Quantifying water productivity in rainfed cropping systems in Limpopo Province, South Africa

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Abstract

This paper reports results of on-farm experimentation to quantify water productivity of maize, groundnut, and cowpea crops in the 2007-08 cropping season in Limpopo Province, South Africa. The observed crop yield and soil water and nutrient data are used to evaluate the APSIM model's performance in simulating WP and soil water balance for maize and legume crops. There was very close agreement between observed and predicted biomass, grain yield, and changes in soil water content. The model provided outputs to fill measurement gaps in water balance components of the field experimentation, thereby allowing more detailed and appropriate calculations for comparing the WP of the different crops.

Media grab

The APSIM model performed remarkably well in predicting the crop yields and water balance of major crops in Limpopo Province, making it a key analytical tool for evaluating technologies for increasing yield and crop water productivity.

Introduction

Maize production dominates the smallholder farming system in Limpopo Province of South Africa, although crop yields in these systems translate into very poor water productivity (WP)–in the order of 1-2 kg grain per mm rainfall per ha. Crop simulation analysis, supported with results from on-farm trials, suggests that WP could be increased by 50-100% if smallholder maize farmers used small doses of topdress N fertilizer and improved agronomy (Dimes and Carberry, 2008). Because the price of fertilizer has increased by more than 100% in recent times, a stronger case for expanding legume production as a means of increasing N inputs into these cropping systems is emerging. A comparison of WP for different crops and fertility management will help guide public and private sector investment aimed at improving agricultural output of smallholder farmers in the province.

Our results of on-farm experimentation to quantify WP of maize, groundnut, and cowpea in the 2007-08 cropping season are given. The observed crop yield and soil water and nutrient data were used to evaluate the performance of the Agricultural Production Systems (APSIM) model in simulating WP, yield, and soil water balance for maize and legume crops in Limpopo province.

Methods

Field experimentation

Field experiments were conducted at Tafelkop, a smallholder farming village located on the Nebo Tableland in Sekukhune District of Limpopo Province. The soils are shallow (up to 1.0 m rooting depth) loamy sands to sandy loams. The rainfall season is unimodal (October/November to March/April) with an average annual total of 500 mm.

The Grain Crops Institute and the smallholder farmer association at Tafelkop established varietal trials of groundnut and bambara nut in the 2007-08 cropping season. Separate trials were established for each legume species, with six cultivars and three replicates laid out in a RCBD design. Demonstration plots of maize (PAN6479) and cowpea (Betch White) were established with the farmer association in adjoining plots to the legume varietal trials. Replicated treatment plots of Nyanda groundnut and SB7-1 Bambara were sampled (9.1 m^2) at crop maturity for stover and grain yield. Bulk samples were also taken from the maize (stover 72 m^2, grain 109 m^2) and cowpea (36 m^2) demonstration plots to determine stover and grain yield. Groundnut and maize were sown on November 14, while bambara and cowpea were sown on December 5. Maize received 15 kg N/ha as starter fertilizer at planting, and a topdress application of 14 kg N/ha on January 14, 2008. Maize was harvested on April 29, groundnut on March 26, and cowpea on March 18.

ICRISAT monitored the trial plots for changes in soil water content during crop growth using gravimetric methods. Soil sampling commenced on December 12, 2007, in the groundnut and bambara trials. Subsequent samplings took place on February 22 (all four crop areas), March 29 (groundnut, maize, and cowpea), and May 5 (Bambara), 2008. Sampling depth intervals were 0-0.1m, 0.1-0.3m, 0.3-0.6m, and 0.6-0.9m. Three soil cores were taken at each sampling, either across treatment replicates or within the final harvest area of the maize and groundnut. Gravimetric water contents were converted to volumetric using a bulk density of 1.5 g/cm^3 in all soil layers. Soils collected on December 12 were analyzed for pH and percentOC. The farm owner of the trial field recorded daily rainfall at the site.

Model analysis
Plant biomass, grain yield, and soil water balance of the maize, groundnut, and cowpea crops were simulated using the APSIM cropping systems model (Keating et al., 2002; Version 6.0), and model outputs were compared to observed data. Model input parameters for the maize (Pan6479) and groundnut (Nyanda) cultivars had been previously estimated (Dimes and Carberry, 2008; Ncube et al., 2008). Growth and yield of Betch White cowpea were adequately simulated using the short duration 'Banjo' cultivar description in APSIM. (As yet, there is no Bambara module in APSIM.) Dates of crop sowing and N fertilizer applications in the model were specified according to experimentation (see above). Plant populations were specified in the model according to measured populations at field harvest: maize–2.3 plants/m^2, groundnut–11.7 plants/m^2, cowpea–8.8 plants/m^2.

Soil parameters for simulation of the soil water and N balances in the nominated rooting depth of the soil (0.9 m) were specified as shown in Table 1. The crop lower limit of plant extractable water (LL) and the soil drained upper limit (DUL) were derived using the measured soil water contents as a guide. The plant available water capacity (PAWC) of the soil layers to the nominated rooting depth is 90 mm. The Runoff Curve Number and soil evaporation coefficients were chosen based on previous simulation studies in these environments (Ncube et al., 2008)

Table 1. APSIM input parameters used in simulation of Tafelkop experiments.

Layer Number	1	2	3	4
SoilWat parameters				
Layer thickness (mm)	100	200	300	300
Bulk density (g/cm^3)	1.50	1.50	1.40	1.40
SAT	0.250	0.270	0.300	0.320
DUL	0.140	0.155	0.176	0.185
LL15	0.052	0.064	0.070	0.081
Airdry	0.045	0.052	0.070	0.081
Swcon	0.5	0.5	0.4	0.4
CN2_bare	85			
U	3			
Cona	4			
Soil N parameters				
Organic C (%)	0.51	0.46	0.32	0.22
Finert	0.40	0.50	0.80	0.90
Fbiom	0.04	0.020	0.01	0.01
Nitrate-N (mg/kg)	3.79	1.52	0.76	0.38
Ammonium-N (mg/kg)	0.98	0.49	0.25	0.25
Soil C:N	12			
Crop parameters				
LL (maize, groundnut, and cowpea)	0.052	0.064	0.070	0.081
Kl	0.08	0.08	0.08	0.08
Xf	1.0	1.0	1.0	1.0

Soil water and N conditions at sowing of crops were not measured. The start date of simulations was therefore chosen as October 1 with the initial soil water content of layers specified at LL and starting mineral N in the profile set to 15 g NO_3^--N/ha and 5 kg NH_4^+-N/ha.

Only daily rainfall data were collected at the site. Daily radiation data from a nearby (within 30 km) climate station (Marble Hall, 29º 37' E, 25º 03' S, altitude 878 m), and daily temperature data from a distant site (150km) of similar altitude to Tafelkop (Polokwane, altitude 1153m), were used as climate inputs to the model, in conjunction with the measured rainfall. The rainfall record collected by the farmer, however, indicated incidences of periodic totals as daily amounts. These were reallocated or adjusted based on the rainfall distribution recorded at Marble Hall and rainfall amounts recorded at a site close by.

Results and discussion

There was very close agreement between observed and predicted total biomass and grain yield ($RMSD_{grain}$ = 257 kg/ha, $RMSD_{tbm}$ = 436 kg/ha) of the three experimental crops grown at Tafelkop (Figure 1). There was closer agreement for predicted maize yields compared to the two legume crops, for which grain and biomass yields were slightly under-predicted. In general, however, the observed differences in plant growth and yield due to species and crop duration and the interaction of these effects and planting dates with rainfall distributions (wet December and January, dry February) were very well captured by the APSIM modelling platform used in this analysis.

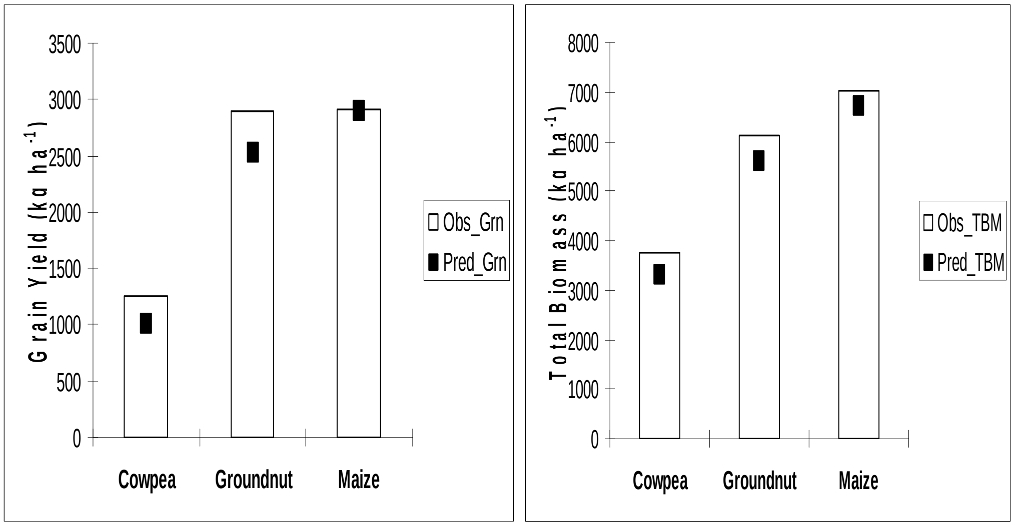

Figure 1. Observed and predicted grain yield and total biomass of cowpea, groundnut, and maize crops grown at Tafelkop in the 2007-08 cropping season.

The observed and predicted soil water contents at sampling dates in maize, groundnut, and cowpea plots are shown in Figure 2. There is close agreement between the predicted and observed soil water contents ($rmsd_{tsw}$ = 7 mm), and their distributions in the sampled rooting layers for all three crops on December 12. Similarly, the crop water use by maize and cowpea up to February 22 is well predicted by the model. This was not the case for groundnut, for which simulated soil water use by the crop below 0.3 m was noticeably overpredicted on this date.

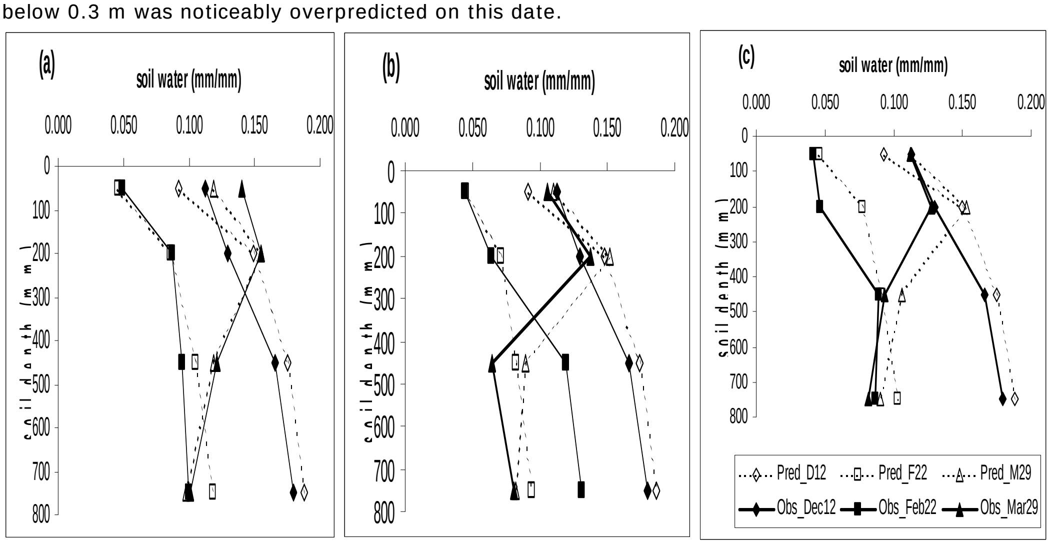

Figure 2. Observed and predicted water contents of soil layers on December 12, 2007, February 22, and March 29, 2008, under (a) maize, (b) groundnut, and (c) cowpea.

An important test of the model's performance in simulating the water balance was how well the model predicted the water content and distribution of the soil layers as measured on March 29, following the late rainfall in March. As seen in Figure 2, the observed refilling and distribution of soil water on March 29 under each crop is well predicted by the model. Overall, the performance of APSIM in predicting changes in soil water under the maize crop was most reliable ($rmsd_{tsw}$ = 7 mm), followed by cowpea ($rmsd_{tsw}$ = 10 mm), and groundnut ($rmsd_{tsw}$ = 14 mm).

The simulated in-crop water balance (i.e. sowing to crop maturity) of the maize and cowpea grown at Tafelkop in the 2007-08 season shows runoff and soil evaporation higher than crop transpiration (Table 2). For groundnut, simulated crop transpiration comprises the largest portion of the water balance, but there is some uncertainty with this estimate given the overprediction of crop water uptake implicit in the predicted soil water contents on February 22, as seen in Figure 2b. Using in-crop rainfall in Table 2 as the reference water for assessing crop productivity in conjunction with measured grain yields (Figure 1), the calculated WP (kg grain/mm of rainfall/ha) of the three crops is maize = 6.0 kg/mm/ha; groundnut = 6.0 kg/mm/ha, and cowpea = 3.8 kg/mm/ha. Including crop water use of stored water at the time of sowing (as estimated by the model), (delta_sw in Table 2), reduces the

WP estimates: maize = 5.6, groundnut = 5.4, and cowpea = 3 kg/mm.ha. A notable aspect of this analysis is the very low WP of the short-duration cowpea relative to the longer duration maize and groundnut. For this above-average rainfall season, and with a distribution favoring the longer duration crops, this result can be considered to be highly season-specific.

Table 2. Simulated components of the soil water balance of maize, groundnut, and cowpea crops grown at Tafelkop in 2007-08.

Crop	In-crop rainfall (mm)	Ep (mm)	Runoff (mm)	Drain (mm)	Es (mm)	Delta_sw (mm)	Water balance (mm)
Maize	485	115	170	78	158	-35	520
Gnut	485	209	119	65	145	-53	538
Cowpea	311	101	123	86	112	-86	417
			% of water use as:				
		Ep	Runoff	Drain	Es		
Maize		22	33	15	30		
Gnut		39	22	12	27		
Cowpea		24	29	21	27		

In-crop rainfall – sowing to crop maturity.
Ep – crop transpiration; Es – soil evaporation; Drain – drainage below 0.9m
Water balance = rainfall - delta_sw
Delta_sw = Soil water storage at crop maturity - soil water stored at sowing.

Conclusions and recommendations

APSIM's good performance in simulating the observed crop growth and yield of the three crops and the associated observed changes in soil water contents in the rooting zones is encouraging with regard to its application to quantify WP of crops in Limpopo Province.

Firstly, reliable prediction of total biomass is a prerequisite to simulation of the soil water balance. This is because simulated crop water uptake and canopy cover estimates by the crop have important feedback mechanisms on simulation of soil water balance processes such as partitioning of rainfall into runoff and infiltration, and soil evaporation. Secondly, reliable partitioning of biomass to grain yield across the species is essential in determining estimates of WP that can be used with confidence in comparing the different cropping options, from a biological yield perspective or, more particularly, on a economic basis (e.g. to take account of the high value of legume grain relative to cereal grain). Thirdly, although the only component of the soil water balance measured in the experimentation was changes in soil water storage, the good agreements achieved in predicting the different soil water distribution profiles observed over the course of the crops provide indirect evidence for having confidence in the simulated outputs for the other components of the water balance: crop water use, runoff, drainage, and soil evaporation. As a consequence, the model offers a cost-effective tool to provide reliable estimates of the water balance in these rainfed cropping systems.

Acknowledgments

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