Adaptation of the APSIM-Wheat module to simulate the growth and production of wheat on hostile soils

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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 North Western Victoria, i.e. Victorian Mallee, where hostile subsoils, i.e. salinity, sodicity and boron toxicity, are known to limit grain yield. With this paper we tested two basic hypothesis that could lead to improve the predictive capacity of APSIM-wheat in the region, i.e. (A) root exploration within a particular soil layer can be reduced by the presence of toxic concentrations of salts, and (B) soil water uptake from a particular soil layer can be reduced by high concentration of salts through osmotic effects. Despite 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 impact of subsoil limitations on growth and yield of wheat in the Victorian Mallee should be explained through 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.

Key Words

Root growth, salinity, sodicity, boron

Introduction

The use of simulation modelling to improve crop management decisions (5), optimise cropping systems (9), quantify environmental risks (1), and evaluate the impact of climate variability and climate change (5) has proven to be important and valuable. However, subsoil limitations such as salinity or sodicity have so far limited the application of simulation models in regions such as in the main cereals 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 (8), and even to toxic levels of soil boron (3). With this paper we aim to test two basic hypothesis that could lead to improve the predictive capacity of APSIM-wheat (11), i.e. (A) root exploration within a particular soil layer can be reduced by the presence of toxic concentrations of salts, and (B) soil water uptake from a particular soil layer can be reduced by high concentration of salts through osmotic effects.

Methods

Soil and crop data was collected from an area of 3600 km^2 in the Birchip district (35?58'67"S, 142?54'58"E) of Victoria, Australia (7). This is a semi-arid region with an average annual rainfall of 376 mm, concentrated between April and November. In this region the average minimum temperature in July is 3.6?C and the average maximum temperature in January is 30.7?C. The soil types are dominantly Calcarosols (7). The data set consisted of soil and crop characteristics determined in transects of ten points at fifteen locations, i.e. 150 sites, within a radius of ca. 30km around Birchip. At each site the following soil variables were determined at different depths in the soil profile: soil boron (mg B kg^{-1} soil), EC (dS m^{-1}), exchangeable sodium (ESP, %), N-NO_3 (ppm), volumetric soil water content at sowing, volumetric soil water content at –15bar (LL15), and bulk density. Among others, crop variables included layered root dry weight at anthesis, and final grain yield.

APSIM-Wheat has been tested against field studies in different regions of Australia. In this exercise the model APSIM-Wheat parameterised with modules SOILN2, SOILWAT2 and RESIDUE2, was used to simulate 19 out of 150, randomly selected sites. The model was calibrated for the wheat crop cv. Frame using an independent data set provided by Dr. R. Flood (unpublished). Values of soil water content at saturation (SAT) were calculated from values of bulk density (2), values of drainage upper limit (DUL) were derived from a relationship between SAT and DUL determined from wet ponds in soils of the Mallee and Wimmera regions, and soil water lower limits (LL) were taken as LL15. Wheat yields were simulated by assuming, (i) no limitation to root growth and measured values of LL15 (control), (ii) the observed root distribution within the soil profile at each site and measured values of LL15 (Hypotheses A), (iii) a median root distribution within the soil profile calculated from the 150 sites (Hypotheses A), (iv) calculating the root distribution out of a function relating root distribution and EC (dS m^{-1}) (Hypotheses A), and (v) calculating the value of lower limit for each soil layer, as a function of their EC (dS m^{-1}) as proposed by Sadras (11) (Hypotheses 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 determination coefficients, root mean squared errors, and by desegregating the mean squared error following the methodology proposed by Kobayashi (4).

Results

Figure 1 shows the main chemical and physical characteristics of the sites. In general terms the concentration and levels of variability in soil salinity, sodicity and B increased with soil depth, while the values of LL15 varied much less. In more than 50% of the sites the values of salinity were higher than the critical value of 0.8 dS m^{-1} below 0.6m; in about 50% of the sites the values of sodicity and boron were above the critical values of 19% and 24 mg kg^{-1} below 0.6m, respectively. The critical values were defined in a previous work (7).

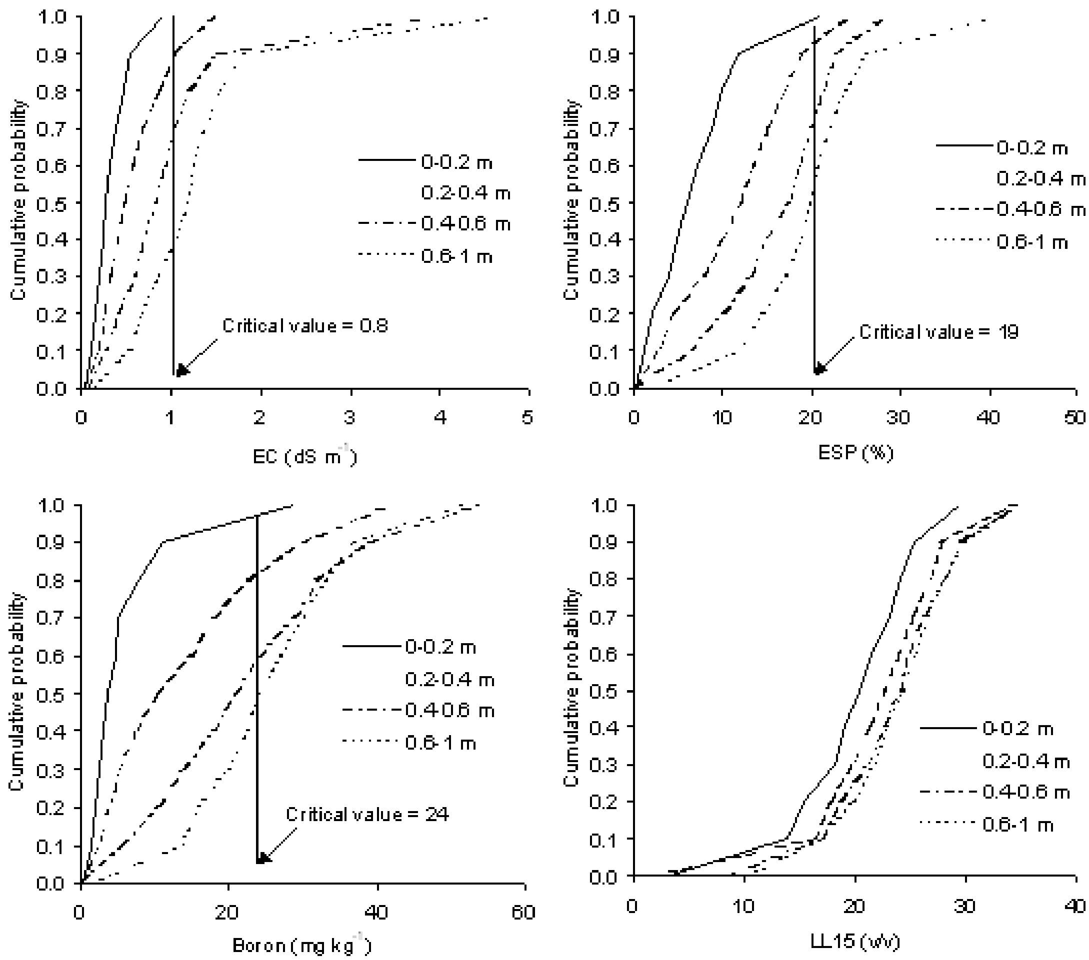

Figure 1. Cumulative probabilities for soil salinity (EC, dS m^{-1}), sodicity (ESP, %), soil boron (Boron, mg kg^{-1}), and volumetric soil water content at –15 bars (LL15). Vertical lines indicate critical levels of the variable for crop growth.

A root distribution factor (RDF) was calculated relative to the root mass density in the upper layer at each of the 150 sites. The median root distribution factor for the layer 0-0.1m was 1, for the layer 0.1-0.2m was 0.74, for the layer 0.2-0.4 m was 0.47, for the layer 0.4-0.6 was 0.41, and for the layer 0.6-1m was 0.12. To eliminate the effect of root mass density declining with root depth, a standardised root exploration factor (SRF) with soil depth was derived for each individual soil layer. SRF was calculated relative to the RDF values of each layer observed in the site that produced the highest grain yield i.e. 6 t ha^{-1}. 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 SRF among soil layers and sites was soil salinity. The values of SRF for the layers 0.4-1m were inversely correlated to EC, r = -0.59, SRF was less related to soil sodicity (r = –0.53) or soil boron (r = -0.47). According to these correlation coefficients, soil salinity was considered to be the main limiting factor for soil root exploration in depth (Figure 2). In Figure 2, we assumed that SRF was 1 at values of EC below 0.75dS m^{-1}, and that SRF sharply decreased to 0 at values of EC higher than 0.75 dS m^{-1}.

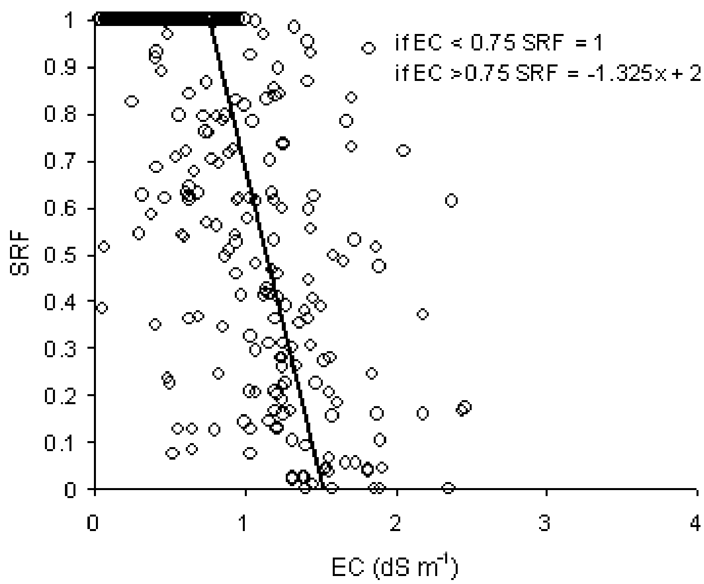

Figure 2. Standardised rooting factor (SRF) as a function of soil salinity (EC, dS m^{-1}) for the layers 0.4-1m.

Simulated outputs were sensitive to the different modelled hypothesis affecting the lack of fit between observed and predicted results (Figure 3a). Assuming no limitation to root growth and the measured values of LL15 as the lower limits for root soil water uptake (control), the model explained only 56% of the observed variability in grain yield with a root mean squared error (RMSE) of 0.98 t ha^{-1}. 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 66% of the observed variability in grain yield (RMSE=0.75 t ha^{-1}), this compared to a 58% when a median root exploration factor calculated from the 150 sites was applied to the 19 simulated sites (Hyp. A) (RMSE=0.97 t ha^{-1}), and to a 64% when the root distribution was calculated from the equations in Figure 2 (Hyp. A) (RMSE=0.9 t ha^{-1}). 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 off the values of EC for each soil layer (Hyp. B) the model explained 72% of the observed variability in grain yield (RMSE=0.86 t ha^{-1}).

A more thorough analysis of the comparison between observed and simulated grain yields was done by subdividing the mean square error into its squared bias (SB), squared difference between standard deviations (SDSD), and lack of correlation weighted by the standard deviations (LCS), components (Figure 3b). See (4) for the calculation methodology. Briefly, a high SB indicates a big bias of the simulation from the measurement, a high SDSD indicates that the model failed to simulate the magnitude of the fluctuation 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 o positive correlation.

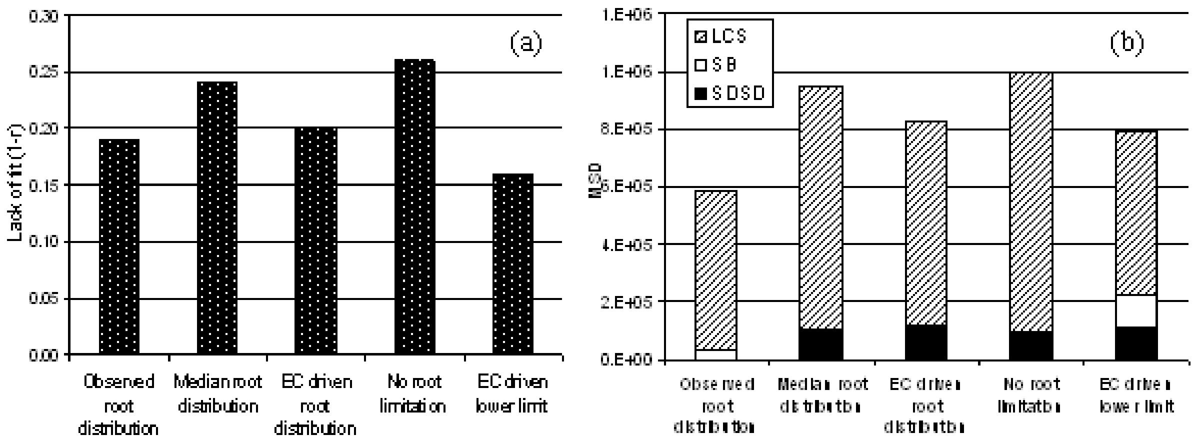

Figure 3. Lack of fit for the simulations assuming the observed root distribution, the median root distribution across the region, root distribution calculated as a function of EC in each soil layer, no root limitation in the soil profile and root distribution as a function a lower limit calculated from the EC values of each soil layer (a), discrimination of the mean squared deviation (MSD) into lack of correlation (LCS), bias (SB) and the squared difference between standard deviations (b).

Lack of fit was lowest when the lower limit for soil water extraction was calculated using the values of EC at each soil layer according to (10). The lack of fit was highest for the control simulation. Modifying the root profile distribution according to the observed, median or EC values at each soil layer gave intermediate results. The value of MSE was lowest when the observed root distribution was assumed for the simulations and highest for the control simulation. In general, the lack of positive correlation between observed and simulated results was the main component explaining the values of MSE. For Hyp. B, the bias and failure of the model to simulate the magnitude of the observed variability were also important. This indicates that other factors could also be active as shown by a positive relationship between EC in the 0.4-0.6m layer and the residuals between observations and simulated results assuming Hyp. B (residuals = 381 EC-55, R^2=0.16, n=19, P<0.08).

Conclusion

Whether the impact of subsoil limitations on growth and yield of wheat in the Victorian Mallee should be explained through toxic, osmotic or both effects acting simultaneously requires still further research. At present, the performance of APSIM-Wheat in the region can be improved either by assuming increased values of LL15, or by modifying the pattern of root exploration in the soil profile both according to readings of EC in each soil layer.

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