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Parameterization of the AquaCrop model for full and deficit irrigated maize for seed production in arid Northwest China

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ABSTRACT

A crop model is a powerful tool for developing an irrigation schedule and simulating crop yield. In this study, both an AquaCrop model using recommended default parameters and a parameterized AquaCrop model were used to simulate the growth of maize for seed production under plastic film-mulch. The model variables that were parameterized include canopy cover (CC), aboveground biomass, yield (Y) and soil water content (SWC). Data from field experiments, which included 23 irrigation treatments on four varieties of maize for seed production, were collected in an arid region of Northwest China from 2012 to 2015. The results from both the default AquaCrop model and the parameterized model were compared with the field data. The parameterized model performed much better than the default model. Overall it predicted CC well for most irrigation treatments, with determination coefficient (R^2) and normalized root mean square error (NRMSE) of 0.818 and 19.3%, respectively. However, the model was rather sensitive to water stress during the vegetative stage and insensitive to water stress during the senescence stage, resulting in underestimation and overestimation of CC during these stages. As for biomass accumulation process, R^2 and NRMSE were 0.929 and 19.1% for all treatments, respectively. The parameterized model estimated biomass accurately in the early and middle stages of growth, but generally overestimated biomass at the mature stage, giving a slightly decreased accuracy of final biomass (B) simulation. The parameterized AquaCrop model simulated B and Y values with errors of less than 5% of measured values for 4 and 7 treatments out of 23 treatments, respectively. There were of less than 15% for 12 and 13 treatments out of 23, of less than 30% for 19 and 16 treatments out of 23, and greater than 30% for 4 and 7 treatments out of 23, respectively. The model gave reasonable estimates of SWC with R^2 and NRMSE of 0.736 and 15.2%, respectively, but tended to overestimate it for most irrigation treatments. Simulation of the variation of WP^* in the growth period, and the differences of HI under different water stress conditions, might be improved in the AquaCrop model.

1. Introduction

Maize for seed production is different from maize grown for other purposes (such as silage or cereal). It has a smaller leaf area, less biomass, lower yield, and consists of separate male and female plants. The tassel of the female parent is removed before flowering, and the ear of the female parent receives the pollen of the male parent to produce the final hybrid seed yield. Hexi Corridor in Northwest China is an important area for maize for seed production, where the planting area is 100,000 ha, which accounts for 39.3% of total area of this crop in China (255,000 ha). The yield of maize for seed production is 580,000 tons, which accounts for 42.6% of the total yield of this crop in China in 2013 (Wang et al., 2013a).

Hexi Corridor is located in a typical arid climate zone, with annual rainfall < 200 mm. There is a serious shortage of water, and agriculture depends heavily on irrigation (Du et al., 2015; Kang et al., 2017). Due to the scarcity of water, the crop often suffers water stress and its yield decreases. An understanding of the effects of different degrees of water stress on maize for seed production is very important for optimal irrigation management and crop production. Field experiments are often time-consuming and costly, so crop models can greatly help to improve crop management (Rötter et al., 2012; Mabhaudhi et al., 2014).

Modelling crop growth can provide a powerful tool for evaluating the effects of environmental factors on crops (Steduto et al., 2009;

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Rötter et al., 2015). There are many widely used crop models, such as WOFOST (Diepen et al., 1989), EPIC (Sharpley and Williams, 1990), CropSyst (Stöckle et al., 2003), DSSAT (Jones et al., 2003), APSIM (Keating et al., 2003) and WAVES (Kang et al., 2003). However, these models are complex; they require many parameters that are often difficult to quantify and can be time-consuming to obtain. To overcome these obstacles, FAO developed the AquaCrop model to be accurate, simple, robust, and easy to use (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009). The model is now used worldwide and it is an important tool for managing and forecasting crop production. It has been successfully used to simulate the development of many crops: maize (Hsiao et al., 2009; Stricevic et al., 2011; Abedinpour et al., 2012; Nyakudya and Stroosnijder, 2014; Paredes et al., 2014), wheat (Andarzian et al., 2011; Mkhabela and Bullock, 2012; Wang et al., 2013b; Iqbal et al., 2014; Toumi et al., 2016), cotton (Garcia-Vila et al., 2009; Linker et al., 2016), rice (Maniruzzaman et al., 2015), sunflowers (Todorovic et al., 2009; Stricevic et al., 2011), barley (Araya et al., 2010a), quinoa (Geerts et al., 2009), teff (Araya et al., 2010b), taro (Mabhaudhi et al., 2014), and others. However, Heng et al. (2009) and Katerji et al. (2013) showed that although AquaCrop can accurately estimate the canopy coverage, biomass, and yield of maize under full irrigation and mild water stress conditions, the accuracy of the simulation is poor when there are severe water deficit conditions, especially when the water deficit occurs in the senescence period. It has been shown that AquaCrop can accurately simulate change in soil water content under full irrigation conditions, but generally overestimates soil water content for deficit irrigation applications, especially for cotton (Farahani et al., 2009). Hsiao et al. (2009) have suggested that AquaCrop should be further validated for different soils, crops, and climates worldwide.

To give good simulation results for crop characteristics such as biomass and yield, the parameters of an AquaCrop model must be calibrated. There is no literature concerning the parameterization of an AquaCrop model for maize that is grown as a seed crop, and it is not clear that the default parameters for other maize crops can be used unaltered for such a model, especially with deficit irrigation. In addition, there has been little research into the use of AquaCrop in the inland arid climate of Northwest China. Thus, the objective of this study is to parameterize an AquaCrop model on maize for seed production in an arid region of Northwest China under both full irrigation and deficit irrigation so that the model provides accurate yield forecasts under different irrigation conditions.

2. Materials and methods

2.1. Experimental site and its description

Field experiments were conducted at the Shiyanghe Experimental Station for Water-Saving in Agriculture and Ecology, part of the China Agricultural University, located in Wuwei City, Gansu Province, Northwest China (37°52′ N, 102°50′ E, elevation 1581 m), from 2012 to 2015. The experimental site is located in an arid inland climate zone with abundant light and heat, but with a water scarcity (Li et al., 2015). The soil has a light sandy loam texture, with mean soil dry bulk density of 1.4 g cm^{-3}, mean saturated water content of 0.41 $cm^3 cm^{-3}$, mean field capacity (FC) of 0.30 $cm^3 cm^{-3}$, mean permanent wilting point of 0.10 $cm^3 cm^{-3}$, and mean saturated hydraulic conductivity of 500 mm d^{-1} for the 0–100 cm soil layer.

2.2. Experimental methods

To generate values for the conservative crop parameters of AquaCrop, field data were collected over four years (2012–2015) for crops of different maize varieties under different irrigation treatments.

In 2012, the following experiment was conducted. Six experimental irrigation treatments were designed to study the responses of maize for seed production to deficit irrigation at different growth stages. Each treatment was classified in one of two groups: full irrigation (CK) and deficit irrigation (DI). In CK sufficient water was applied to reach 100% crop evapotranspiration (ET) during the whole growth stage of the maize. In DI a planting was deficit irrigated at one of a number different growth stages with a limited amount of water so that ET over the growth stage was 55%; the plants were fully irrigated (i.e. ET was 100%) during the other stages. The five growth stages were the seedling stage (SD), the jointing stage (JD), the heading stage (HD), the filling stage (FD), and the maturing stage (MD). The maize for seed production (*Zea mays* L., cultivar Zhengdan 958) was sown on April 19, 2012 and harvested on September 20, 2012.

In 2013, the following experiment was conducted. Three irrigation treatments (W1, W2, and W3) were designed to study the responses of maize for seed production to different degrees of water stress during the growth period. For each treatment, irrigation water was supplied until the soil water content reached 65–70% (W1), 55–60% (W2), or 45–50% (W3) of field capacity (FC). The upper irrigation limit was the field capacity. The maize for seed production (*Zea mays* L., cultivar Funong 340) was sown on April 20, 2013 and harvested on September 11, 2013.

In 2014, two experiments were conducted. The first of them was a repeat of the 2013 experiment. The second experiment, consisting of four irrigation treatments (CK, IV3, IV2, and IR2), was designed to study the responses of maize for seed production to irrigation at different times. In treatment CK, full irrigation, the crop was irrigated four times during the whole crop season. In treatment IV3 the crop was irrigated three times during the vegetative stage. In treatment IV2, the crop was irrigated twice during the vegetative stage. In treatment IR2 the crop was irrigated twice during the reproductive stage. For all treatments, each irrigation supplied 120 mm water. Maize for seed production (*Zea mays* L., cultivar Funong 963) was used in both experiments and was sown on April 15, 2014 and harvested on September 20, 2014.

In 2015, the following experiment was conducted. Seven irrigation treatments (CK, IV3, IR3, IV2, IR2, IV1, and IR1) were designed to study the responses of maize for seed production to different irrigation times. In treatment CK, full irrigation, there were five irrigations during the whole growing season. In treatment IV3 there were three irrigations during the vegetative stage. In treatment IR3 there were three irrigations during the reproductive stage. In treatment IV2 there were two irrigations during the vegetative stage. In treatment IR2 there were two irrigations during the reproductive stage. In treatment IV1 there was one irrigation during the vegetative stage. In treatment IR1 there was one irrigation during the reproductive stage. In every treatment, each irrigation supplied 120 mm water. Maize for seed production (*Zea mays* L., cultivar Funong 588) was sown on April 15, 2015 and harvested on September 16, 2015.

Every experiment was conducted in a randomized complete block design, and each treatment had three replicates. The maize for seed production was sown alternating one row of male plants with five rows of female plants under plastic film mulch, with plant spacing of 0.25 m and row spacing of 0.4 m. Nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied at 500 kg ha^{-1}, 240 kg ha^{-1} and 50 kg ha^{-1} respectively, according to average long-term fertilization data, in each of the four years. Except for irrigation, other farming management measures were similar for all treatments. Each plot field had an area of 86.8 m^2 (12.4 m × 7 m) during the five one-year experiments. The plots were separated by ridges (0.3 m wide and 0.5 m high), and 1 m wide strips were left around the inside of each plot for protection. Uniform border irrigation was adopted as the irrigation method. Irrigation pipelines were buried in the ridges. For each plot, the main pipes were equipped with a water meter to measure the irrigation amount, and a water outlet was installed at the head. The irrigation time and depth data for each treatment are shown in Table 1.