Proceedings of the 15th Australian Agronomy Conference. November 2010, Christchurch, New Zealand.

Oliver, Y. M., and M. J. Robertson, 2013: Quantifying the spatial pattern of the yield gap within a farm in a low rainfall Mediterranean climate. Field Crops Res. 150, 29–41.

Peverill, K. I., L. A. Sparrow, and D. J. Reuter, 1999: Soil Analysis: An interpretation Manual. pp. 288. CSIRO publishing, Collingwood, Victoria, Australia.

Priestley, C., and R. J. Taylor, 1972: Assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100, 81–92.

Probert, M. E., J. P. Dimes, B. A. Keating, R. C. Dalal, and W. M. Strong, 1998: APSIM's Water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56, 1–28.

Rab, M. A., P. D. Fisher, R. D. Armstrong, M. Abuzar, N. J. Robinson, and S. Chandra, 2009: Advances in precision agriculture in south-eastern Australia. IV. Spatial variability in plant-available water capacity of soil and its relationship with yield in site-specific management zones. Crop Pasture Sci. 60, 885–900.

Rayment, G. E., and F. R. Higginson, 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. pp. 330. Inkata Press, Port Melbourne, Vic., Australia.

Rayment, G. E., and D. J. Lyons, 2011. Soil Chemical Methods: Australasia. pp. 495+20. CSIRO Publishing, Melbourne, Vic., Australia.

Ritchie, J. T., C. H. Porter, J. Judge, J. W. Jones, and A. Suleiman, 2009: Extension of an existing model for soil water evaporation and redistribution under high water content conditions. Soil Sci. Soc. Am. J. 73, 792–801.

Robertson, M. J., R. S. Llewellyn, R. Mandel, R. Lawes, R. G. V. Bramley, L. Swift, N. Metz, and C. O'Callaghan, 2012: Adoption of variable rate technology in the Australian grains industry: status, issues and prospects. Precision Agric. 13, 181–199.

Rodriguez, D., J. Nuttall, and V. O. Sadras, 2006: Impact of subsoil constraints on wheat yield and gross margin on fine-textured soils of the southern Victorian Mallee. Aust. J. Agric. Res. 57, 355–365.

Sadras, V. O., 2002: Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: economic and environmental risk analysis. Field Crops Res. 77, 201–215.

Sadras, V. O., and J. F. Angus, 2006: Benchmarking water-use efficiency of rainfed wheat in dry environments. Aust. J. Agric. Res. 57, 847–856.

Sadras, V. O., and D. Rodriguez, 2010: Modelling the nitrogen-driven trade-off between nitrogen utilisation efficiency and water use efficiency of wheat in eastern Australia. Field Crops Res. 118, 297–305.

Sadras, V. O., J. Baldock, D. Roget, and D. Rodriguez, 2003a: Measuring and modelling yield and water budget components of wheat crops in coarse-textured soils with chemical constraints. Field Crops Res. 84, 241–260.

Sadras, V. O., D. Roget, and M. Krause, 2003b: Dynamic cropping strategies for risk management in dry-land farming systems. Agric. Syst. 76, 929–948.

Tisdall, J., and J. Oades, 1982: Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

USDA, 1982. Particle size analyses. In: Procedures for Collecting Soil Samples and Methods of Analysis for Soil Survey. Soil Survey Investigation Report No. 1. SCS, Washington, DC, USA.

Whitbread, A. M., C. Davoren, V. V. S. R. Gupta, R. Llewellyn, and D. Roget, 2015: Long-term cropping system studies support intensive and responsive cropping systems in the low rainfall Australian Mallee. Crop Pasture Sci. 66, 553–565.

Wong, M. T. F., and S. Asseng, 2006: Determining the causes of spatial and temporal variability of wheat yields at sub-field scale using a new method of upscaling a crop model. Plant Soil 283, 203–215.

Yunusa, I., W. Bellotti, and A. Moore, 2004: An exploratory evaluation of APSIM to simulate growth and yield processes for winter cereals in rotation systems in South Australia. Aust. J. Exp. Agric. 44, 787–800.