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Short communication

Variation in water extraction with maize plant density and its impact on model application

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ABSTRACT

The use of maize simulation models to determine the optimum plant population for rainfed environments allows the evaluation of plant populations over multiple years and locations at a lower cost than traditional field experimentation. However the APSIM maize model that has been used to conduct some of these 'virtual' experiments assumes that the maximum rate of soil water extraction by the crop root system is constant across plant populations. This untested assumption may cause grain yield to be overestimated in lower plant populations. A field experiment was conducted to determine whether maximum rates of water extraction vary with plant population, and the maximum rate of soil water extraction was estimated for three plant populations (2.4, 3.5 and 5.5 plants m^{-2}) under water limited conditions. Maximum soil water extraction rates in the field experiment decreased linearly with plant population, and no difference was detected between plant populations for the crop lower limit of soil water extraction. Re-analysis of previous maize simulation experiments demonstrated that the use of inappropriately high extraction-rate parameters at low plant populations inflated predictions of grain yield, and could cause erroneous recommendations to be made for plant population. The results demonstrate the importance of validating crop simulation models across the range of intended treatments.

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1. Introduction

Crop simulation models are increasingly being used to conduct 'virtual' experiments that investigate the effect of alternative agronomic practices on crop production or the environment (e.g. Lyon et al., 2003; Saseendran et al., 2005; Feyereisen et al., 2006; Whish et al., 2005). Simulation experiments are advantageous because they allow hypotheses to be tested across a wide range of environmental conditions (e.g. soil fertility, climate) that vary geographically or temporally, but at a lower cost than the traditional field experiments. However, generating meaningful recommendations from simulation experiments depends on appropriate parameterisation of the simulation model, which should be demonstrated through accurate simulation of validation data obtained from field experiments (Passioura, 1996; Sinclair and Seligman, 1996).

The northern cropping region of eastern Australia has a highly variable seasonal rainfall pattern, and dryland crop production is limited by water availability in most seasons. Under these conditions the ability to accurately simulate crop water uptake is particularly important for modelling crop growth (Dardanelli et al., 2004). In their review of crop root system modelling, Wang and Smith (2004) pointed out that while above-ground crop development has been the main focus for many years, most crop and agricultural systems models have simplified the modelling of crop root growth and function, and, under certain conditions, some of the assumptions in the models restrict their validity.

The APSIM crop simulation model (Keating et al., 2003) simulates soil water extraction using the framework developed by Passioura (1983) and Monteith (1986). Termed an 'extraction front depth' model by Wang and Smith (2004), the extraction of soil water in APSIM is limited to soil layers into which roots have penetrated (as determined by the extraction front velocity). The maximum rate at which the crop root system can extract water from the soil is specified for each soil layer and is expressed using the '*kl*' parameter: the fraction of plant available water (PAW) that can be extracted from a particular soil layer on a given day. It is a combined estimate of the limits to water uptake imposed by the soil conductivity (k) and root length density (l). The value of *kl* varies with soil type, distance below soil surface, and crop species (Meinke et al., 1993; Robertson et al., 1993; Dardanelli et al., 1997, 2004). Genotypic differences in the value of *kl* have also been reported between two sunflower cultivars (Dardanelli et al., 1997), while Manschadi et al. (2006) recommended different values for cultivars in wheat that possessed different root architecture.

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In a previous study (Peake et al., 2008) APSIM was used to determine the optimum maize (*Zea mays* L.) population densities necessary to maximise grain yield and gross margin for a range of water input regimes. In field experiments used to validate the model, APSIM was found to over-predict maize grain yield at low population densities by up to 20% while satisfactorily predicting grain yield at higher plant populations. These simulations used the same *kl* value across a range of plant populations from 2 to 8 plants m^{-2}. Substituting lower *kl* values substantially improved the prediction of grain yield at low plant populations, but no field data was available to confirm whether lower rates of maximum water extraction were the underlying cause of the inaccuracy in the simulations (Peake et al., 2008). An initial attempt to publish that study using linearly declining *kl* values with plant density was rejected due to an absence of evidence to support such parameterisation. Yet there was no evidence to support the constant *kl* values parameterised by default in the model, and logically, a decline in the ability of a crop to extract soil water must occur at an unknown population threshold.

Little is known about the effect of plant population on either water extraction rates or root length density in field crops in general and maize in particular. Robertson et al. (1993) reported data from two experiments which suggested that *kl* differed for sorghum plant densities of 10 and 20 plants m^{-2} at depths between 1000 and 1500 mm, but was unable to make a statistical comparison due to the experimental design. Sadras et al. (1989) found small differences in root length density between different sunflower populations, which suggested that extraction rate parameters could vary with plant population in single stalked crops. The aim of this study therefore was to test the hypothesis that the maximum rate of soil water extraction (*kl*) varied with plant population in maize.

2. Materials and methods

The cultivar used in this study was a tropically adapted sweet corn cultivar (Hybrix 5) bred by the Queensland Department of Agriculture, Fisheries and Forestry (QDAFF), and marketed by Pacific Seeds Pty Ltd. Hybrix 5 is unlike most Australian sweet corn cultivars, possessing a plant type more similar to tropical maize hybrids than to traditional, temperate sweet corn hybrids. In this experiment it grew to a height of 2.2 m. The experiment was carried out at the QDAFF research station at Gatton (27° 32.597′ S 152° 19.729 E) approximately 75 km west of Brisbane in the Lockyer Valley, a vegetable producing region in the south-east corner of Queensland, Australia.

2.1. Soil characterisation

Soil characteristics, including drained upper limit (DUL), saturation moisture content and bulk density, were determined using the methods described by Dalgliesh and Foale (1998) for a rigid soil. Bulk density was sampled using a hand sampling kit with slide hammer and 75 mm diameter sampling rings, working from the soil surface by sampling consecutive depths down three vertical sampling holes. Crop lower limit (CLL) was determined as described in sections below, using the *x*-intercept of a regression of the rate of water extraction against volumetric water content. This method provides an estimate of CLL for such a situation where full extraction of plant available water is not achieved, although CLL was not calculated for the two deepest soil layers herein because the regression slopes were not significantly different from zero. Plant available water capacity (PAWC) was calculated as the difference in volumetric water content between DUL and CLL multiplied by the depth of the soil layer, summed across layers. The values obtained for these parameters are listed by soil layer in Table 1. PAWC of the soil for Hybrix 5 was determined to be 168 mm to a depth of 1200 mm, and at sowing (prior to irrigation) there was 145 mm of plant available water.

Soil samples were taken at sowing and analysed for gravimetric soil water content, nitrate-nitrogen concentration, soil organic carbon and pH. Samples for nitrogen analysis were dried at 40 °C and the nitrate-nitrogen content of the samples was determined by using a 1:5 soil/water extraction, method 7B1 (water soluble nitrate) from Rayment and Higginson (1992). The 1:5 soil/water extraction was also used to determine pH, while organic carbon assays followed the Walkley & Black method (methods 4A1 and 8B1 respectively from Rayment and Higginson (1992)). Data from the chemical analyses are also reported in Table 1.

2.2. Experimental design

Three populations of Hybrix 5 were grown in a randomised complete block design, with three replicates. The plots were planted at 0.75 m row spacing into 10 cm high beds that were 1.2 m wide and separated by 0.3 m furrows, with two rows of plants per bed. Experimental plots were 6 m long and 4 rows (3 m) wide. Replicates consisted of three plots (one of each plant density) planted in the same planting run, being 18 m long and 4 rows wide. The entire experimental area measured 20 m × 15 m, including a 4-row border planted outside replicates 1 and 3.

The entire experimental area was sown at 65,000 seeds ha^{-1} (the maximum seeding rate used by local sweet corn production companies to achieve maximum yield) on the 21st of November, 2005. Neutron moisture meter (NMM) access tubes were installed the same day, positioned half-way along the centre bed of each plot, and 19 cm from the nearest plant row such that the field of soil measurement was approximated to cover the row and inter-row root zones equally. The experiment was fully irrigated with trickle irrigation from sowing until 32 days after sowing (DAS).

Plant population was constant across the three treatments until 34 DAS to ensure that the three populations had equal access to water and nitrogen to that day. At 34 DAS (early stem elongation), the experimental area was thinned to create the three experimental populations, 5.5, 3.5 and 2.4 plants m^{-2}, with the high density (5.5) much lower than the seeding rate due to poor establishment.

Following thinning (from 35 DAS), a water limited management regime was imposed by ceasing irrigation, and installing 200 μm black plastic sheeting on the ground between rows. The plastic was stapled together between plants in each row to prevent infiltration of rainfall and minimise evaporation. The plastic was covered with strips of hessian to prevent the plastic from becoming excessively hot prior to canopy closure.

2.3. Experimental measurements

NMM readings were taken using a CPN 503 DR Hydroprobe, with a 16 second count. Approximately 45 min elapsed between reading the first and last NMM access tube each day. Access tubes were read in the same order on each occasion with the first tube read between 10.30 am and 12.30 pm. Calibration equations were developed for the NMM using soil samples taken during access tube installation. The first NMM readings were taken during access tube installation at sowing, then two weeks after sowing, and thereafter at three or four day intervals until the experiment was concluded. NMM readings were taken from the midpoint of each of the top six soil layers presented in Table 1.

Root length density (RLD) was determined by washing roots from soil samples that were taken once the sweet corn was harvested on DAS 86 (mid-grain fill for traditional maize). Intact soil cores were taken using a hydraulically operated soil sampling device using a 31 mm diameter core taken to a depth of 1500 mm.

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