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# Modeling irrigation management for water conservation by DSSAT-maize model in arid northwestern China

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ABSTRACT

Water shortage is a chronic problem in arid Northwest China, where agriculture cannot exist without irrigation. Efficient irrigation and water uses are important to sustainable development and management of water resources in the region. This paper applied DSSAT-maize v4.5 to the Yingke Irrigation District in the middle reach oasis of the Heihe River Watershed in Northwest China to explore the optimal irrigation strategies under different climatic conditions, and to improve the beneficial water consumption and reduce non-beneficial water consumption while maintaining yields at the same time. The model was first calibrated based on the crop yield, phenological phases and soil water content data, and good agreements were achieved between the simulated and observed data in both the calibration and validation periods. In the calibration period, the simulated maize phenological phases differed by two days of the observed phases, and nRMSE (normalized root mean square errors) for grain yield was 6%. In the validation period, the values of nRMSE of yield were 4.95% in 2006 and 2.96% in 2008, respectively, while the RMSE for soil water content ranged from 0.118 to 0.046. Subsequently the calibrated model was used to simulate the effects of planting dates and different irrigation treatments on maize yield and the potentially reduced water amount was calculated. Results show that in the Yingke Irrigation District, the best planting dates range from early April to mid-April, and the best irrigation periods are the jointing and tassel phases. The optimal irrigation amounts vary under different climatic conditions, ranging from about 1000 $m^3$/ha, to 4200 $m^3$/ha, and to 4800 $m^3$/ha in wet, normal and dry years respectively. Nearly half of the irrigation amount could be reduced under the simulated irrigation schedule for the district. Once validated by field tests, the simulated irrigation scenarios would provide partial basis for effective water resources management in the study area.



## 1. Introduction

In arid and semi-arid regions, water resources are limited, while the competition for the limited water resources for crop irrigation, domestic water supplies, and ecosystem services are intensifying (Wang, 2012; Molden, 1997; Seckler, 1998; Gleick, 1993). Hence, it is vital to improve the beneficial water consumption and reduce non-beneficial water consumption in agriculture for the sustainable management of water resources (Deng et al., 2006; Hsiao et al., 2007). Decision makers often face the following questions: How much water is needed for crop growth? When is the best irrigation time? How much water can be saved by different irrigation schedules?

Many previous studies mainly depended on field experiments, which were necessary but time-consuming and expensive to carry out, also vulnerable to external disturbance (Bhatia et al., 2008). With the rapid advancement of information technology, various crop system models have been developed, such as Wageningen (van Ittersum et al., 2003), DSSAT (Decision Support System for Agrotechnology Transfer) (Jones et al., 2003), EPIC (Erosion-Productivity Impact Calculator) (Sharpley and Williams, 1990; Ko et al., 2009), APSIM (Agricultural Production Systems Simulator) (McCown et al., 1995), RZWQM (Root Zone Water Quality Model) (Keating et al., 2003; Saseendran et al., 2005) and so on. With these models, we can simulate crop growth, development and its yield

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under the background of climate change (Stockle et al., 1992), the soil carbon and nitrate dynamics (Ma et al., 2007), and soil water balance (Asadi and Clemente, 2003; Kumar et al., 1998; Izaurralde et al., 2006). Hu et al. (2006) calibrated and tested the RZWQM model to assess N and water management in a double-cropping system comprised of winter wheat and corn at Luancheng, in the North China Plain. Rinaldi (2001) applied EPIC model to optimize irrigation for sunflower in Southern Italy. Farre et al. (2002) simulated phenology and yield response of canola to sowing date in Western Australia using the APSIM model.

Compared with the above models, DSSAT models are much more comprehensive as they consider the crop genetic traits, soil, climate, management and so on. DSSAT has already been successfully used all over the world under different conditions and for a variety of purposes, such as yield forecast (Bannayan et al., 2003; Bhatia et al., 2008), irrigation management (Panda et al., 2004), the effect of climate change on crop (Nelson et al., 2009; Kapetanaki and Rosenzweig, 1997), and N leaching (Asadi and Clemente, 2003), etc. He (1997, 1999a,b) estimated the irrigation requirements of crop production and the related impacts on the water level of the Great Lakes Basin in North America. Dai et al. (2009) analyzed the spring corn growth conditions in Beijing at different sowing dates and different irrigation levels using DSSAT-maize model based on the meteorological data from 1976 to 2005. Yang et al. (2006a) calibrated and validated the DSSAT-wheat model in the North China Plain to simulate the water consumption by winter wheat and analyze the relationship between irrigation water management and groundwater level. Despite these studies on water management, most of them focused on irrigation schedules for normal climatic years, few focused on irrigation strategies under different climatic years and assessed the potentially reduced water amount. Exploring the optimal irrigation scenarios under different climatic years is important to improve the beneficial water consumption and reduced non-beneficial water consumption (Fang et al., 2008; Dai et al., 2009; Wang, 2012). Thus, it is necessary to understand how much water is needed for crop irrigation under different climatic conditions in arid regions and what best management practices can be implemented that combine planting dates, irrigation schedules and even irrigation techniques to ensure both water and food security in arid regions.

In recent years, DSSAT models have already been used in many regions of China, such as Jilin in Northeastern China (Yang, 2011; Liu et al., 2012, 2013), Shijiazhuang and Beijing in Northern China (Hu et al., 2010b; Chen et al., 2010; Yang et al., 2006a,b), Henan in Central China (Cheng et al., 2009; Jiang, 2009) and Shaanxi and Ningxia in Northwest China (Hu et al., 2010a; Wang, 2012; Lei, 2001). However, so far little has been done in the oases of the Heihe River Watershed in Northwest China. The irrigation districts in the Heihe River Watershed are concentrated in the Middle Reach oases (Li et al., 2012). The Middle Reach is the main water consumption area of the Heihe River, and agriculture is the primary water user. Overconsumption of the water resources by the middle oases has caused a number of social instability and environmental problems downstream. According to the study of Zhang et al. (2006), water demand in the Middle Reach of the Heihe River Watershed was projected to have an increasing trend in the future, and the conflicts between the water supply and demand would further intensify. Therefore it is essential to improve beneficial water consumption and reduce non-beneficial water consumption to ensure sustainable use of water resources for both ecosystem protection and food security (Chen et al., 2000).

This paper first describes calibration and validation of the DSSAT model, then estimates crop irrigation demand in the study area by the calibrated DSSAT, simulates the effects of different irrigation strategies and sowing dates on crop production and water uses, and evaluates how much water could be reduced under the optimal irrigation practices.

## 2. Study area and data

### 2.1. Study area

The study area is the Yingke Irrigation District (Fig. 1) in the middle reach oasis of the Heihe River Watershed with an area of 210 km$^2$. As the second largest inland river (terminal lake) watershed with a drainage area of 128,000 km$^2$ (Pan and Tian, 2001), the Heihe River Watershed is only second to the Tarim River Basin in China. Administratively, it flows across Qinghai, Gansu Provinces and Inner Mongolia Autonomous Region. With its relatively sufficient source of irrigation water supply, the middle reach oasis is an important grain production base and uses over 80% of the available water resources (Lv et al., 2008). Overconsumption of the water resources by the middle oasis users leaves little flow downstream, causing a number of environmental problems such as sandstorms and desertification, etc. (He et al., 2009a). The Yingke Irrigation District is a representative of the irrigation districts in the middle reach oasis. Simulation of the best irrigation practices by the DSSAT in the study district would provide insights for irrigation management in the Heihe River Watershed and the rest of the Northwest China.

The main crops are maize and wheat at the Yingke Irrigation District, after the crop pattern adjustment in 2000, maize became to be the dominant crop (Shi et al., 2011) and it is irrigated by the streamflow of the Heihe River. The Yingke Irrigation District is relatively flat, and its elevation ranges from 1463 m in the east to 1620 m in the west. The climate in the area is typical temperate continental, with the mean annual precipitation of 125 mm and evaporation of 1291 mm, respectively, and the mean annual temperature ranges from 6.5 to 7.5 °C.

### 2.2. Datasets

#### 2.2.1. Crop management information

DSSAT modeling system consists of a number of crop models. In this study, DSSAT-maize is selected to simulate growth and water consumption of maize, the main crop in the study area. The model requires crop cultivar-specific parameters and genotypes (Jones et al., 2003), planting date, planting density, planting depth and the row spacing, the application frequency, types, dates, and amount of the irrigation and fertilizer management locally, maize is usually sowed around April 20 in rows with a depth of 5 cm, and row spacing of approximately 60 cm. The fertilization and irrigation practices as well as the specific growing stage dates are based on field investigation by interviewing the local farmers and crop specialists (Table 1).

**Table 1**
Fertilization and irrigation applications in the Yingke Irrigation District.

| Fertilize frequency | Date | Fertilizer material |
|---|---|---|
| 4 | April 5 | Ammonium polyphosphate |
| | May 16 | Ammonium polyphosphate |
| | June 15 | Urea |
| | August 14 | Urea ammonium nitrate solution |
| Irrigation frequency | Date | Irrigation amount (mm) |
| 5 | May 18 | 150 |
| | June 15 | 150 |
| | July 16 | 180 |
| | August 15 | 180 |
| | September 8 | 225 |

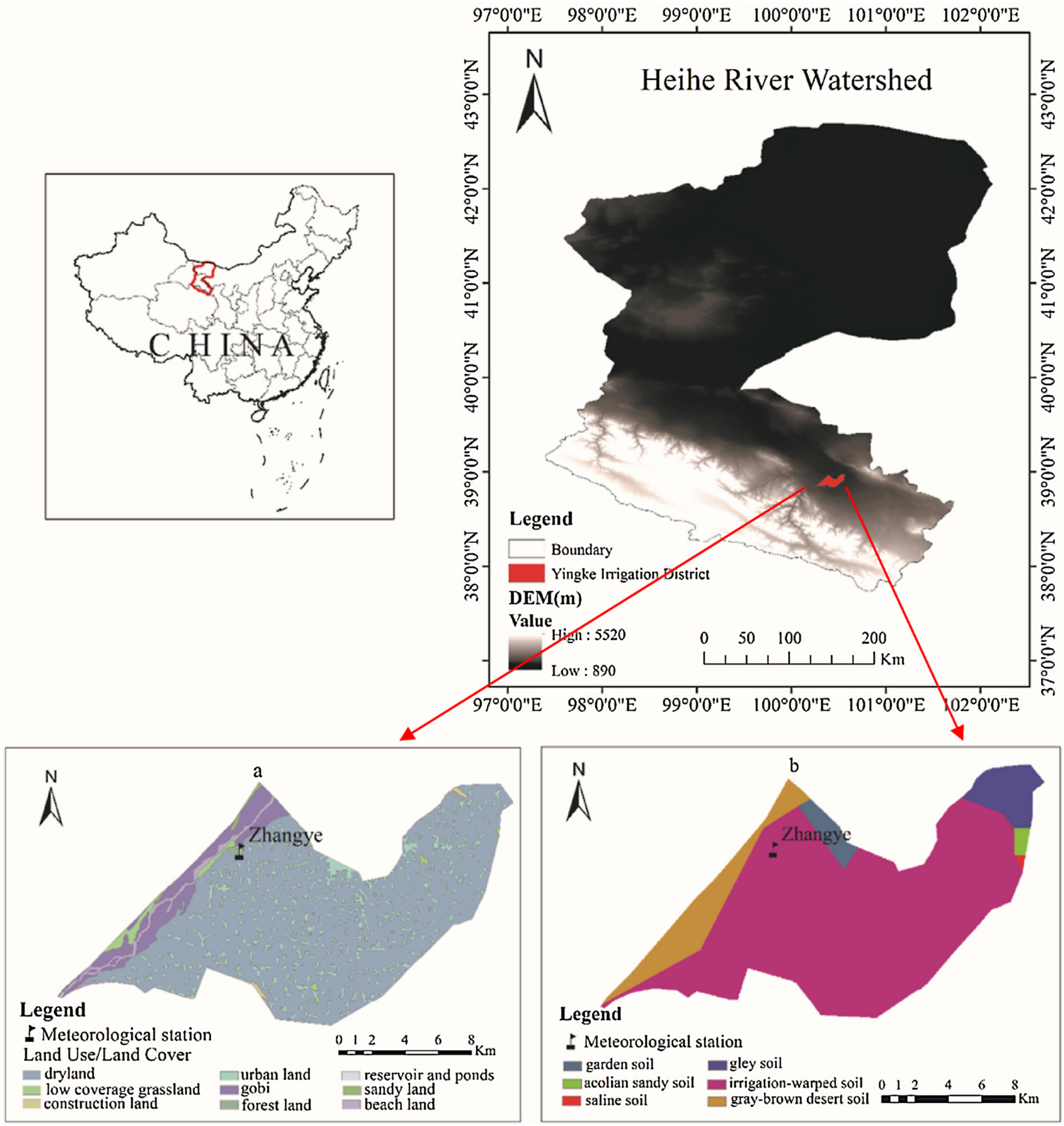


**Fig. 1.** Map of study area—the Yingke Irrigation District (a. LU/LC spatial pattern in the Yingke Irrigation District; b. soil types in the Yingke Irrigation Distrit).

### 2.2.2. Daily weather data

As the DSSAT-maize model simulates in daily step, the weather data is also required to be in daily format. The minimum weather input requirements of the model are daily solar radiation (MJ $m^{-2}$ $d^{-1}$), maximum and minimum temperature (°C) and precipitation (mm). All these data for the period of 1971–2010 were collected from the Zhangye Meteorological Station (38°55′58″N, 100°22′58″E) located in the Yingke Irrigation District at an elevation of 1483 m above sea level. The collected data were converted and formatted for model input using Weather module. The mean annual solar radiation data that were converted from the sunshine duration by the Weather module were found to be consistent with the data published in "Solar Radiation of Gansu Province" (Yang and Lv, 1987), and thus were adopted in the simulations.

### 2.2.3. Soil profile data

The main soil type in the irrigation district is irrigation-warped soil due to long term irrigation with water containing high level of sediment. It accounts for nearly 80% of the total area, and is quite uniform in color, characteristics, structure, and organic content. The required soil input includes soil bulk density, pH, organic matter content, cation exchange capacity (CEC), wilting point, drainage, saturated hydraulic conductivity, runoff coefficients, soil albedo, and water-holding characteristics for each individual soil layer (Jones et al., 2003). The physical and chemical parameters for the irrigation district are summarized in Tables 2 and 3. The map of relevant soil type data was obtained from the 1:1,000,000 scale "Soil Types of China", compiled by the Institute of Soil Sciences, Chinese Academy of Sciences based on national soil survey of China (Zhu, 1995). The attributes of the soil types for the Yingke Irriga-

**Table 2**
Physical and chemical parameter values at different soil layers for the soil profile in the Yingke Irrigation District. (source: http://westdc.westgis.ac.cn/).

| Soil depth (cm) | Bulk density ($g\,cm^{-3}$) | Sand content (%) | Silt content (%) | Clay content (%) | pH | CEC (mg/100 g) | Soil depth (cm) | Organic carbon (%) | Total Nitrogen (%) | Total Phosphorus (%) | Total Potassium (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0–5 | 1.41 | 46.9 | 38.8 | 14.3 | 8.3 | 23.6 | 0–5 | 1.282 | 0.14 | 0.08 | 2.04 |
| 5–20 | 1.41 | 46.8 | 38.9 | 14.3 | 8.3 | 20.4 | 5–20 | 1.280 | 0.14 | 0.08 | 2.03 |
| 20–40 | 1.42 | 46.3 | 39.3 | 14.4 | 8.5 | 12.7 | 20–40 | 1.096 | 0.12 | 0.08 | 1.97 |
| 40–120 | 1.42 | 42.2 | 42.9 | 14.9 | 8.2 | 10.1 | 40–120 | 0.922 | 0.1 | 0.069 | 1.82 |
| 120–160 | 1.42 | 42.0 | 43.2 | 14.8 | 8.3 | 9.6 | 120–160 | 0.766 | 0.09 | 0.08 | 1.69 |

**Table 3**
Irrigation schedules simulated with the DSSAT-maize model.

| Irrigation frequency | Irrigation amount (mm) | Total amount of growing season (mm) | Irrigation at phenological phase[a] |
|---|---|---|---|
| 0 (Rainfed) | 0 | 0 | None[1] |
| 1 | 80 | 80 | E[2], J[3], T[4], G[5], M[6] |
| 2 | 80 | 160 | EJ[7], ET[8], EG[9], EM[10], JT[11], JG[12], JM[13], TG[14], TM[15], GM[16] |
| 3 | 80 | 240 | GMT[17], GMJ[18], GME[19], GJT[20], GJE[21], THE[22], TJM[23], ETM[24], ETG[25], EJM[26] |
| 4 | 80 | 320 | EJTM[27], EJTG[28], EJGM[29], ETGM[30], JTGM[31] |
| 5 | 80 | 400 | EJTGM[32] |
| Automatic irrigation | When required | When required | When required[33] |

*Notes*: E represents Emergence stage; J represents Jointing stage; T represents Tassel stage; G represents Grain filling stage; M represents Maturity stage. The marked number äŘepresents the irrigation treatment number.

**Table 4**
Genetic parameters of Zhizhong maize after calibration.

| | P1 | P2 | P5 | G2 | G3 | PHINT |
|---|---|---|---|---|---|---|
| Range | (100–400) | (0.1–0.8) | (600–1000) | (560–850) | (5–12) | (35–55) |
| Calibrated value | 312.5 | 0.289 | 790 | 700 | 7.05 | 40 |

*Notes*: P1: Degree days (base 8 °C) from emergence to end of juvenile phase.
P2: Photoperiod sensitivity coefficient (0–1.0).
P5: Degree days (base 8 °C) from silking to physiological maturity.
G2: Potential kernel number.
G3: Potential kernel growth rate mg/(kernel d).
PHINT: Degree days required for a leaf tip to emerge (phyllochron interval) (°C d).

tion District were compiled from soil survey data of Chen and Xiao (2003), Xiao (2006), unpublished reports of the Zhangye Academy of Agricultural Sciences and the Yingke Irrigation District, and literature. The soil sampling sites were determined using a stratified random soil sampling in the study area, soil samples were collected in the field at different layers of 0–10 cm, 10–20 cm, 20–30 cm, 30–70 cm, and >70 cm with standard steel cylinder, weighed and then taken back to the laboratory for analysis of soil parameters like pH, organic matter content, cation exchange capacity (CEC), bulk density, and saturated hydraulic conductivity, etc. (Chen and Xiao, 2003). Soil bulk density was determined by the volumetric weight measurement method, and available water content was calculated as water content difference between field capacity and permanent wilting point of soil at any given depth (Chen and Xiao, 2003).

### 2.2.4. Cultivar parameters

Crop cultivar coefficients are required to simulate crop growth rates and stages, biomass production and grain yield, etc. (Liu et al., 2013). There are six cultivar coefficients for maize, which are P1: Degree days (base 8 °C) from emergence to end of juvenile phase, P2: Photoperiod sensitivity coefficient (0–1.0), P5: Degree days (base 8 °C) from silking to physiological maturity, G2: Potential kernel number, G3: Potential kernel growth rate mg/(kernel d), PHINT: Degree days required for a leaf tip to emerge (phyllochron interval) (°C d). In this study, we first obtained these values of the maize based on Rezzoug et al. (2008) and Lu (2010), and then used the GLUE Coefficient Estimator combining with trial-and-error method to estimate the genetic parameters (He et al., 2009b) (Table 4).

## 3. Methodology

DSSAT-maize is a crop growth model of the DSSAT family (Version 4.5), which comprises crop simulation models for over 28 crops. It can simulate the phenological development, photosynthesis, biomass allocation and yield of maize as a function of the soil-plant-atmosphere dynamics on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon and nitrogen over time. All these simulations are conducted at daily steps. At the end of each day, the plant growth and soil water, carbon and nitrogen balances are updated (Jones et al., 2003). The biomass formation is directly driven by solar radiation and affected by the external environment, and the biomass allocations are different at different growth stages (Yang et al., 2006b).

The soil water balance module of the DSSAT models computes all processes that directly affect water content in the soil profile throughout the simulation. Ritchie (1985) described many of these algorithms in detail. The model evaluates the soil water balance in daily step as a function of precipitation, infiltration, transpiration, soil evaporation, and drainage from the soil profile (Jones et al., 2010), as the following equation shows:

$$\Delta S = P + I - EP - ES - R - D$$

Where, $\Delta S$ = Change in soil water content
$P$ = Precipitation
$I$ = Irrigation
$EP$ = Transpiration
$ES$ = Soil Evaporation
$R$ = Surface Runoff
$D$ = Drainage from Soil Profile

### 3.1. Model calibration and validation

Model calibration is the adjustment of parameters so that the simulated values fit well with the observed data. To evaluate the model performance, the simulated values of crop yields, soil water content, and phenological phases were compared with the observed values. The county-level crop yield data were collected from Zhangye Academy of Agricultural Sciences in the study area. Soil samples were collected at 5 depths (0–5, 5–20, 20–40, 40–120, 120–160 cm) and then oven dried at 105 °C for 24 h to derive soil water content. Eight soil samples were collected over the growing season. Crop phenological phases were obtained through interviewing with local farmers and extension specialists. To quantify the goodness of model fitting, three common statistical indicators were used: root mean square errors (RMSE), normalized root mean square errors (nRMSE), and mean error (ME) (Yang et al., 2000; Panda et al., 2003). These statistics are defined as follows:

$$nRMSE = \frac{RMSE}{\overline{M}} \times 100 = \frac{\sqrt{\sum_{i=1}^{n}(S_i - M_i)^2/n}}{\overline{M}} \times 100 \quad (1)$$

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

$$ME = \frac{1}{n}\sum_{i=1}^{n}(S_i - M_i) \quad (3)$$

where $n$ is the total number of data, $S$ and $M$ represent the simulated and measured values, $\overline{S}$ and $\overline{M}$ are the average of simulated and measured values, respectively.

For the nRMSE, it is generally believed that when its value is less than 10%, the model performance is excellent, when it is between 10%–20%, the model performance is considered good, when it is between 20%–30%, the model performance is fair, and when it is greater than 30%, the model performance is poor (Jamieson et al., 1991).

Here RMSE was chosen to evaluate the goodness of fit of soil water content, when RMSE is less than 0.1, it indicates an excellent fit; when it is between 0.1–0.2, the fit is good; when it is between 0.2–0.3, the fit is moderate; if it is larger than 0.3, the fit is poor (Lu, 2010).

### 3.2. Simulation controls

#### 3.2.1. Planting date treatments

The analysis of the effects of different planting dates on maize yield was conducted based on 35 years of historical weather data from the Zhangye Meteorological Station. According to local practices, which were obtained from field interviews with local farmers and crop specialists, four different planting dates were chosen for simulations under different irrigation conditions. The planting dates started on April 5 and ended on May 20 with an interval of 15 days, namely April 5, April 20, May 5, and May 20 (The Ministry of Agriculture of the People's Republic of China, 2002).

#### 3.2.2. Irrigation treatments

The irrigation treatments consisted of irrigation schedules based on different phenological phases with various irrigation levels. Seven irrigation regimes under different combinations of phenological phase (Emergence, Jointing, Tassel, Grain filling, Maturity) were simulated: no irrigation, one irrigation, two irrigations, three irrigations, four irrigations, five irrigations (each irrigation with the amount of 80 mm of water) and automatic irrigation (Table 3). All these simulations were conducted with the assumption of no nutrition stress. At present, in the study area, the most popular irrigation method farmers used is flood irrigation, and we used it as a control in simulating the irrigation scenarios.

## 4. Results and discussion

### 4.1. Model calibration

Based on the available datasets, we chose the year 2007 with relatively abundant rainfall (216.3 mm) to calibrate the model. The initial soil water conditions were specified based on the antecedent precipitation and the measured soil moisture content of the collected soil samples. Table 4 shows the values of the six genetic coefficients for maize obtained by fitting the model simulation results against the measured data. Table 5 shows the difference between the measured and simulated data including harvest yield, emergence, anthesis and grain filling dates. It confirms that the simulated values were in good agreement with the measured ones.

**Table 5**
Comparison of the measured and simulated maize yield and growing stage in 2007 using the calibrated cultivar coefficients.

| | Measured | Simulated | Error | nRMSE(%) |
|---|---|---|---|---|
| Yield (kg/ha) | 7159 | 7202 | 6.00% | 6.00 |
| Emergence (DAP) | 16 | 15 | 1 day | 6.25 |
| Anthesis (DAP) | 97 | 95 | 2 day | 2.11 |
| Begin of Grain filling (DAP) | 107 | 107 | 0 day | 0.00 |
| End of Grain filling (DAP) | 153 | 153 | 0 day | 0.00 |

*Note*: DAP means day after planting.

**Table 6**
Comparison of the simulated and measured maize yields after calibration.

| | Yield (kg/ha) | | nRMSE | Absolute Error (kg/ha) |
|---|---|---|---|---|
| Year | Simulated | Measured | (%) | |
| 2006 | 7340 | 7722 | 4.95 | −382 |
| 2008 | 7556 | 7339 | 2.96 | 217 |

### 4.2. Model validation

The measured data in 2006 (117.4 mm precipitation, a relatively dry year) and 2008 (141.5 mm precipitation, a relatively normal year) was used to validate the model for the study area, which were measured by the staff and researchers of the Bureau of Agricultural Administration of the City of Zhangye and published in "Zhangye Comprehensive Yearbook" (He and Zhang, 2009, 2011). For the validation, nRMSE was 4.95% for maize yield in 2006 and 2.96% in 2008 (Table 6), which indicates that the simulated and measured grain yields fitted each other quite well. Since the purpose of this study was to see how different irrigation schedules would affect grain yield, it was important to test if the model would accurately simulate the soil water content as well. As shown in Fig. 2, the RMSE values of the whole soil profile between the simulated and measured soil water content ranged from 0.118 to 0.046 for each of the soil layers. Above the 40 cm the RMSE was slightly greater than 0.1, and below that it was less than 0.1, the goodness of fit was satisfactory. Moreover, the model accurately simulated the effects of four irrigations on the change of soil water content. Thus the DSSAT-maize model can simulate well the soil water content and the potential yield of crops under water stress in the study area.

### 4.3. Effect of planting dates on potential yield

Four different planting dates (April 5, April 20, May 5, and May 20) were simulated from 1971 to 2005 to find the optimum maize planting dates with the highest yield locally. The simulations were conducted under the conditions of rainfed and automatic irrigation respectively, and all these simulations assumed no nutrient stress. The simulation results show that under both the no irrigation and the automatic irrigation scenarios, especially the latter one, the peak yield was reached for April 5 and April 20 planting dates (Fig. 3). For the rainfed condition, there was only a 2% difference in the average yield between the April 5 and April 20 planting dates, while a 7% difference between the April 20 and May 5, a 16% difference between the May 5 and May 20 and a 21% difference between the earliest and latest planting dates. Under the automatic irrigation scenario, the decrease in yield was much more evident than under the rainfed scenario, with a 40% difference between the earliest and latest planting dates, and a 1% difference in the average yield between the April 5 and April 20, a 10% difference between

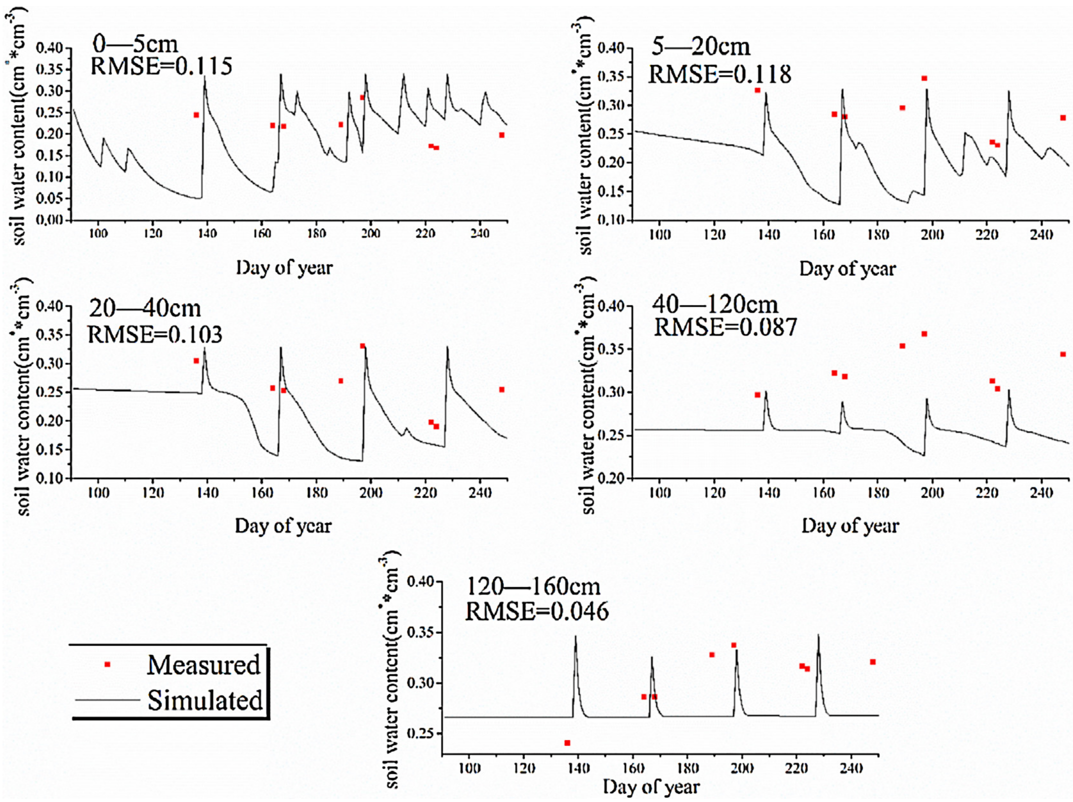


**Fig. 2.** Comparison between the simulated and measured soil moisture at different depths in 2008. The observed soil water content data were from the website: http://westdc.westgis.ac.cn/, accessed March 6, 2014.

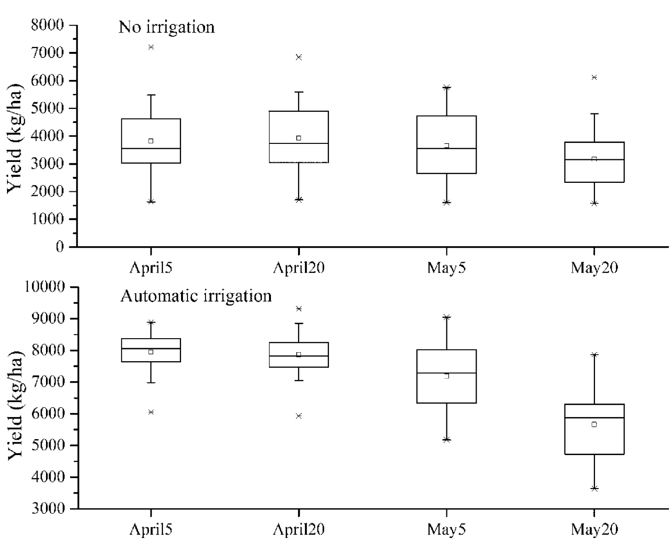


**Fig. 3.** Simulated maize yield for different planting dates under the rainfed and automatic irrigation conditions.

the April 20 and May 5, a 27% difference between the May 5 and May 20. For the rainfed scenario, with the coupling impact of water and planting date (temperature, solar radiation) on the final yield, the effect of planting dates was not as obvious as the automatic irrigation scenario and the decreasing amplitude was smaller than the automatic irrigation scenario. Thus it seems that the best planting date in this region is from early April to mid-April.

### 4.4. Effect of irrigation schedule on maize yield

Due to the scarce precipitation and high evaporation, irrigation is necessary to ensure the growth of the crops in this region. As the crop water requirement changes at different growth stages, and the precipitation is unevenly distributed within a year, the effect of irrigation at different growth stages on final yield varies. In the model, we set 33 ($C_5^0 + C_5^1 + C_5^2 + C_5^3 + C_5^4 + C_5^5 + Automatic$) irrigation combinations in total at five key growth stages with 0 irrigation, 1 irrigation, 2 irrigations, 3 irrigations, 4 irrigations, 5 irrigations and automatic irrigation (Table 3). The five key irrigation stages are emergence, jointing, tassel, grain filling, and maturity. As shown in Fig. 4, the average yield at all four planting dates reached the high point first at the treatment 11, which was the combination of jointing and tassel. After that, with the increasing number of irrigation times and volume, the yield increment was relatively small. Thus irrigation at jointing and tassel stages may be optimal and economic. At the jointing phase, maize grows vigorously, and stems and leaf area expand quickly, and water deficit would lead to poor vegetative growth (Tan et al., 2010). Tassel is the most critical stage of maize that determines the final yield, and at the tassel stage, maize requires most nutrients, water, temperature and light (The Ministry of Agriculture of the People's Republic of China, 2002).

After confirming the best irrigation stages, it was necessary to find the optimal irrigation amount. Based on the precipitation data during 1971–2010 (Fig. 5) from Zhangye Meteorological Station, we used the P III frequency curve view software to define different climatic years: p = 25% as wet year, meaning the amount of annual precipitation in that year would be greater than the computed threshold 25% of time; p = 50% as normal year, meaning that the amount of annual precipitation in that year would be higher than the computed threshold 50% of time, and p = 75% as dry year, indicating the amount of annual precipitation in that year is

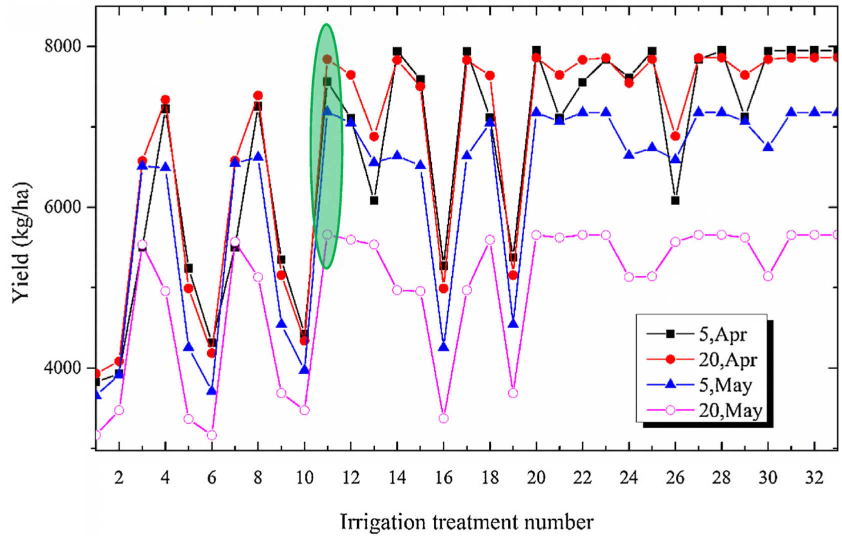


**Fig. 4.** Simulated maize yield for different planting dates at different irrigation treatments from 1971 to 2005 (refer to Table 3 for the representation of irrigation treatment number).

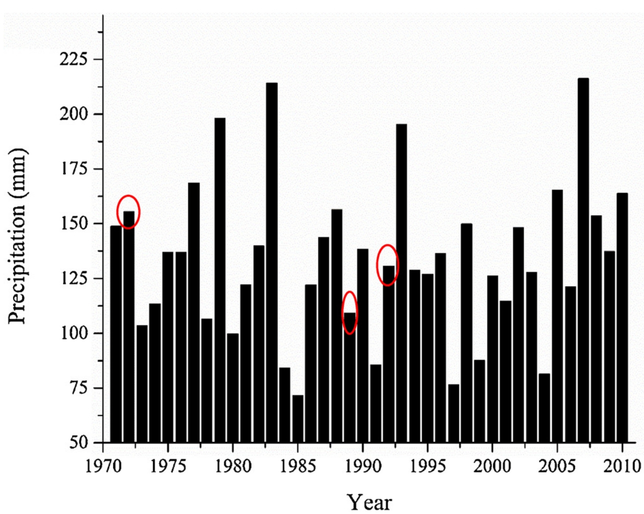


**Fig. 5.** Precipitation distribution from 1971 to 2010 (the 1972, 1992, and 1989 marked by red circles represent the wet year, normal year, and dry year, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

below the computed threshold 75% of time. Thus we selected 1972, 1992, and 1989 as the wet year, normal year, and dry year with the annual precipitation 155.60 mm, 130.70 mm, and 109.40 mm, respectively. Subsequently, 15 simulations under different irrigation scenarios were conducted to obtain the appropriate irrigation amount. Table 7 suggests that for 1989, the dry year, the optimal irrigation was 480 mm, for 1992 the normal year, the optimal irrigation was 420 mm, slightly less than the 1989 irrigation amount, while for 1972, the wet year, the optimal irrigation amount was the least, just 100 mm. The yield of 1992 was higher than that of 1972, because the rainfall in 1972 was mainly concentrated in August, and the rainfall in June, the jointing stage, was less than that of 1992 (Fig. 6), that might have lowered the maize yield in 1972.

*4.5. How much water could be saved?*

With different irrigation scenarios, how much water could be available for other water sectors such as industrial development, travel and tourism, and ecosystem services? To answer this ques-

**Table 7**
Simulated maize yield for different climatic years under different irrigation conditions (the 1972, 1992, and 1989 represent the wet year, normal year, and dry year, respectively).

| Irrigation amount (mm) | Yield (kg/ha) | | |
|---|---|---|---|
| | 1989 | 1992 | 1972 |
| 0 | 3639 | 4418 | 4362 |
| 20 | 4761 | 4893 | 5814 |
| 40 | 5553 | 5961 | 7432 |
| 50 | 6027 | 6323 | 7718 |
| 60 | 6363 | 6708 | 7961 |
| 100 | 7556 | 7499 | 8093 |
| 120 | 7812 | 7892 | 8093 |
| 140 | 7839 | 8268 | 8093 |
| 160 | 7831 | 8463 | 8093 |
| 200 | 7838 | 8465 | 8093 |
| 300 | 7831 | 8524 | 8093 |
| 360 | 7837 | 8509 | 8093 |
| 420 | 7840 | 8530 | 8093 |
| 480 | 7845 | 8506 | 8093 |
| 500 | 7845 | 8507 | 8093 |

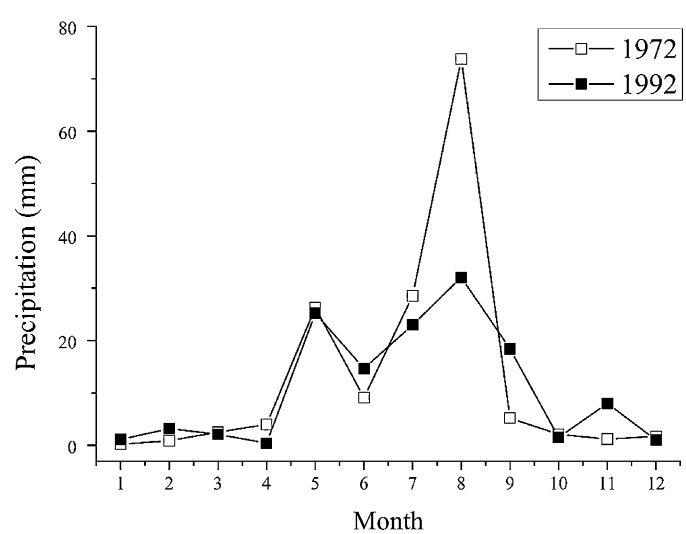


**Fig. 6.** Distribution of rainfall during the year of 1972 and 1992.

**Table 8**
Potentially reduced water amount for a 5-year precipitation cycle.

| Current Situation | Simulated | | | Water Saving Potential |
|---|---|---|---|---|
| irrigation quota = 6900 m$^3$/(ha year) | dry year = 480 mm | normal year = 420 mm | wet year = 100 mm | |
| 6900 m$^3$/(ha year) × 5 year = 34,500 m$^3$/ha | 480 mm/(ha year) × 2 year + 420 mm/(ha year) × 1 year + 100 mm/(ha year) × 2 year = 1580 mm/ha = 15,800 m$^3$/ha | | | 18,700 m$^3$/ha × 20,960 ha = 391.95 million m$^3$ |

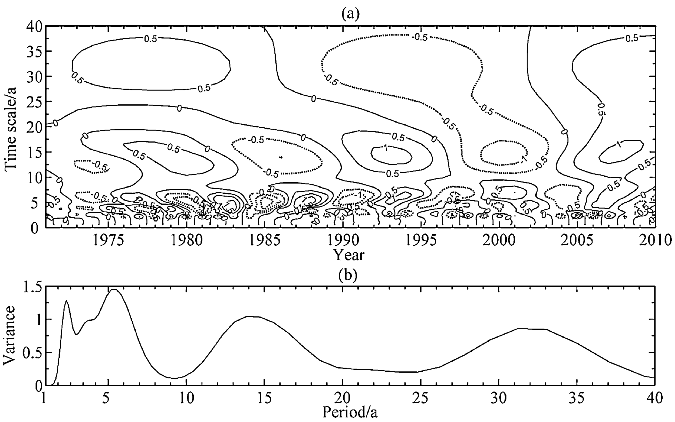


**Fig. 7.** Wavelet analysis results of precipitation for the period of 1971–2010 (a. contour map of wavelet real part, here positive contours indicated by solid lines, represent rainfall above normal; negative contours indicated by dashed lines, represent the rainfall below normal, the wavelet coefficients of zero corresponds to the mutation point; b. variance map of wavelet).

tion, the cycle of local precipitation was first analyzed by using wavelet analysis. As shown in Fig. 7, the primary cycle of precipitation is about 5 years. From Fig. 5, one 5-year cycle mostly includes two wet years, two dry years and one normal year. In that case, 15,800 m$^3$/ha of irrigation would be needed in a 5-year precipitation cycle to assure the high yield if the proposed irrigation schedule were timely carried out according to the precipitation distribution of that very year. The current irrigation quota in the irrigation district is 6900 m$^3$/ha per year, that is 34,500 m$^3$/ha for a 5-year precipitation cycle. Therefore 18,700 m$^3$/ha irrigation water could be reduced for a 5-year precipitation cycle had the optimal irrigation schedule been implemented. In the Yingke Irrigation District, if all the 20,960 ha of the cropland were planted in maize, the minimum amount of water needed to satisfy the irrigation requirement would be about 331 million m$^3$ for one 5-year period, which means about 392 million m$^3$ water, nearly half of the current irrigation amount, would be reduced (Table 8).

## 5. Conclusions

The DSSAT maize model was applied to the Yingke Irrigation District to simulate the growth and water consumption of maize for the period of 1971–2010. The model was first calibrated using the locally measured crop yield and soil moisture content. Subsequently, the well-calibrated model was used to simulate the best planting dates and irrigation scenarios under different climatic conditions to identify the best irrigation management practices and combining with wavelet analysis method, the potentially reduced water amount was evaluated. The main findings are as follows:

(1) In the Yingke Irrigation District, the best planting dates range from early April to mid-April, and the best irrigation period is the jointing and tassel stages for maize.
(2) The optimal irrigation amount varies over different climatic years, ranging from about 1000 m$^3$/ha in wet years, to 4200 m$^3$/ha in normal years, and 4800 m$^3$/ha in dry years.
(3) More than half of the irrigation amount at current practices could be reduced with the simulated irrigation schedules in the study area over a 5-year precipitation cycle.

All these estimates, once tested in the field, serve to provide partial basis for policy makers in planning irrigation programs, and can assist farmers with effective crop production.

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