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Evaluation of the AquaCrop model for simulating the impact of water deficits and different irrigation regimes on the biomass and yield of winter wheat grown on China's Loess Plateau

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ABSTRACT

Accurate models of crop growth are important for evaluating the effects of water deficits on crop yield or productivity. AquaCrop was developed by the FAO (Food and Agricultural Organization) of the United Nations to simulate yield responses to changes in the supply of water. The objectives of this study were to evaluate the model's ability to simulate winter wheat performance under full and deficit water conditions on China's Loess Plateau and to study the effect of different irrigation scenarios on wheat yield. The model's output was compared to experimental data collected between 2006 and 2011 at the Changwu Agri-ecological Station on the Loess Plateau. The model accurately estimated the soil water content of the root zone as well as the biomass and grain yields of winter wheat. When simulating the soil water during the 2008–2009 growing season, the calculated values of r^2, RMSE, ME, and the d-index were 0.98, 8.4 mm, 0.98, and 0.99 for no irrigation; 0.95, 14.4 mm, 0.93, and 0.98 for double irrigation; 0.88, 22.9 mm, 0.68, and 0.90 for triple irrigation; and 0.93, 17.5 mm, 0.75, and 0.9 for quadruple irrigation, respectively. For the grain yield, the r^2 values for the model's outputs under the single irrigation, double irrigation, triple irrigation, and quadruple irrigation treatments were 0.80, 0.98, 0.99, and 0.77, respectively. Comparing to no irrigation the highest increases in grain yield were observed for scenarios in which irrigation was applied during the over-wintering and turning green stages. Moreover, the simulations indicated that under double irrigation regimes, water can be withheld during over-wintering and either turning green or stem elongation without greatly reducing yields. The minimum amounts of irrigation water required to achieve high WUE in wet, normal and dry years were 225, 150 and 150 mm, respectively.

1. Introduction

Dryland farming is common in Northern China and agricultural dryland accounts for around 55% of China's total cultivated land (Xin and Wang, 1999). The low and variable rainfall in the dry plain region of China restricts the scope for rainfed crop production there, while the availability of soil water is the main factor limiting crop production on the Loess Plateau. Although it has been demonstrated that crop rotation would allow for significant yield increases in the Weibei dryland (Huang et al., 2003), farmers prefer to plant only winter wheat for reasons of tradition and because of the region's climatic conditions. In this region, precipitation can only meet a fraction of the water requirements of typical crops – 58.6% in the case of winter wheat (Li and Su, 1991). The primary techniques used for maintaining and increasing crop yields in the region are based on adjusting fertilization regimes, which has been demonstrated to have significant effects for wheat (Hao et al., 2007; Yadav et al., 2000). However, analyses of several long-term experiments carried out throughout Asia indicate stagnating or declining trends in crop yield (Addiscott et al., 1995; Bhandari et al., 2002; Ladha et al., 2003; Regmi et al., 2003; Yadav et al., 2000). It has been demonstrated that the combined application of N and P fertilizers yielded better results than either fertilizer alone in terms of increasing and sustaining the productivity of rain-fed continuous winter wheat farming on dark loess soil. In fact, the use of a single fertilizer reduced yields relative to the control treatment, although the trend was not statistically significant (Hao et al., 2007). Some reports indicate that improving crop water productivity could stabilize yields

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Abbreviations: OW, over-wintering; TG, turning green; SE, stem elongation; FL, flowering; GF, grain filling.

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(Ghahraman and Sepaskhah, 1997; Pereira et al., 2002) and deficit irrigation has been proposed as an irrigation strategy that may be useful for this purpose (Debaeke and Aboudrare, 2004; Farré and Faci, 2009; Fereres and Soriano, 2007; Ghahraman and Sepaskhah, 1997; Kipkorir et al., 2002). To use such strategies effectively, it will be necessary to develop a good understanding of crops' responses to water stress along with tools for modeling responses to water deficits and other environmental factors. Although deficit irrigation involves subjecting crops to water stress and would thus be expected to depress yields, it is possible to maintain good yields by ensuring that sufficient water is supplied during critical stages of crop growth and only imposing water stress during growth stages that can tolerate it (Geerts and Raes, 2009). However, it is laborious and expensive to study yield responses to different irrigation regimes in the field or under more controlled conditions. Modeling techniques are therefore very useful for studying and developing new deficit irrigation strategies (Benli et al., 2007; Geerts and Raes, 2009; Heng et al., 2007; Kipkorir et al., 2001; Lorite et al., 2007; Pereira et al., 2009). Models make it possible to evaluate the effects of different yield-affecting factors simultaneously in order to identify optimal irrigation regimes for specific scenarios (Liu et al., 2007; Pereira et al., 2002). They also make it possible to examine transpiration and evaporation separately rather than having to consider evapotranspiration as a single process, and to use a range of specific sub-models to describe crop production (Raes et al., 2006). This can be useful when attempting to elucidate the mechanisms that yield high water productivity under deficit irrigation.

In the case of wheat, several models have been tested, for example, CROPWAT (Song et al., 2003), DSSAT (Jones et al., 2003). However, most of these models (application software) are not free, demanding large number of parameters, and require advanced skills for their operation. The newly developed AquaCrop model (Raes et al., 2009; Steduto et al., 2009) is free and practitioner-oriented for the users, and requires a relatively small number of parameters to calculate the yield and biomass. As it aims at maintaining a balance between accuracy, robustness, however, the model has not been tested in Northern west China where crop yields is often limited by moisture deficit. If it can be used to optimize the irrigation scheme in Northern west china remains unknown. So, the main objective of the present study was to evaluate and validate the AquaCrop model by using it to simulate winter wheat growth under full and deficit irrigation at a major irrigation scheme on the Loess Plateau in northwestern China.

2. Materials and methods

2.1. Site description

The data used in this work were collected between 2006 and 2011 at the Changwu Agri-ecological Station on the Loess Plateau (35.28N and 107.88E) in the Shaanxi Province of China. The experimental site is located about 1206 m above sea level. The loess at the site is more than 100 m thick, and the soil is a Cumuli-Ustic Isohumosol according to the Chinese Soil Taxonomy system (Gong et al., 2007), containing 37% clay, 59% silt, and 4% sand. The average soil pH is 8.4, and bulk density is 1.35 g cm^{-3}. The saturated hydraulic conductivity is 240 mm d^{-1}. Soil's contents of organic matter, total nitrogen, available phosphorus, available potassium and inorganic nitrogen are 11.8 g kg^{-1}, 0.87 g kg^{-1}, 14.4 mg kg^{-1}, 144.6 mg kg^{-1}and 3.15 mg kg^{-1}, respectively. The field capacity, saturated water content, permanent wilting point and threshold point are 29% (cm^3 cm^{-3}), 46% (cm^3 cm^{-3}), 0.1 (cm^3 cm^{-3}) and 0.21(cm^3 cm^{-3}), respectively. The depth of groundwater in the study area is up to 50–80 m. It is difficult for winter wheat to get water from the groundwater. And the course of retention lines in the soil is shown in Fig. 1. Most farms in the region harvest a single crop (wheat or maize) each year using rain-fed agriculture.

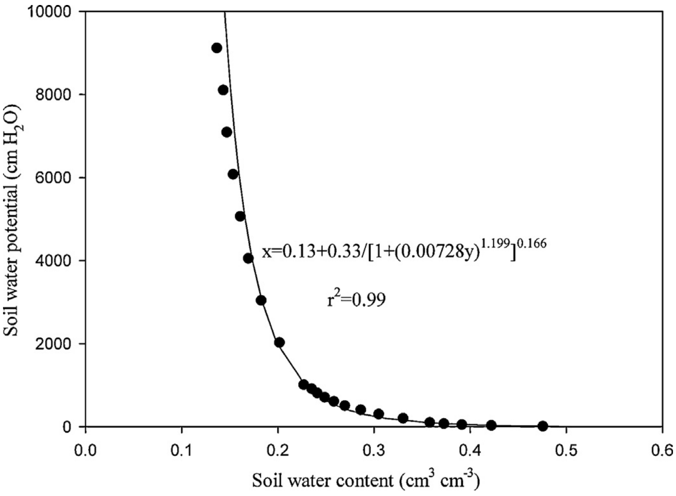

Fig. 1. The course of retention lines in the soil on the investigated sites.

Each experimental plot had an area of 16 m^2 and five different irrigation treatments were tested (no irrigation, single irrigation, double irrigation, triple irrigation, quadruple irrigation) (Table 1). The treatments were applied using a randomized complete block design with three replicates for each treatment. Five growth stages were defined: over-wintering, turning green, stem elongation, flowering, and grain filling. In the single irrigation treatment, irrigation was applied during the over-wintering stage only. Fertilizer was applied to the plots in the middle of September during each year of the experiment and the "changhan-58" wheat variety was sown immediately afterwards. The wheat was harvested at the end of the following June, and plots were left fallow between July and September. Irrigation water was applied using the surface flood method. In the deficit irrigation treatments, irrigation was withheld during some or all of the over-wintering, turning green, stem elongation, flowering and grain filling stages.

2.2. Climate data

Data on daily maximum and minimum air temperatures (°C), hours of sunshine, rainfall (mm), relative humidity, wind speed and evaporation (mm/day) were obtained from the meteorological apparatus at Changwu experimental station (35.28 N, 107.88E, ca. 1200 m above sea level), which is located in close proximity (within 0.5 km) of the experimental site. The site's average annual precipitation is 578 mm, with 55% falling between July and September. The annual average temperature is 9.28 °C. Daily meteorological data including rainfall and potential rates of evapotranspiration during each of the studied growing seasons are presented in Fig. 2. The reference evapotranspiration (ETo) was estimated using the ETo calculator (Raes et al., 2009). The input data used in these calculations were the maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperature, the maximum ($RH_{\max}$) and minimum ($RH_{\min}$) relative humidity, daily hours of sunshine (n/N), and the wind speed at a height of 2 m (u2), all of which were recorded at the Changwu experimental station. The ETo calculator used in this work is based on the Penman-Monteith equation, which is the most general and widely used method for computing daily reference evapotranspiration (ET) rates and is recommended by the FAO (Allen et al., 1998).

Yearly precipitation patterns were classified using the criteria proposed by Tao et al. (2000), as shown below:

$$\text{Wet year}: P_i > P + 0.33\delta; \text{ dry year}: P_i < P - 0.33\delta$$