Evaluation of the AquaCrop model for simulating yield response of winter wheat to water on the southern Loess Plateau of China

Wanhong Zhang, Wenzhao Liu, Qingwu Xue, Jie Chen and Xiaoyang Han

ABSTRACT

The objective of this study was to evaluate the performance of the FAO-AquaCrop model in winter wheat in the southern Loess Plateau of China. Multi-year field experimental data from 2004 and 2011 were used to calibrate and validate the model for simulating biomass, canopy cover (CC), soil water content, and grain yield under rainfed conditions. The model performance was evaluated using root mean square error (RMSE) and Willmott index of agreement ($d$) as criteria. The RMSE ranged from 0.16 to 0.38 t/ha for simulating aboveground biomass, 1.87 to 4.15% for CC, 0.50 to 1.44 t/ha for grain yield, and 5.70 to 22.56 mm for soil water content. The $d$ ranged from 0.22 to 0.89, 0.25 to 0.43, 0.36 to 0.62 and 0.95 to 0.98 for aboveground biomass, CC, soil water content and grain yield, respectively. Generally, the model performed better for simulating CC and yield than biomass and soil water content. The results further indicated that AquaCrop is capable of simulating winter wheat yield under rainfed conditions. Further improvement may be needed to capture the variation of different management practices such as fertility and irrigation levels in this region.

INTRODUCTION

The Loess Plateau of China is one of the main agricultural regions for growing winter wheat (Triticum aestivum L.). The rainfall and soil fertility have major impacts on wheat production in the Loess Plateau. The average annual rainfall of the Loess Plateau ranges from 300 to 600 mm. In particular, the rainfall is relatively deficit during the crop growing season. Therefore, the available water is the most important factor limiting the agricultural production in this region (Kang et al. 2005).

In order to improve the crop production in the Loess Plateau, development of management strategies is necessary under the limited water resources conditions (Kang et al. 2001). In this context, crop models are useful as decision support tools for effective field management (Heng et al. 2009; Steduto et al. 2009). However, most models are complicated and require a large number of parameters. They also require advanced skills from end-users for model calibration and operation (Heng et al. 2009). For example, the DASST (Jones et al. 2003) and APSIM (McCown et al. 1996) models require many parameters (Hsiao et al. 2009), and the CropSyst (Stöckle et al. 2003), WOFOST (Diepen et al. 2007) and SPAC (Kang et al. 2003) models are relatively complicated for end-users (Kang et al. 2001; Todorovic et al. 2009). These disadvantages partly inhibit the development and extensive application of these models.

The Food and Agriculture Organization (FAO) in the United Nations newly developed a water-driven model (AquaCrop) (Hsiao et al. 2009; Raes et al. 2009; Steduto et al. 2009) with the aim to improve crop production for the regions in which water is relatively scarce. The AquaCrop model is a user-friendly and practitioner-oriented type of model, as it maintains an optimal balance between accuracy, robustness, and simplicity, and requires a relatively small number of parameters that are mostly easy to obtain. The AquaCrop model may also simulate many herbaceous crops such as maize, wheat, cotton, and barley (Hsiao et al. 2009).

Before making use of the AquaCrop model, an extensive validation for various crops across a wide range of climate, soil, water deficit, and management conditions is necessary (Hsiao et al. 2009). Once the model is validated with a reasonable performance, it can be used as an easy and

doi: 10.2166/wst.2013.305
powerful tool for crop production management (Soltani & Hoogenboom 2007). Recently, several researchers have used the AquaCrop model for simulating different crops growth in diverse environments, such as maize (Heng et al. 2009; Hsiao et al. 2009), cotton (Farahani et al. 2009) and sunflower (Todorovic et al. 2009). The simulation studies showed that the AquaCrop model was satisfactory under the full irrigated and moderate water stress conditions.

The studies of wheat simulation using the AquaCrop model have been carried out in Iran and western Canada (Andarzian et al. 2010, 2011; Salemi et al. 2011; Mkhabela & Bullock 2012). However, there is salt stress in the studied areas in Iran (Andarzian et al. 2011; Salemi et al. 2011). The acquired parameters in the areas may not be suitable for application in other regions where the salt stress is not existing or weak. In western Canada, although the AquaCrop model may simulate the spring wheat yields and soil water content well, the simulation results were still unknown for winter wheat. In the southern Loess Plateau of China, winter wheat is one of the major crops, and the distinctive soil type and climatic characteristics make it different from most agricultural production areas in China. In addition, salt stress for crop production rarely exists in this region. So far, there is no study of using the AquaCrop model to simulate winter wheat growth, yield and soil water content on the Loess Plateau. The objective of this study was to parameterize and evaluate the AquaCrop model for winter wheat simulation on the Loess Plateau under the rainfed conditions.

MATERIALS AND METHODS

Description of AquaCrop model

The AquaCrop model is a water-driven crop growth model and it simulates attainable yields of major herbaceous crops as a function of water consumption under rainfed, full, supplemental and deficit irrigation conditions. In the model, the daily water balance is calculated and the evapotranspiration is separated into the evaporation and transpiration. Transpiration is proportional to the crop cover and the AquaCrop model uses crop cover instead of leaf area index (LAI) to calculate transpiration. Usually, the transpiration is used to derive the amount of above-ground biomass gained through the normalized water productivity. In the AquaCrop, the crop responds to four water stress conditions, which triggered crop cover reduction, stomatal closure, acceleration of canopy senescence and change in harvest index (HI). In the model, the yield is determined by multiplying the aboveground biomass and HI. HI increases linearly during the yield formation phase until reaching a maximum value.

Study site geography

The multi-year field experiments data were derived from the Changwu Agro-ecological Experiment Station (107°40'E and 35°12'N) on the Loess Plateau. The climate belongs to a warm temperate semi-humid continental monsoon climate with a mean annual precipitation of 580 mm, a mean temperature of 9.1 °C and 171 frost-free days. The underground water level in this region is at a depth of 50–80 m. The topography belongs to the typical gully region of the Loess Plateau. Rainfed farming is the typical agriculture in this region.

Field site and data collection

The climate data are obtained from a meteorological station at the Changwu Agro-ecological Experiment Station. The daily reference evapotranspiration (ET0) was calculated using the ET0 calculator (FAO 2009).

Soil in the region belongs to dark loessial soils with a parent material of deep moderate loamy Malan loessial soil and good permeability. The physical properties used as data input for the AquaCrop model were collected from field experiments (Table 1).

To study the field water balance, changes of soil water content were measured in the field during the wheat

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Soil texture</th>
<th>SAT (VOL%)</th>
<th>FC (VOL%)</th>
<th>PWP (VOL%)</th>
<th>BD (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>Heavy loam</td>
<td>50.57</td>
<td>28.18</td>
<td>11.24</td>
<td>1.31</td>
</tr>
<tr>
<td>10–20</td>
<td>Loam</td>
<td>51.69</td>
<td>27.71</td>
<td>9.87</td>
<td>1.28</td>
</tr>
<tr>
<td>20–30</td>
<td>Light loam</td>
<td>47.17</td>
<td>27.91</td>
<td>6.58</td>
<td>1.40</td>
</tr>
<tr>
<td>30–40</td>
<td>Heavy loam</td>
<td>49.43</td>
<td>28.66</td>
<td>12.34</td>
<td>1.34</td>
</tr>
<tr>
<td>40–60</td>
<td>Loam</td>
<td>47.55</td>
<td>28.94</td>
<td>10.98</td>
<td>1.39</td>
</tr>
<tr>
<td>60–80</td>
<td>Loam</td>
<td>46.79</td>
<td>29.12</td>
<td>10.91</td>
<td>1.41</td>
</tr>
<tr>
<td>80–100</td>
<td>Loam</td>
<td>53.58</td>
<td>27.15</td>
<td>8.77</td>
<td>1.23</td>
</tr>
<tr>
<td>100–120</td>
<td>Loam</td>
<td>54.72</td>
<td>26.80</td>
<td>8.32</td>
<td>1.20</td>
</tr>
<tr>
<td>120–150</td>
<td>Loam</td>
<td>52.85</td>
<td>27.23</td>
<td>8.41</td>
<td>1.25</td>
</tr>
<tr>
<td>150–180</td>
<td>Light loam</td>
<td>51.32</td>
<td>26.5</td>
<td>5.20</td>
<td>1.29</td>
</tr>
</tbody>
</table>

SAT: saturated soil water content; FC: field capacity; PWP: permanent wilting point; BD: bulk density.
growing season using a neutron probe. Neutron probe observations were taken every 10 days at 0.1 m intervals from the soil surface to a depth of 1 m and at 0.2 m intervals to a depth of 2–3 m. The gravimetric method (Schmugge et al. 1980) was used to calibrate the neutron probe every 2 months. The data of actual evapotranspiration were measured using a lysimeter located near wheat plots.

Field experimental design

Six years’ field experiments were conducted in an area with a production scale (50 × 50 m) of two different sites (Wang Dong and Du Jiaping) under rainfed conditions. Wheat was generally sowed in September and harvested in June of the next year. Seeding rate was 150 kg ha⁻¹ and fertilizers were applied before sowing (138 kg N and 38.7 kg P₂O₅ ha⁻¹). Two cultivars (ChangHan 58 and ChangWu 89134) were used in the experiments. Other cultural practices were based on regional recommendations.

Aboveground biomass was measured before the wintering, turning green, jointing, and heading stages during the growing season. Biomass was determined by sampling 20 wheat plants from one of the four 1 × 1 m plots after oven drying to constant weight.

Leaf area was measured using CI-203 (CID Bioscience, Inc., WA, USA) Portable Laser Leaf Area Meter, from the 20 plants for biomass sampling before wintering, turning green, jointing and heading. The area and dry weight of about 100 leaves chosen from the biomass sample were determined. For the rest of the leaf samples, only leaf dry weight was measured. The LAI was calculated based on the equation of:

\[ \text{LAI} = \frac{[S1 \times (W1 + W2)]}{(W1 \times S2)} \]  

where S1 and S2 are the measured leaf area and the land area, respectively. W1 is the dry weight of the 100 leaves and W2 is the weight of the rest of the leaves from each sample.

The crop canopy cover (CC) was determined using digital photographs taken by a Canon PowerShot SX20 IS. In order to ensure the accuracy of CC measured, the CC was calculated by analyzing digital images using the SamplePoint program (Booth et al. 2006) and a program created by MATLAB (Mathworks, Inc., MA, USA). The CC values calculated using the MATLAB program agreed well with the ones calculated by SamplePoint (Figure 1).

A mean extinction coefficient \( \chi \) value of 0.47 for the winter wheat was determined by Equation (2) (Farahani et al. 2009) using measured LAI and their corresponding CC values. The missing CC values were calculated based on Equation (3) (Farahani et al. 2009; Araya et al. 2010):

\[ \chi = -\text{LN}(1 - \text{CC})/\text{LAI} \] (2)

\[ \text{CC} = 1 - \exp(-\chi \text{LAI}) \] (3)

Grain yield was measured after maturity from 6 plots with an area of 1 × 1 m by hand. Date of sowing, date of 90% emergence flowering, duration of flowering and maximum CC were recorded. The dates when the CC start to decline and reached to nearly zero were also recorded.

Model calibration

The FAO-AquaCrop model was calibrated using measured data from three growing seasons (2004–2005, 2005–2006, and 2007–2008). The change of CC over the growing season was calculated using Equation (3). The initial canopy cover (CC0) was estimated from seeding rate, 1,000-kernel weight and estimated germination rate in the model. The canopy expansion rates were automatically calculated by the model after entering some of the phenology dates such as dates to maximum CC, senescence, maturity and emergence. The values of canopy growth coefficient (CGC), canopy decline coefficient (CDC), stress indices for water stress affecting leaf expansion, and early senescence
can be obtained by phenology data inputted to the model. Then, the values of CGC, CDC and stress indices were calibrated by trial and error.

The calibration of water productivity ($WP^*$) was based on Equations (4)–(6) (Brisson et al. 1992; Steduto et al. 2009):

$$E = \frac{ET_0}{K_L A_I}$$  \hspace{1cm} (4)

$$Tr = ET_a - E$$  \hspace{1cm} (5)

$$WP^* = \left[\frac{BY}{\sum (Tr/ET_0)}\right]_{CO_2}$$  \hspace{1cm} (6)

where $E$ is evaporation, $ET_a$ is actual evapotranspiration, $Tr$ is transpiration, $ET_0$ is reference evapotranspiration, and $BY$ is aboveground biomass. Using Equations (4) and (5), $Tr$ may be separated from evapotranspiration. Because the ratio of transpiration to evapotranspiration increases with the increase in CC (Kato et al. 2004), $WP^*$ (normalized biomass water productivity) is a constant for a given species (Steduto et al. 2009). The constant is the slope of aboveground dry biomass versus cumulated normalized transpiration \[\Sigma (Tr/ET_0)\] (Farahani et al. 2009). The $CO_2$ outside the bracket indicates that the value of $WP^*$ is for a given year with its specific mean annual $CO_2$ concentration. A regression equation (Equation (7)) was fitted between the aboveground biomass and cumulated normalized transpiration as:

$$BY = 10.68 \left(\sum \frac{Tr}{ET_0}\right) - 1.04$$  \hspace{1cm} (7)

Using the slope value of Equation (7), the $WP^*$ value was estimated as 15. Finally, a set of conservative values were obtained from the field data measured in the three growing seasons (Table 2).

### Model validation

The AquaCrop model was evaluated using measured data from 2008–2009, 2009–2010 and 2010–2011 wheat growing seasons. The $Y$ (grain yield), $BY$, $WP$, $CC$ and soil water content in the root zone were simulated in different years using the calibrated constants. To evaluate the goodness of fit between observed $Y$, $BY$, $WP$, $CC$ and soil water content simulated outputs, the Willmott index of agreement ($d$) and root mean squared error (RMSE) were used to compare simulated and measured values. $d$ was calculated with

$$d = 1 - \frac{\sum_{i=1}^{n} (S_i - M_i)^2}{\sum_{i=1}^{n} (|S_i - MM| + |M_i - MM|)^2}$$  \hspace{1cm} (8)

where $S$ is simulated values, $M$ is measured values and $MM$ is the mean measured values. The model's fit improves as $d$ approaches unity.

RMSE (Steduto et al. 2009) indicates the extent to which the results of simulation are overestimated or underestimated. RMSE was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - M_i)^2}{n}}$$  \hspace{1cm} (9)

### RESULTS AND DISCUSSION

Figure 2 shows the simulated and measured $CC$ before wintering, turning green, jointing, heading for the calibration
period. Figure 2 indicates that the AquaCrop model slightly overestimated the CC at turning green and underestimated before wintering. At the jointing and heading stages, the simulated CC approached the measured results. Figure 3 shows the soil water content during the whole crop growth period for the calibration phase, too. It indicated that the general varying tendency of soil water content simulated in the root zone of 1.8 m was consistent with the measured soil water content during the whole growth period except for the soil water content in the 2004–2005 season. Figures 4 and 5 show the validation of the AquaCrop model. A similar trend was observed between the simulated and measured CC and soil water content for calibration and validation. Figure 6 shows the results of measured and simulated aboveground biomass and grain yields for both the validation and calibration periods. Generally, the simulated aboveground biomass was overestimated and the simulated grain yields approached the measured results.

Table 3 shows the statistical analysis of the model performance for aboveground biomass, CC, soil water content and grain yields. The $d$ values (0.95–0.98) (Table 3) and the RMSE values (0.50–1.44 t/ha) (Table 3) confirmed that the model accurately simulated the grain yields. Although the variability of $d$ values for aboveground biomass, CC, soil water content and grain yields during the validation period was similar.
biomass, CC and soil water content is slightly different compared with the grain yield, the RMSE values range for aboveground biomass (0.16–0.38 t/ha) (Table 3), CC (1.87–4.15%) (Table 3) and soil water content (5.7–22.56 mm) (Table 3) indicated reasonable agreement between simulated and measured results.

The three growing seasons’ (2008–2009, 2009–2010 and 2010–2011) data of crop growth and soil water content were used to validate the model under rainfed conditions in order to further test whether the model was applied or not. The value of WP* was within the range (15–20 g/m²) of default of the AquaCrop model for C3 plants in the model. The indices of soil water depletion (p) thresholds impacting on canopy development were defined within 0.35–0.65. The upper threshold for stomatal closure was 0.4. The canopy senescence stress coefficient was 0.75.

In this study, the performance of the model was validated with respect to simulating biomass, crop yield, CC and soil water content. Generally, the AquaCrop model was able to accurately simulate the CC development over the growing season under rainfed conditions with the exception of the turning green and wintering stage (Figures 2 and 4). A good agreement between simulated and observed CC was also reflected in the statistical analysis given in Table 3, with relatively consistent $d$ (0.25–0.43) and low RMSE (1.87–4.15%). Three reasons could cause the rather large difference at the turning green stage and wintering stage between simulated and observed CC. Firstly, much of the snowfall that failed to dissolve in the winter began to melt when the weather became warm gradually. But the time of the model responding to the snowfall was specific; a day or several days on which days the snowfall had just occurred and not the day when the snow melted. Consequently, the model responded to snowfall in advance. Therefore, it is reasonable to conclude that much melted snow entered the soil before the turning green stage promoted the winter wheat growth and expanded the leaf areas at the turning green stage. It is not surprising that the larger deviation occurred between simulated and measured values during the turning green stage. Secondly, winter wheat in the Changwu region generally has a period of dormancy from December to March. During the dormancy period, canopy development became smaller or even stopped. However, the model cannot accurately predict changes of canopy during the dormancy period. Finally, the AquaCrop model cannot simulate wheat tillering well. The tillering of winter wheat that occurs before the wintering stage expands the leaf area. It is not difficult to understand that the CC of prediction was lower than that

<table>
<thead>
<tr>
<th>Year</th>
<th>Soil water content RMSE (mm)</th>
<th>d</th>
<th>Aboveground biomass RMSE (t/ha)</th>
<th>d</th>
<th>Grain yield RMSE (t/ha)</th>
<th>d</th>
<th>Canopy cover RMSE (%)</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>22.56</td>
<td>0.39</td>
<td>0.19</td>
<td>0.45</td>
<td>0.50</td>
<td>0.98</td>
<td>2.11</td>
<td>0.25</td>
</tr>
<tr>
<td>2006</td>
<td>10.51</td>
<td>0.53</td>
<td>0.38</td>
<td>0.37</td>
<td>0.72</td>
<td>0.97</td>
<td>2.95</td>
<td>0.43</td>
</tr>
<tr>
<td>2008</td>
<td>5.7</td>
<td>0.49</td>
<td>0.16</td>
<td>0.22</td>
<td>0.96</td>
<td>0.97</td>
<td>4.15</td>
<td>0.39</td>
</tr>
<tr>
<td>2009</td>
<td>5.83</td>
<td>0.62</td>
<td>0.22</td>
<td>0.89</td>
<td>1.33</td>
<td>0.98</td>
<td>1.87</td>
<td>0.32</td>
</tr>
<tr>
<td>2010</td>
<td>9.49</td>
<td>0.50</td>
<td>0.17</td>
<td>0.32</td>
<td>0.91</td>
<td>0.95</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2011</td>
<td>18.35</td>
<td>0.36</td>
<td>0.17</td>
<td>0.70</td>
<td>1.44</td>
<td>0.96</td>
<td>2.58</td>
<td>0.40</td>
</tr>
</tbody>
</table>

$d$: index of agreement; RMSE: root mean square error (all values are averaged over different fields).
of measurement, owing to the positive effects of winter wheat tillering. In general, the simulation of CC is satisfactory. This result also indicates that soil water depletion threshold \( p \) values, which affect the development of CC and canopy senescence were well selected.

The model accurately simulated the grain yield (Table 3). In the AquaCrop model, grain yields are calculated as the result of biomass multiplying HI. The high \( d' \) (0.95–0.98) (Table 3) values for grain yields indicated that there was a very good agreement between simulated and measured grain yields. The low RMSE (0.16–0.38 t/ha) (Table 3) showed that the aboveground biomass simulations were in general in line well with the measured aboveground biomass although a few \( d' \) values were also lower (Table 3). In general, the model simulated yield was better than the simulated biomass. A possible explanation was that HI may offset the shortcoming for the simulated biomass.

The simulation of soil water content is satisfactory, even though there is a larger difference between simulated and measured results from middle to late developmental stages. This is probably because the snowfall melts in the beginning of spring on the Loess Plateau and snowfall supplies water to the soil for the winter wheat growth in the early spring when plants are actively growing. But the parameters of time inputted to the AquaCrop model for snowfall were the time when snowfall had just happened and not the time when the snow began to melt. Thus, the effects of wheat responding to soil water change might be delayed. Consequently, the soil water content simulated was a little higher in the middle of the growing season and lower in the late stage compared with the measured results.

**CONCLUSION**

The AquaCrop model was used to simulate the aboveground biomass, grain yield, CC and soil water content under rainfed conditions in the southern Loess Plateau of China. A set of conservative parameters were obtained after calibrating the AquaCrop model. Using the measured data from field experiments, the reliability of these conservative parameters was evaluated. Overall, the simulated grain yield, aboveground biomass, CC and soil water content agreed well with measured values. However, the field experiments in this study were conducted using optimum management practices under rainfed conditions. Further improvement may be needed to capture the variation of different management practices such as fertility and irrigation levels in this region.

**ACKNOWLEDGEMENT**

The work is supported by the Chinese National Nature Science Fund (No. 41171035).

**REFERENCES**


First received 7 January 2013; accepted in revised form 2 April 2013