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Impact of subsoil constraints on wheat yield and gross margin on fine-textured soils of the southern Victorian Mallee

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Abstract. The APSIM-Wheat module was used to investigate our present capacity to simulate wheat yields in a semi-arid region of eastern Australia (the Victorian Mallee), where hostile subsoils associated with salinity, sodicity, and boron toxicity are known to limit grain yield. In this study we tested whether the effects of subsoil constraints on wheat growth and production could be modelled with APSIM-Wheat by assuming that either: (*a*) root exploration within a particular soil layer was reduced by the presence of toxic concentrations of salts, or (*b*) soil water uptake from a particular soil layer was reduced by high concentration of salts through osmotic effects. After evaluating the improved predictive capacity of the model we applied it to study the interactions between subsoil constraints and seasonal conditions, and to estimate the economic effect that subsoil constraints have on wheat farming in the Victorian Mallee under different climatic scenarios. Although the soils had high levels of salinity, sodicity, and boron, the observed variability in root abundance at different soil layers was mainly related to soil salinity. We concluded that: (*i*) whether the effect of subsoil limitations on growth and yield of wheat in the Victorian Mallee is driven by toxic, osmotic, or both effects acting simultaneously still requires further research, (*ii*) at present, the performance of APSIM-Wheat in the region can be improved either by assuming increased values of lower limit for soil water extraction, or by modifying the pattern of root exploration in the soil profile, both as a function of soil salinity. The effect of subsoil constraints on wheat yield and gross margin can be expected to be higher during drier than wetter seasons. In this region the interaction between climate and soil properties makes rainfall information alone, of little use for risk management and farm planning when not integrated with cropping systems models.

Additional keywords: root growth, salinity, sodicity, boron toxicity, El Niño, La Niña, ENSO.

Introduction

Simulation modelling has proven to be important and valuable in improving crop management decisions (Meinke and Hochman 2000), optimising cropping systems (Robertson *et al*. 2000), quantifying environmental risks (Asseng *et al*. 1998), and evaluating the effect of climate variability and climate change (Hammer *et al*. 1996). However, subsoil limitations such as salinity or sodicity have so far limited the application of simulation models in regions such as the main cereal-growing areas of north-western Victoria. In this region, restrictions to root growth and water uptake have been attributed to high levels of salinity and sodicity (Rengasamy 2002), and even to toxic levels of soil boron (Holloway and Alston 1992). Simulation exercises in the region have been published (O'Leary and Connor 1996*a*, 1996*b*); however, these studies were limited to non-saline soils from the Mallee and Wimmera regions. The effect of soil properties and crop type on plant-available water capacity requires the measurement of the crop lower limit (CLL). CLL has been defined as the volumetric soil water remaining in the soil after a healthy crop, with uninterrupted root development, has reached maturity under soil water-limited conditions (Hochman *et al*. 2001). Methods to determine CLL in the field are laborious, expensive, and site specific, which make them unsuitable to be used in precision agriculture. Precision agriculture requires modelling tools able incorporate spatial attributes of the landscape in a simple and inexpensive way such as from

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the determination of subsoil salinity from EM38 surveys (O'Leary *et al*. 2004). However, before this can be achieved a better understanding of the mechanisms linking subsoil constraints and crop growth and yield in simulation models is required. In this study we aim to: (*i*) test whether the effects of subsoil constraints on wheat growth and production can be modelled with APSIM-Wheat by assuming that either (*a*) root exploration within a particular soil layer is reduced by the presence of toxic concentrations of salts, or (*b*) soil water uptake from a particular soil layer is reduced by high concentration of salts through osmotic effects; (*ii*) study the importance of the interactions between subsoil constraints and seasonal conditions; and (*iii*) quantify the economic effect of both subsoil constraints and climate variability in the Victorian Mallee of Victoria.

Methods

Field experiments

Data sets from wheat (*Triticum aestivum* L.) crops grown in on-farm experiments in the southern Mallee of Victoria, Australia, were obtained for the cropping seasons 1993, 1994, and 1999. During the first 2 years (Expt 1), soil and crop data were collected from 2 commercial crops at Brim (36.07°S, 142.42°E) and Birchip (35.98°S, 142.92°E), and during 1999 (Expt 2), 16 sites were randomly selected from 150 surveyed sites (Nuttall *et al*. 2003*a*) covering an area of 3600 km^2 in the Birchip district. The soils in the region are mainly Calcarosols (Nuttall *et al*. 2003*a*), and the long-term (1957–2002) average seasonal (1 April–1 November) rainfall is 257 mm.

Field Expt 1

During the 1993 and 1994 cropping seasons, 2 wheat fields (*Triticum aestivum* L. cv. Frame) from the Brim and Birchip areas were sampled to determine soil water, N-NO_3 (mg/kg), organic carbon (%), electric conductivity (EC, dS/m), bulk density (g/cm^3), and pH at 0–0.1, 0.1–0.6, and 0.6–1 m depths. Crop data included date of anthesis, maximum rooting depth, grain yield, and above-ground biomass. After sowing the wheat crop in autumn 1993 the soil water content of the different soil layers was measured at about monthly intervals using a neutron moisture meter (Model 503, Campbell Pacific Nuclear Crop, Martinez, CA). Surface-layer soil water (0–0.25 m) was measured gravimetrically. Results are averages of 3–5 replications within each paddock.

Field Expt 2

Soil and crop data were collected from the Birchip district of Victoria, Australia (Nuttall *et al*. 2003*a*). The data set consisted of soil and crop characteristics determined in transects of 10 points at 15 locations, i.e. 150 sites, within a radius of *c*. 30 km around Birchip, collected during the 1999 season. At each site the following soil variables were determined at different depths in the soil profile: soil boron (mg B/kg soil), EC (dS/m), exchangeable sodium (ESP, %), N-NO_3 (mg/kg), volumetric soil water content at sowing, volumetric soil water content at wilting point (WP), and bulk density. Among others, crop variables included layered root dry weight at anthesis, and final grain yield.

Simulation Expt 1

The Agricultural Production Systems Simulator (APSIM) (McCown *et al*. 1996) allows the simulation of diverse crops and cropping systems targetting issues such as land degradation (Asseng *et al*. 2001), crop rotation (Carberry *et al*. 1996), cropping strategies (Robertson *et al*. 2000), and management alternatives (Goyne *et al*. 1996). APSIM-Wheat (APSIM version 2.1 patch 2) has been tested against field studies in different regions of Australia and locally for this study. In this exercise we used the model APSIM-Wheat parameterised with modules SOILN2, SOILWAT2, and RESIDUE2. The phenology parameters of the model were calibrated for the wheat crop cv. Frame using an independent data set provided by Dr R. Flood (unpublished data). Values of soil water content at saturation (SAT) were calculated from values of bulk density (Dalgliesh and Foale 1998), values of drainage upper limit (DUL) were derived from a relationship between SAT and DUL determined from wet ponds in soils of the Mallee region, and soil water lower limits (LL) were taken as soil water contents determined in the laboratory at −15 kPa (WP). Wheat yields were simulated assuming: (*i*) the observed root distribution within the soil profile at each site and measured values of LL15 as inputs to the model (Hypothesis A), (*ii*) ignoring the presence of subsoil constraints and using measured values of LL15 (control), (*iii*) calculating the root soil profile distribution from a function relating root distribution and EC (dS/m) (Hypothesis A), and (*iv*) calculating the value of the crop lower limit (parameter *ll* in APSIM) for each soil layer, as a function of the EC (dS/m) as proposed by Sadras *et al*. (2003) (Hypothesis B). Within APSIM the effects of EC on root distribution were incorporated by modifying the value of the parameter '*xf*', i.e. root exploration factor for each soil layer. The agreement between observed and simulated results was evaluated by comparing the coefficient of determination, root mean squared error, and by desegregating the mean squared error following the methodology proposed by Kobayashi and Salam (2000).

Simulation Expt 2

To study the interactions between subsoil constraints and seasonal conditions on grain yield and economic return at Birchip, we used crop lower limits (parameter *ll* in APSIM) calculated as a function of EC (dS/m) as in Sadras *et al*. (2003). Historical climate data for the period 1900–2002 years (Birchip Post Office, station no. 77007), were obtained from the Silo Patched Point Data Set (http://www.bom.gov.au/silo). Simulated treatments included 3 levels of soil salinity, i.e. low (decile 1), median (decile 5), and high (decile 9) (see Fig. 1*a*). Simulation outputs are presented for all the simulated years and for those years defined as El Niño years and La Niña years (as in http://www.longpaddock.qld.gov.au). Gross margin in A$/ha was estimated as the product of yield and price minus variable costs; we did not take into account fixed costs. Variable costs, including fertilisers, were set at A$158.76/ha, and included the cost of contracting machinery works (including harvest), seed, and chemicals. Grain price was calculated depending on grain quality following the Australian Wheat Board standards. Initial conditions for model simulations were reset every 1 January to 10% of plant-available water, 50 kg N/ha, and 1000 kg/ha of canola residues from previous crop. Every year, 50 kg N/ha were applied at sowing.

Results

Subsoil constraints

Figure 1 shows the main chemical and physical characteristics of the sites under study. In general terms the concentration and levels of variability in soil salinity, sodicity, and boron increased with soil depth, whereas the values of wilting point varied little. The 'regional' variability, i.e. coefficient of variation, %, for each of these parameters at each of the soil depths was greatest for boron in the upper layers (0–0.4 m), and for salinity in the deeper layers (0.4–1 m) (Table 1). Interestingly the coefficients of variation for soil sodicity

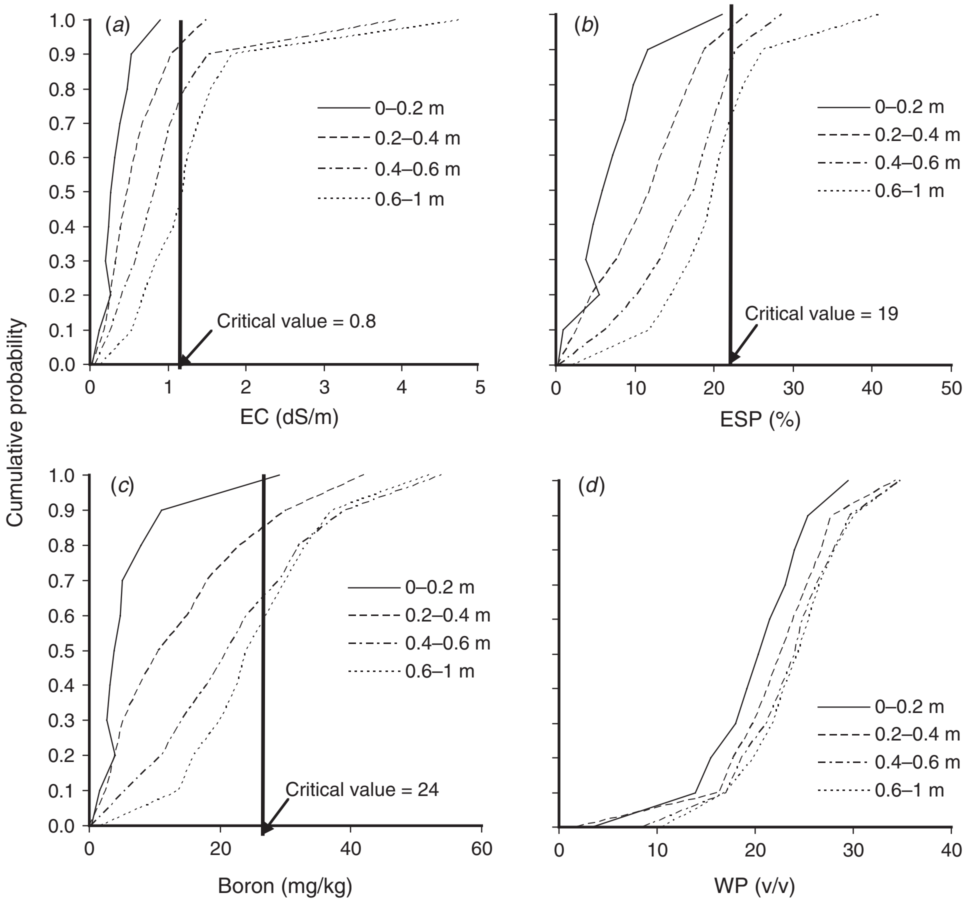

Fig. 1. Cumulative probability distribution of (*a*) soil salinity, EC (dS/m); (*b*) (%) exchangeable sodium percentage, ESP; (*c*) soil boron; and (*d*) volumetric soil water content at −15 kPa (WP), at 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–1 m depths from 150 sites around Birchip. Vertical lines in *a*, *b*, and *c* indicate critical threshold values for grain yield. After Nuttall *et al*. (2003*a*).

Table 1. Coefficients of variation (%) for salinity (EC), exchangeable sodium percentage (ESP), boron (B), cation exchange capacity (CEC), and soil water −15 kPa (WP), at different depths, observed in soil samples from the Birchip region (after Nuttall *et al*. 2003*a*)

Soil layer (m)	EC	ESP	B	CEC	WP
0–0.2	55.0	67.8	94.1	28.5	25.9
0.2–0.4	59.4	54.2	79.5	19.3	24.0
0.4–0.6	68.8	39.8	58.5	17.9	22.4
0.6–1	54.8	33.7	40.0	17.1	20.0

Table 2. Correlation matrix for the coefficients of variation across different soil chemical and physical properties

Soil salinity (EC), exchangeable sodium percentage (ESP), boron (B), cation exchange capacity (CEC), and soil water –15 kPa (WP) at different depths, observed in soil samples from the Birchip region

	EC	ESP	B	CEC
EC	1			
ESP	−0.32	1		
B	−0.16	0.98	1	
CEC	−0.42	0.91	0.83	1
WP	−0.094	0.97	0.99	0.85

were highly correlated with the coefficients of variation for boron, cation exchange capacity, and soil lower limit (Table 2), but not with the coefficients of variation for soil salinity.

Frequency distributions of key soil chemical constraints were compared with the critical values derived by Nuttall *et al*. (2003*b*). In more than 50% of the sites, salinity was higher than the critical value of 0.8 dS/m at depths below 0.6 m. In about 50% of the sites, sodicity and boron were above the critical values of 19% and 24 mg/kg at depths below 0.6 m.

Simulation Expt 1

A soil rooting distribution factor, i.e. relative root mass density, was calculated from the measured values of root mass in each layer, relative to the root mass density in the upper layer (0–0.1 m) at each of the 150 sites (Fig. 2). The

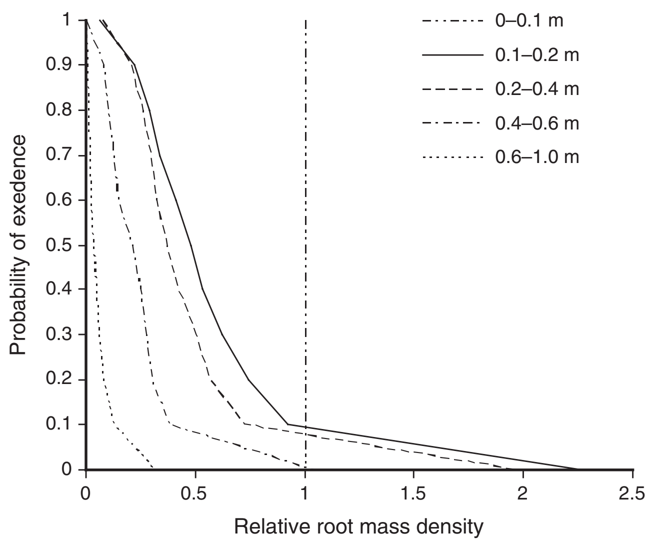

Fig. 2. Probability distribution for the root mass density in different soil layers relative to that in the 0–0.1 m layer for 150 sites around Birchip. After Nuttall *et al*. (2003*b*).

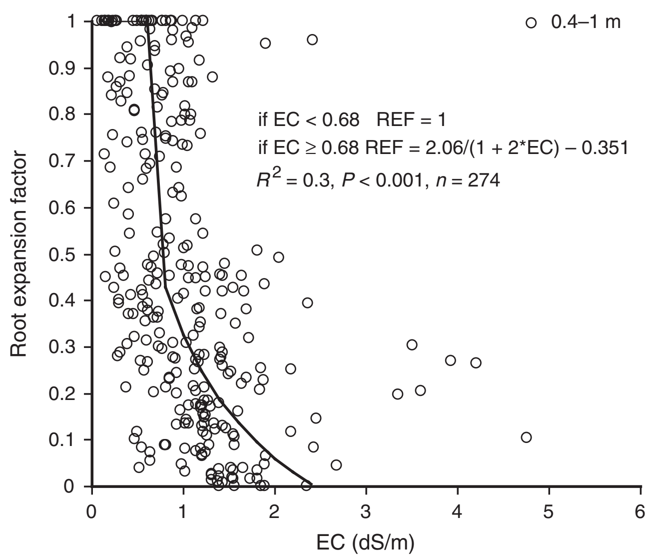

Fig. 3. Derived root expansion factor as a function of soil EC (dS/m).

median root distribution factor (RDF) for the layer 0.1–0.2 m was 0.74, for the layer 0.2–0.4 m was 0.47, for the layer 0.4–0.6 m was 0.41, and for the layer 0.6–1 m was 0.12. To eliminate the effect of declining root mass density with depth, a standardised root expansion factor was derived for each soil layer. This factor was calculated relative to the RDF values observed in each layer at the site that produced the highest grain yield, i.e. 6 t/ha. At this site the values of salinity, sodicity, and boron were low in all soil layers.

The soil characteristic that best explained the observed variability in the root expansion factor among soil layers and sites was soil salinity. The values of the root expansion factor in the 0.4–1 m layer were inversely correlated with EC ($r = -0.59$), soil sodicity ($r = -0.53$), and soil boron ($r = -0.47$). In this exercise we assumed that soil salinity was the main limiting factor for soil root exploration at depth. From the relationship shown in Fig. 3, we assumed that the root expansion factor had a value of 1 for EC below 0.68 dS/m, and that it decreased hyperbolically to 0 at values of EC higher than 0.68 dS/m (Eqn 1):

$$\text{if EC} < 0.68,\ \text{Root expansion factor} = 1$$

$$\text{if EC} \geq 0.68,\ \text{Root expansion factor} = \frac{2.06}{(1 + 2 \cdot \text{EC})} - 0.35 \quad (1)$$

Figure 4 shows the performance of the model APSIM-Wheat when 16 randomly selected sites around Birchip were simulated assuming: (*i*) the observed root distribution within the soil profile at each site and measured values of WP as inputs to the model (Hypothesis A), (*ii*) ignoring the presence of subsoil constraints and using measured values of WP (control), (*iii*) calculating the root soil profile distribution from a function relating root distribution and EC (dS/m) (Hypothesis A), and (*iv*) calculating the value of the crop lower limit (parameter *ll* in APSIM) for each soil layer, as a function of the EC (dS/m) as proposed by Sadras *et al*. (2003) (Hypothesis B). Simulated outputs were sensitive to the different assumptions and affected the degree of fit between observed and predicted values (Fig. 4). Assuming no limitation to root growth and the measured values of WP as the lower limit for soil water uptake by roots (control), the model explained only 43% of the observed variability in grain yield with a root mean squared deviation (RMSD) of 0.98 t/ha (Fig. 4*b*). Assuming the observed root distribution at each site and the measured values of LL15 as the lower limits for soil water uptake (Hyp. A), the model explained 70% of the observed variability in grain yield (RMSD = 0.75 t/ha) (Fig. 4*a*). This compared with 58% when a median root exploration factor calculated from the 150 sites was applied to the 16 simulated sites (Hyp. A) (RMSD = 0.97 t/ha) (not shown in Fig. 4), and to 60% when the root distribution was calculated from Eqn 1 (Hyp. A) (RMSD = 0.9 t/ha) (Fig. 4*c*). When the root exploration factor was set to 1 for all soil layers at all sites and the lower limit for soil water extraction was calculated as a function of the EC for each soil layer (Hyp. B) the model explained 65% of the observed variation in grain yield (RMSD = 0.86 t/ha) (Fig. 4*d*).

A more thorough analysis of the comparison between observed and simulated grain yield was done by subdividing the mean square deviation (MSD) into its squared bias (SB), squared difference between standard deviations (SDSD), and lack of correlation weighted by the standard deviations (LCS) (Fig. 5). Briefly, a high SB indicates large bias of the simulation from the measurement, a high SDSD indicates that the model failed to simulate the magnitude of the fluctuation

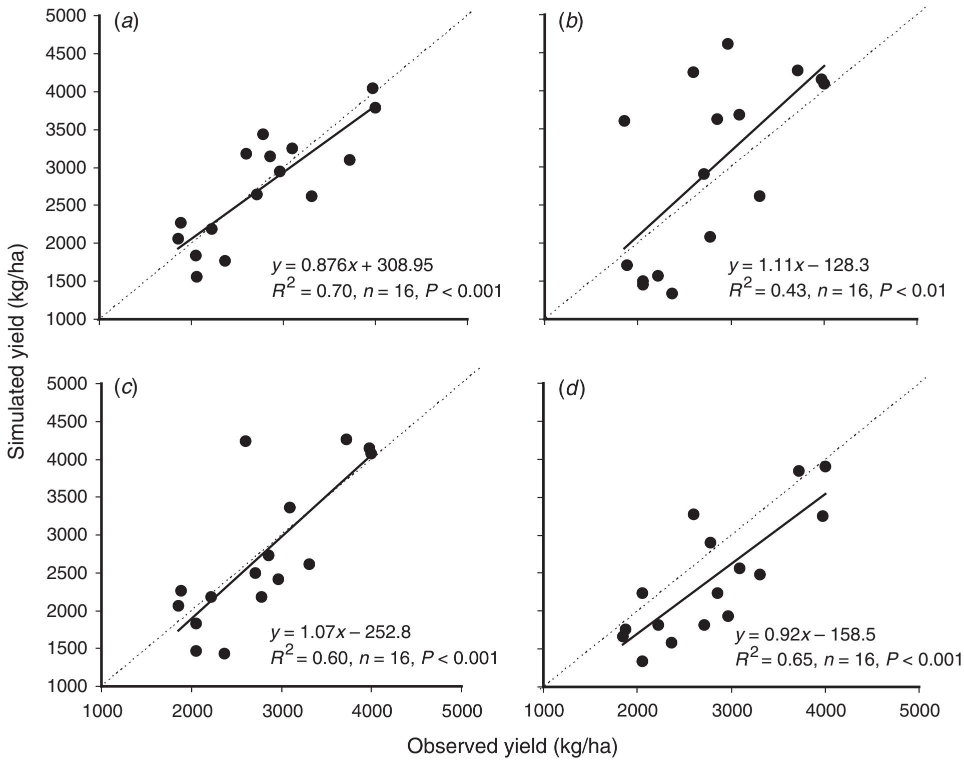

Fig. 4. Simulated *v.* observed wheat yields at 16 sites around Birchip in 1999. Simulated results were obtained after (*a*) using observed root profile distributions as input in the model; (*b*) ignoring the presence of subsoil constraints; (*c*) estimating a potential root distribution factor as a function of soil salinity; and (*d*) modifying the crop lower limit for soil water uptake as a function of soil salinity. After Nuttall *et al*. (2003*b*).

among the measurements, and a high LCS means that the model failed to simulate the pattern of the fluctuation across the measurements, i.e. lack of positive correlation.

The lack of fit $(1 - r)$ and MSD were lowest in simulation using observed root distribution, and highest for the control simulation, for which subsoil constraints were ignored. Assuming the median root profile distribution of the 150 sites, or deriving the root profile distribution from EC values (SRF–EC in Fig. 5), gave intermediate results (Fig. 5). In general, the lack of positive correlation between observed and simulated results was the main component explaining the values of MSD. For Hypothesis B (LL–EC in Fig. 5), the bias and failure of the model to simulate the magnitude of the observed variability were also important. This indicated that other factors could have also been active as shown by a positive relationship between EC in the 0.4–0.6 m layer and the residuals between observations and simulated results assuming Hypothesis B (residuals = 381*EC – 55, $R^2 = 0.16$, $n = 16$, $P < 0.08$).

Figure 6*a* and *b* shows the performance of the APSIM-Wheat model in simulating the soil water balance at Birchip and Brim, respectively, over 2 consecutive cropping seasons, assuming: (*i*) the observed crop lower limit for soil water extraction (parameter *ll* in APSIM) derived as the minimum soil water content observed in each soil layer during 2 consecutive cropping seasons (Observed CLL), (*ii*) root soil profile distribution factor derived from Eqn 1 (SRF), and (*iii*) the value of the crop lower limit (parameter *ll* in APSIM) estimated for each soil layer as a function of EC (dS/m) as proposed by Sadras *et al*. (2003) (LL–EC). At both locations and for all soil depths, estimating the crop lower limit for soil water uptake using values of EC (Sadras *et al*. 2003) closely followed both the observed values (symbols), and the results from the simulations when the observed crop lower limit (Observed CLL) was used as input in the model. Assuming that salinity reduced root exploration according to Eqn 1, overestimated soil water availability at Birchip. At Brim, all tested assumptions gave similar results for the upper layers (Fig. 6*a* and *b*), whereas in the deeper layers (Fig. 6*c* and *d*) both approaches underestimated the crop lower limits observed in the field. Figure 7 illustrates that the approach using EC to estimate the crop lower limit was able to explain 68% of the variability in the average farm yields in Birchip and Brim.

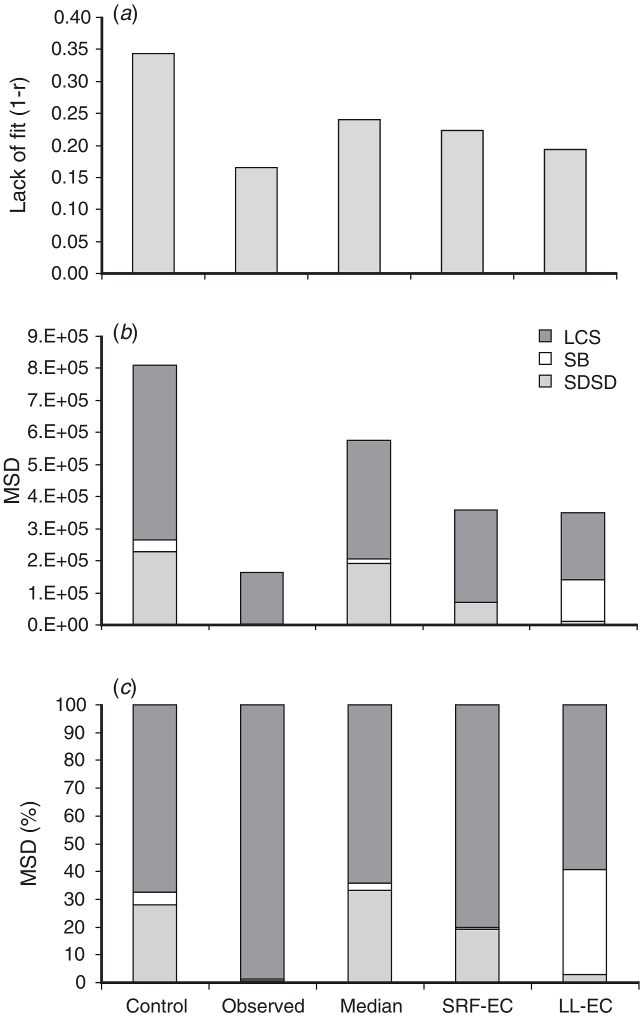

Fig. 5. Lack of fit (*a*), and (*b* and *c*) partitioning of the mean square deviation (MSD) into squared difference between standard deviations (SDSD), bias (SB), and lack of positive correlation (LCS), for simulations ignoring the presence of subsoil constraints (Control), and simulations assuming: the observed root distribution (Observed), the median root distribution observed in the region (Median), a root distribution calculated as a function of the salinity of each soil layer (SRF–EC), and the changes in the lower limit for crop water uptake estimated from the soil salinity in each soil layer (LL–EC).

Simulation Expt 2

To study the importance of the interactions between subsoil constraints and climate variability, and quantify the economic effect of subsoil constraints in the southern Mallee of Victoria, we conducted long-term simulations assuming 3 levels of soil salinity: low (decile 1), regional median (decile 5), and high (decile 9), as derived from Fig. 1*a*. The effect of soil salinity on crop growth and yield was modelled following the assumptions of Sadras *et al*. (2003). Figure 8, shows the simulated relationship between grain yield and in-crop rainfall for 2 contrasting levels of salinity (decile 5 and decile 9) for the period 1900–2002. The solid line in Fig. 8 indicates an average ‘rainfall water-use efficiency’ and ‘non-productive water loss’ of 15.4 kg/mm and 63 mm for a median level of salinity. These values are reduced by 12% and increased by 46%, for a high salinity (decile 9) level, respectively. Figure 9 illustrates the relationship between the effect of subsoil salinity and in-crop rainfall. The effect is estimated as the ratio of simulated grain yield at high level to that at medium level. The response indicates that the effect of a severe subsoil constraint would be less during wetter seasons and that it is more likely to have greater impact during El Niño years than during La Niña years. Both the level of soil salinity and whether the season was defined as El Niño or as La Niña had an important effect on the probability distribution of gross margin (Fig. 10). With median levels of salinity, negative margins can be expected in this region once every 5 years over the period 1900–2002. However, for high salinity soils, losses can be expected up to once every 3 years, whereas for low salinity conditions there was only one loss every 20 years (Fig. 10*a*). When the season is defined either as El Niño or La Niña, these risks change dramatically (Fig. 10*b* and *c*). During El Niño years the chance of making a loss is 50, 40, and 15% for high-, median-, and low-salinity areas, respectively. During La Niña years the chances of making a loss are very small even in high-salinity areas (Fig. 10*c*).

Discussion

With this work we tested the predictive capacity of the model APSIM-Wheat for a region having soils with important physicochemical subsoil constraints; applied the APSIM-Wheat model to study the interactions between subsoil constraints and seasonal conditions; and estimated the economic effect that subsoil constraints have on wheat farming in the Victorian Mallee under different climatic scenarios.

Soil constraints in the Birchip region

Soils from the Victorian Mallee (Birchip region) are mostly Calcarosols with vertic subsoils (i.e. Vertic Calcarosols), which generally present gilgai microrelief (Imhof *et al*. 2003). Proportionally less important, Vertosols are found in some of the gilgai depressions (Imhof *et al*. 2003). In this region, spatial variability in crop water use and production is highly related to the presence of gilgaied plains with hummocks or rises, and associated variability in the depth at which high levels of salinity, sodicity, and boron are found. Generally, the shallower (Calviño and Sadras 1999) and the more intense the limitation (Munns 1996), the more severe will be the effect on the crop. Nuttall *et al*. (2003*a*, 2003*b*) produced important advances in the description and extent of subsoil constraints in the southern Mallee region of Victoria, and Sadras *et al*. (2003) produced the first quantitative analysis of the effect of subsoil constraints on the water budget components of wheat in coarse-textured soils from the northern Mallee.

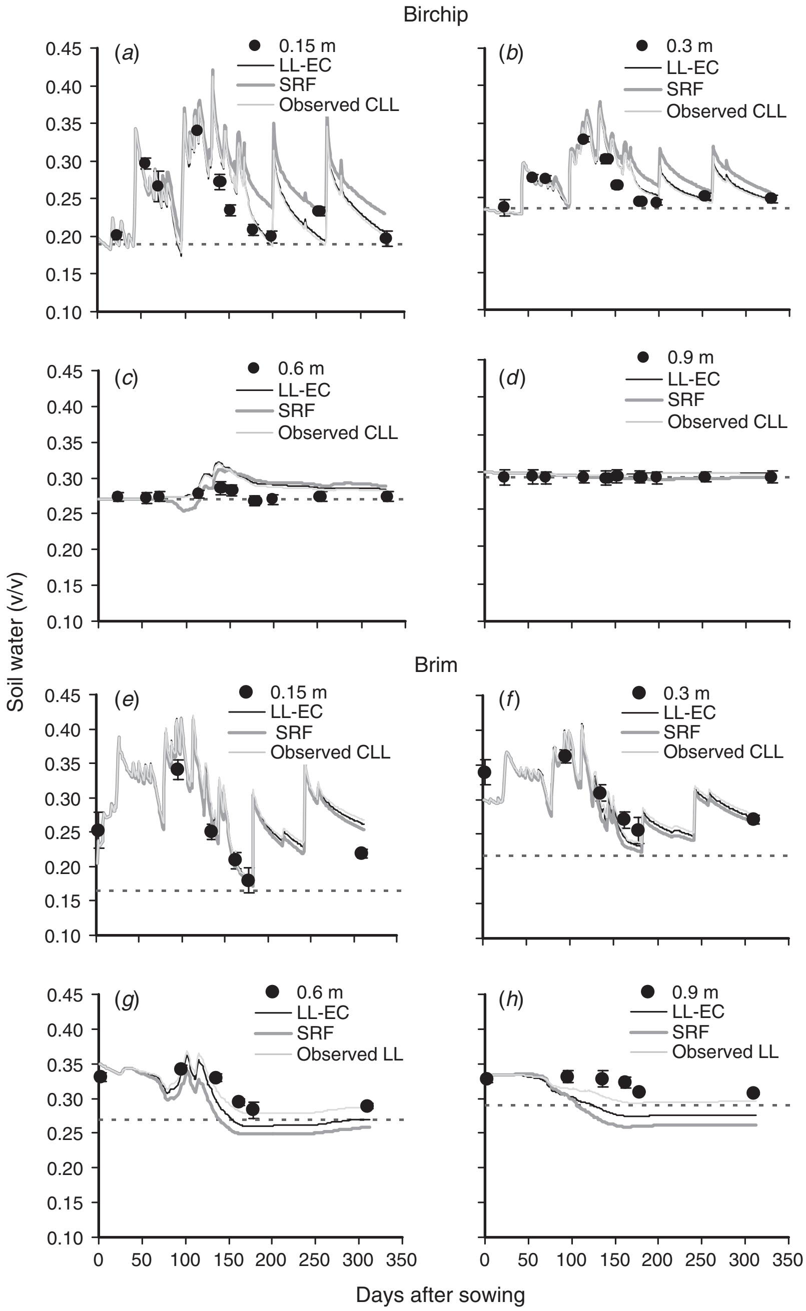

Fig. 6. Observed (symbols) and simulated (lines) volumetric soil water content at (*a*) 0.15 m, (*b*) 0.3 m, (*c*) 0.6 m, and (*d*) 0.9 m for a wheat crop during the 1993–94 season in Birchip, and (*e*) 0.15 m, (*f*) 0.3 m, (*g*) 0.6 m, and (*h*) 0.9 m at Brim. Simulated results are derived assuming values of crop lower limit estimated from (*i*) soil salinity (LL–EC), (*ii*) a root distribution factor derived from soil salinity (SRF), and (*iii*) a crop lower limit (Observed CLL) estimated as in Dalgliesh and Foale (1998). The lowest soil water content observed in the field for each soil layer is included as a horizontal dashed line.

Critical thresholds for the effect of salinity (8 dS/m), and sodicity (19%), were derived empirically from fig. 6 of Nuttall *et al*. (2003*b*), and are represented here in Fig. 1. Using these thresholds we found that more than 50% of the tested sites had salinity higher than the critical value in the 0.4–0.6 m layer, whereas in about 50% of the sites the values of sodicity and boron were above the critical values in the 0.6–1 m layer. In the work of Nuttall *et al*. (2003*a*) in the

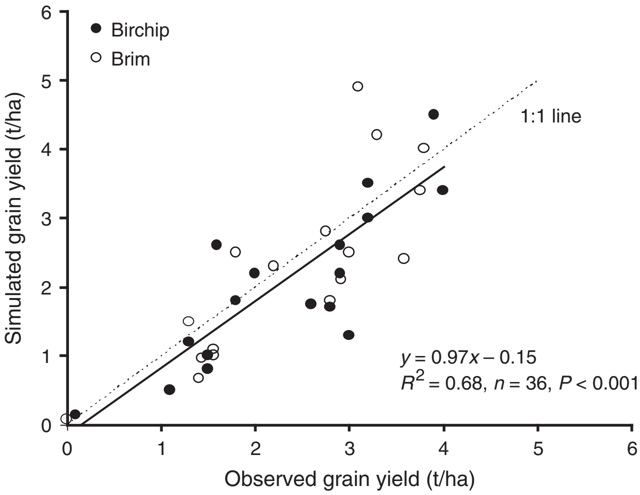

Fig. 7. Observed *v.* simulated average farm wheat yields for 2 farms at Brim and Birchip, for the period 1983–2002. Results for 1992 and 1993 were excluded due to effects of diseases and frost damage, respectively.

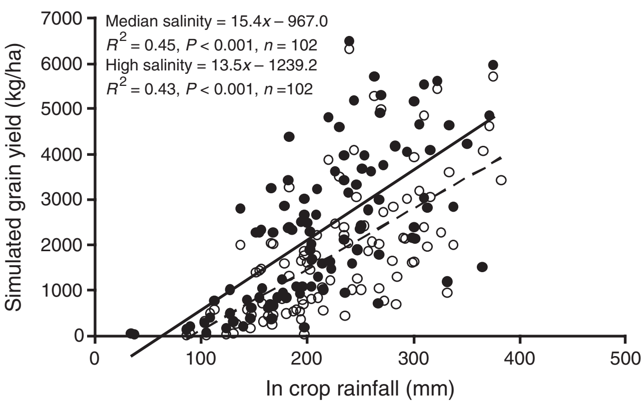

Fig. 8. Simulated grain yields as a function of in-crop rainfall assuming the median and high levels of salinity observed in the region.

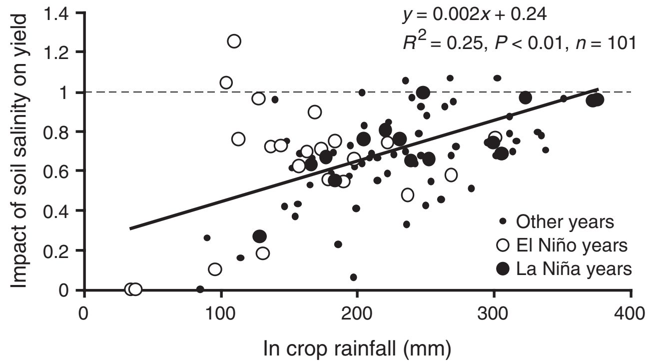

Fig. 9. Effect of soil salinity as a function of in-crop rainfall. The effect is estimated as the ratio of simulated grain yield at high soil salinity and that at median level of soil salinity.

Victorian Mallee as well as in Sadras *et al.* (2003) in the northern Mallee, salinity was identified as the main subsoil constraint. Both studies also presented interrelationships among pH and boron, salinity, and sodicity. These relationships were obtained by pooling information from a range of soil depths and locations, disregarding interrelationships between the parameters and the change in soil texture with soil depth as shown in Sadras *et al.* (2002, 2003). As an example, a simple correlation between the coefficients of variation for the different soil properties across Nuttall's data set, showed very little relationship between sodicity and salinity (Table 2). However, as previously found by Nuttall *et al.* (2003*a*) and Sadras *et al.* (2002), strong relationships can be expected between soil sodicity and boron concentration, cation exchange capacity, and textural properties such as the laboratory-determined lower limit for soil water extraction. We think this supports the argument by Nuttall *et al.* (2003*a*) that the accumulation of salts in these soils might have occurred later than their alkalinisation, which limits our capacity to predict soil sodicity from rapid determinations of soil salinity.

Performance of algorithms

Unquestionably, subsoil constraints have to be taken into account in any model-based analysis of cropping on soils of the Victorian Mallee. In APSIM, the potential effect of subsoil properties on crop growth and production is generally assumed to be incorporated after measuring the lower limit of crop water extraction in the field under rain-out shelters installed around anthesis (parameter *ll* in APSIM) (Dalgliesh and Foale 1998). Sadras *et al.* (2003) determined the parameter *ll* for APSIM more accurately by continuously recording soil water at different soil depths, over a period of more than 3 years, involving 2 canola crops and 1 wheat crop. Given the high variability in subsoil properties observed in the Victorian Mallee (Fig. 1 and Nuttall *et al.* 2003*a*), we suggest that any modelling exercise should not ignore existing within-paddock spatial variability in subsoil constraints. In order to account for such spatial variability and to capture its importance, algorithms and methods to capture such variability are required. It is possible that key variables could be rapidly and inexpensively collected using mobile electromagnetic induction techniques (Nelson and Ham 2000; O'Leary *et al.* 2003), and results translated into inputs for crop simulation models. To develop these algorithms we tested whether the effect of subsoil constraints on wheat yield in soils of the Victorian Mallee could be explained by assuming either (*a*) that root exploration within a particular soil layer was reduced by the presence of toxic concentrations of salts; or (*b*) that soil water uptake from a particular soil layer was reduced by high concentrations of salts through osmotic effects.

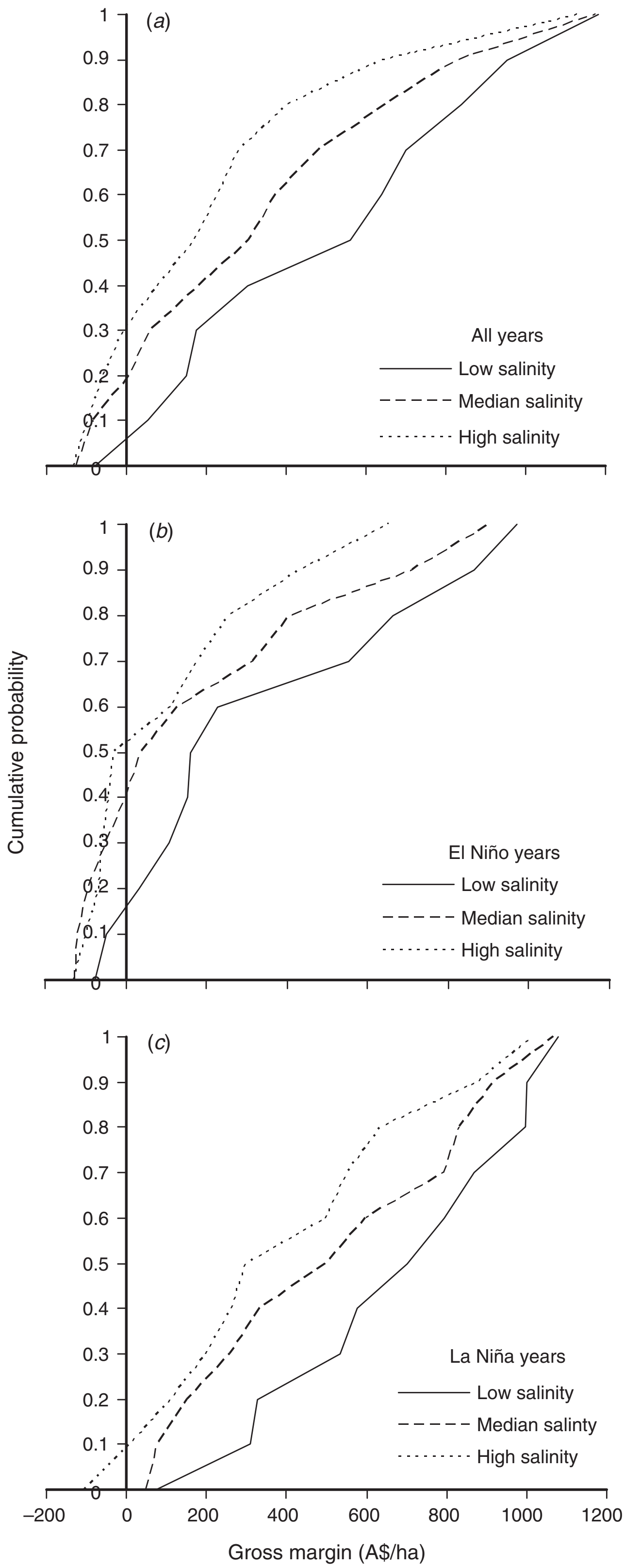

Fig. 10. Cumulative probabilities for the gross margin of growing wheat in the Victorian Mallee for 3 levels of salinity for (*a*) all the years (102 years), (*b*) 24 El Niño years, and (*c*) 16 La Niña years.

The algorithms developed here and those of Sadras *et al.* (2003) improved the capacity of the APSIM-Wheat model to simulate wheat yield on soils having severe subsoil constraints (Fig. 4). The simulation analysis of wheat yield (Fig. 5) showed no clear advantage for Hypothesis *a* or *b*. However, the soil water simulations suggested some advantage for Hypothesis *b*. Furthermore, the results shown in Fig. 7 indicate that this approach was also able to reliably reproduce average farm wheat yields when a decile 5 of soil salinity was assumed.

Effect of subsoil constraints in the Victorian Mallee

Crop responses to subsoil constraints, particularly salinity, are consistent with many symptoms of crop response to drought stress (Munns 2002). Common subsoil constraints found in western Victoria generally reduce the capacity of the crop to take up water, leading to reductions in growth and grain yield. In addition, under extreme conditions, accumulation of toxic levels of salts in leaf tissue can cause premature senescence, particularly of the older leaves, i.e. leaves that have been transpiring and accumulating salts for a longer time. In saline soils the root is the first organ to be in contact with a hostile environment; therefore, roots could also dramatically reduce their growth in saline soil layers. Reductions in root growth in saline solutions have been attributed to cell-wall hardening rather than to changes in turgor in maize (Neumann *et al.* 1994; Rodríguez *et al.* 1997). Plant responses to subsoil constraints have been observed to vary according to factors including crop variety, soil texture, agronomic practice, and climate (Ulery *et al.* 1998; Rengasamy 2002). Seasonal variations in the amount and distribution of rainfall could produce variation in the effect of subsoil constraints, as a result of changes in the pattern of root density distribution in the soil profile. In cereals, salinity can reduce the number of florets per ear, and alter the time of flowering and hence maturity (Munns and Rawson 1999). Similar effects can be observed under drought stress, which may complicate our capacity to separate both effects. Our modelling exercise reproduced the general observation, by farmers and consultants, that the effect of subsoil constraints is greater during dry seasons. This magnifies the effect of climate variability on productivity in soils from the Victorian Mallee. A similar association between seasonal rainfall and subsoil constraints was found for long-term simulations at Parafield in South Australia (Sadras *et al.* 2003). In their study, more complex patterns emerged when interactions were investigated over a broader range of rainfall environments, i.e. 200–600 mm. They identified a seasonal rainfall threshold of 273 mm. Above this rainfall level, the relationship between the effect of a subsoil constraint on grain yield and seasonal rainfall shifted from negative or neutral to positive. This agrees with our finding for the Birchip region, which has an average seasonal rainfall close to that threshold level (257 mm). A strong influence of the El Niño Southern

Oscillation was also observed on the effect of soil salinity level on grain yield (Fig. 9) and gross margin (Fig. 10). The more frequent occurrence of drier seasons during El Niño years increased the chance of low or negative gross margins, whereas the more frequent wetter seasons during La Niña years significantly decreased this chance. These results indicate an important interaction between seasonal conditions and the intensity of the subsoil constraints.

Conclusions

On soils having subsoil constraints, climate variability and soil properties interact in such a way that rainfall information alone will provide an incomplete picture of the effect of climate variability on yield. This highlights the importance of the integration of soil properties and climate conditions with cropping systems models for risk management and farm planning. Simulation exercises in the Victorian Mallee should account for the presence of subsoil constraints. Here we have shown that methods developed for coarse-textured soils of the South Australian and Victorian Mallee can be extrapolated to highly saline and sodic, fine-textured soils of the Victorian southern-Mallee and northern Wimmera regions. However, we could not conclude whether limiting root exploration or rate of water extraction or both was the preferable approach for model adaptation.

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