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How well do we need to estimate plant-available water capacity to simulate water-limited yield potential?

Renye Wu[a,b,*], Roger Lawes[b], Yvette Oliver[b], Andrew Fletcher[b], Chao Chen[b]

[a] College of Crop Science, Fujian Agriculture and Forestry University, Fuzhou, 350002, China
[b] CSIRO Agriculture and Food, Private Bag 5, Wembley, WA, 6913, Australia

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ABSTRACT

A key determinant of water-limited yield potential in dryland agriculture is the soil's plant available water capacity (PAWC), the difference between drained upper limit and crop lower limit over the rooting depth. To simulate water-limited yield potential (Yw), a crop model must be parameterised for the local edaphic conditions, which require a quantitative description of drained upper limit, crop lower limit and rooting depth. Often, these soil properties have to be estimated from existing soil surveys, which creates uncertainty for drained upper limit, crop lower limit or rooting depth. The impact of uncertainty in these soil properties on the estimation of Yw has not previously been reported. Using the Agricultural Production Systems sIMulator (APSIM), a sensitivity analysis was performed to identify the effect of uncertainties in drained upper limit, crop lower limit and rooting depth on wheat Yw for two contrasting rainfall sites (high and low) with two typical soil types (shallow sandy duplex and clay) in Western Australia. Simulation results demonstrated that the resultant change in PAWC was the dominant driver of a change in the estimate of Yw, irrespective of whether such a change was caused by drained upper limit, crop lower limit or rooting depth. Estimated errors that underestimated or overestimated PAWC by up to 20 mm only had a marginal impact on Yw (less than 200 kg ha^{-1}) in all environments (soil type × location). But when this error was more than 20 mm, an underestimation would cause more severe deviation of Yw of wheat than an overestimation. On average, 40 mm underestimation of PAWC resulted into 530 kg ha^{-1} of Yw, while this amount of overestimation caused overestimation of Yw about 290 kg ha^{-1}. The bias of underestimated wheat Yw due to underestimation of PAWC was generally increased with rainfall up to 350 mm. We conclude that it is better to estimate soil hydrological parameters towards overestimating PAWC than to underestimate PAWC. However, where possible, all three soil hydrological parameters should be estimated as accurately as possible.

1. Introduction

Process-based crop simulation models are useful tools for agricultural analysis. They have been widely used for predicting crop yield (Batchelor et al., 2002; Gabrielle et al., 2002; Wart et al., 2013) and yield gaps (Lobell et al., 2010; Wart et al., 2013), as well as understanding the adaptation of crops to their environments (Chapman, 2008; Kirkegaard and Hunt, 2010; Shorter et al., 1991; Villalobos et al., 1996) and improving management practices in agricultural systems (Matthews et al., 2002; Yu et al., 2006). Crop models require inputs of soil physical and hydrological properties, besides climate and crop data. However when crop models, like the Agricultural Production Systems sIMulator (APSIM) that requires inputs of drained upper limit, crop lower limit and rooting depth, are used to simulate crops at regional or larger spatial scales, it is often difficult to precisely characterise these attributes of the soil, due to the inherent variability in natural processes, costly monitoring, or imperfections in data measurements (Wang et al., 2005; Wu et al., 2010). National soil maps often provide information on a local dominant soil, but at a field scale, the soil may be misrepresented. Therefore, unlike climate data, soil databases that precisely define the soil hydrological properties at an appropriate scale rarely exist. As a result these parameters have to be inferred from nearby soil surveys and local knowledge. However, estimating soil hydrological parameters may be imprecise, which in turn leads to biased estimates of plant available water capacity (PAWC), the total amount of water a soil can store. It is defined as the volumetric difference between drained upper limit and crop lower limit over a crop's rooting depth (Dalgliesh and Foale, 1998). Biased estimates of PAWC

* Corresponding author at: College of Crop Science, Fujian Agriculture and Forestry University, Fuzhou, 350002, China.
E-mail address: renye.wu@fafu.edu.cn (R. Wu).

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can consequently lead to the miscalculation of how much water can enter the storage. The PAWC is a key factor impacting the availability of water to plants and therefore a biased estimate of PAWC can lead to errors in yield of crop in rainfed cropping.

The imprecise estimates of drained upper limit, crop lower limit and rooting depth, and their impact on PAWC, inevitably result in incorrect estimates of crop yield or yield gaps (Aggarwal, 1995; Makowski et al., 2006; Tremblay and Wallach, 2004). This is particularly the case in dryland agriculture in arid and semi-arid regions, where cropping depends heavily on PAWC and rainfall. The effect that poor estimation of soil hydrological characterisation can have on crop yield predictions in dryland cropping system has occasionally been considered. For instance, Lawless et al. (2008) used the Sirius wheat simulation model to analyse the effect of uncertainty in soil moisture characteristics on the precision of simulated crop growth and development and concluded that quantitative soil moisture attributes should be made in order to accurately predict crop yield. Pogson et al. (2012) assessed the sensitivity of crop model predictions to entire meteorological and soil input datasets and their results highlighted that the estimation of soil water parameters (wilt point and field capacity) was likely to become increasingly critical in areas affected by climate change. However, it is still unclear how much error can be tolerated for soil hydrological parameters to generate acceptable yield potential estimates in water-limited environments (Yw). It is also unclear which hydrological parameter has more relative importance to affect Yw.

In this study we used APSIM to conduct a sensitivity analysis of the estimation of wheat Yw to the change in soil hydrological parameters (drained upper limit, crop lower limit and rooting depth) at two contrasting rainfall sites for two typical soil types in Western Australia. The objective of this study was to produce a detailed understanding of the effects of uncertainties of PAWC resulted from biased estimation of soil hydrological attributes on crop Yw. It was hypothesised that the biased estimation of soil hydrological parameters would have more effects on wheat Yw for the low PAWC soil in high rainfall zone. Moreover rooting depth and the time course of its development are crucial processes in the model, which controls the water uptake pattern. Water deficit can slow down the rooting depth development, and vice versa, resulting in an ‘overreaction’ of the crop to water shortage (Asseng et al., 1998b). As such it was also hypothesised that rooting depth would have more relative importance among the three parameters as it affects both crop growth and water budget. Thus the aims of this study were to: 1) quantify the bias in simulated wheat Yw due to the uncertainties of PAWC caused by inputs of drained upper limit, crop lower limit, and rooting depth; 2) to determine the relative importance of the three parameters; and 3) to identify the relationship between the biased crop Yw with variable rainfall.

2. Materials and method

2.1. APSIM model description

APSIM (Agricultural Production Systems Simulator) is a cropping systems simulation model that allows models of crops, pastures, soil water, nutrients, and erosion to be flexibly configured to simulate diverse agricultural systems (Holzworth et al., 2014). It runs at a daily time-step using daily meteorological data, including maximum and minimum temperatures, rainfall and total solar radiation. The model has been widely used to assess on-farm management practices, climate risk/change adaptation strategies, farming systems design for production or resource management objectives and many other applications (Anwar et al., 2009; Asseng et al., 1998a,b, 2004; Keating et al., 2003; McCown et al., 1996; Wang et al., 2011; Wessolek and Asseng, 2006). APSIM is also being used by commercial growers as a decision support tool for in-season crop management via the Yield Prophet online management tool (Hochman et al., 2009).

In the APSIM model, the SoilWat module simulates the various vertical water movements in a layered soil system using a multi-layer cascading approach. The water characteristics of the soil are specified in terms of air dry, the lower limit, drained upper limit and saturated volumetric water content in each soil layer. While, to conduct on-farm crop simulations, parameter of crop lower limit, at each layer in the soil profile is also needed. Drained upper limit and crop lower limit represent the maximum and minimum soil water content available to a specific crop over the potential rooting depth. Together they are used to define PAWC of the soil following the procedure of Dalgliesh and Foale (1998). Thus, PAWC is the measure of the plant available water capacity, directly related to crop yield potential, especially under water-limited conditions (Oliver et al., 2006).

2.2. Modelling the effects of the uncertainties in soil parameters on rainfed wheat yield potential

Two typical soils, shallow sandy duplex (called thereafter sand) and clay were selected to evaluate the effects of the uncertainties in drained upper limit, crop lower limit and rooting depth, which cause the uncertainties in PAWC accordingly, on wheat Yw in Western Australia, where wheat grows under rain-fed conditions, producing about 50% of Australia's total wheat production. Sand and clay are ranked second and third in terms of area distribution (gravel accounts for the largest area), accounting for 14.9% and 10.0%, respectively, across the Western Australia wheat belt. In the baseline simulation (Table 1), 150 cm of rooting depth was used for both soils, based on Asseng et al. (2000). Twelve layers were considered, with 10 cm depth in each of the top 10

Table 1
The baseline values of saturation (SAT), drained upper limit (DUL), crop lower limit (CLL) and plant available water capacity (PAWC) for two selected soils of shallow shandy duplex (sand) and clay in Western Australia. Note: The data were obtained from the APSoil database (Oliver and Robertson, 2009) (https://www.apsim.info/Products/APSoil.aspx).

Layer	Depth (cm)	Sand					Clay				
		SAT –	DUL (mm/mm)	CLL –	PAWC (mm)	OC (Total %)	SAT –	DUL (mm/mm)	CLL –	PAWC (mm)	OC (Total %)
0–10	10	0.33	0.126	0.052	7.4	1.0	0.44	0.260	0.108	15.2	1.0
10–20	10	0.33	0.148	0.079	6.9	0.7	0.44	0.307	0.165	14.1	0.7
20–30	10	0.37	0.169	0.094	7.5	0.4	0.44	0.291	0.159	13.2	0.4
30–40	10	0.37	0.226	0.161	6.6	0.1	0.44	0.316	0.216	10.0	0.1
40–50	10	0.44	0.238	0.182	5.6	0.1	0.44	0.285	0.216	6.9	0.1
50–60	10	0.44	0.238	0.182	5.6	0.1	0.44	0.285	0.216	6.9	0.1
60–70	10	0.44	0.225	0.171	5.4	0.1	0.44	0.279	0.216	6.3	0.1
70–80	10	0.44	0.225	0.171	5.4	0.1	0.44	0.279	0.216	6.3	0.1
80–90	10	0.44	0.203	0.137	6.6	0.1	0.44	0.303	0.244	5.9	0.1
90–100	10	0.44	0.203	0.137	6.6	0.1	0.44	0.303	0.244	5.9	0.1
100–120	20	0.44	0.201	0.160	8.2	0.1	0.44	0.292	0.201	18.2	0.1
120–150	30	0.44	0.214	0.160	16.2	0.1	0.44	0.291	0.240	15.3	0.1