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Modelling irrigated maize with a combination of coupled-model simulation and ensemble forecasting, in the west of China

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Abstract

The hydrologic model HYDRUS-1D and the crop growth model WOFOST were coupled to efficiently manage water resources in agriculture and improve the prediction of crop production through the accurate estimation of actual transpiration with the root water uptake method and a soil moisture profile computed with the Richards equation during crop growth. The results of the coupled model are validated by experimental studies of irrigated-maize done in the middle reaches of northwest China's Heihe River, a semi-arid to arid region. Good agreement was achieved between the simulated evapotranspiration, soil moisture and crop production and their respective field measurements made under maize crop. However, for regions without detailed observation, the results of the numerical simulation could be unreliable for policy and decision making owing to the uncertainty of model boundary conditions and parameters. So, we developed the method of combining model simulation and ensemble forecasting to analyse and predict the probability of crop production. In our studies, the uncertainty analysis was used to reveal the risk of facing a loss of crop production as irrigation decreases. The global sensitivity analysis was used to test the coupled model and further quantitatively analyse the impact of the uncertainty of coupled model parameters and environmental scenarios on crop production. This method could be used for estimation in regions with no or reduced data availability.

1 Introduction

In semi-arid and arid regions, there is an increasing competition between the limited water resources and the increasing demand for crop irrigation (Molden, 1997; Seckler et al., 1998). The efficient utilization of water in agriculture and tackling the issue of optimal water use are needed to balance water supply and demand (Tuong and Bhuiyan, 1999; Ines et al., 2002). In the last 20 yr, irrigation planning methods have switched from the allocation approach, e.g. based on socio-political considerations, to

HESSD

8, 3841–3881, 2011

technological ones (Paudyal and Das Gupta, 1990; Raman et al., 1992). The development of mathematical models allows fundamental progress to guide irrigation quantitatively. The accurate estimation of soil moisture change, evaporation, and transpiration is important for determining availability of water resources (Scanlon et al., 2002) and the sustainable management of limited water resources, especially in arid and semi-arid regions (e.g., Gartuza-Payán et al., 1998). Variation in available soil moisture is one of the main causes of variation in crop yields (Rodriguez-Iturbe et al., 2001; Shepherd et al., 2002; Anwar et al., 2003; Patil and Sheelavantar, 2004). Meanwhile, actual evapotranspiration is the main variable for water loss in the soil-plant system and determines soil moisture status (Burman and Pochop, 1994; Monteith and Unsworth, 1990). Crops can only absorb the soil moisture that is present within the reach of their roots. Therefore, the root growth algorithm and plant water uptake modules are critical to estimate soil moisture and crop production in crop and ecological models. However, these processes are represented in hydrologic models, the coupling of hydrologic and crop growth models are useful for both hydrology and agronomy.

In the last few years numerous scientists have oriented their research towards enhancing the knowledge of the complex interactions between ecological systems and the hydrological cycle, contributing to the development of eco-hydrologic models and soil-plant-atmosphere models (Smettem, 2008; De Willigen, 1991; Engel and Priesack, 1993; Diekkrüger et al., 1995; Smith et al., 1997; Shaffer et al., 2001; van Ittersum and Donatelli, 2003). Kendy et al. (2003) evaluated recharge specifically for irrigated cropland using a model in which soil water flow was governed by a tipping-bucket-type mechanism, and actual transpiration was computed based on the soil water condition using a method introduced by Campbell and Norman (1998). By coupling of hydrologic and crop growth models, Eitzinger et al. (2004) studied soil water movement during crop growth processes and concluded that the coupled modeling approach is better than a single model method. A few studies have been conducted to investigate the effects of soil moisture distribution along the vertical soil profile on crop transpiration (Varado et al., 2006).

HESSD
8, 3841–3881, 2011

Complex mathematical models could help to understand interactions between water and energy cycle in soil-plant-atmosphere systems. However, models have many degrees of freedom (with many parameters, state- variables and non linear relations) and can be made to produce virtually any desired behavior (Hornberger and Spear, 1981). Debates on the reliability of environmental models have emerged both in the academy and among practitioners (Veld, 2000; Lomborg, 2001; Van der Sluijs, 2002). The United States Environmental Protection Agency (EPA)'s science panel found that quantitative evidence must be characterized as having high uncertainties (David, 2008). The International Food Policy Research Institute (IFPRI) had raised about $460 000 for the modeling, which would have provided insights to help policymakers compare the outcomes of four broad policy scenarios, such as futures with more free trade or green technologies. But Greenpeace's Haerlin and others objected that the models were not "transparent". (Stokstad, 2008). Columbia University published the book titled "Useless Arithmetic: why Environmental Scientists Can't Predict the Future" (Pilkey and Pilkey-Jarvis, 2007) presented "Quantitative mathematical models used by policymakers and government administrators to form environmental policies are seriously flawed". The main problem is that models are often asked to answer specific questions about the present or future behaviour of the system under uncertainty conditions (e.g. is climate change, different environmental scenarios and presumptive boundary conditions of the dynamics). However, the model only can be confirmed or corroborated by demonstrating agreement between observations and predictions. So, we need a combination of model simulation and ensemble forecasting to analyse and predict the scientific problem from a probabilistic viewpoint. In this view, uncertainty and sensitivity analysis (UA/SA) can help investigating the propagation of different sources of uncertainties to the output variables through ensemble sampling. Sensitivity analysis was used to identify the effect of model parameters and structure on the output estimation. Uncertainty analysis quantifies the variability of the output caused by the incomplete knowledge or misspecification of the modeller.

HESSD
8, 3841–3881, 2011

An overview of UA/SA methodologies can be found in Saltelli et al. (2000, 2004, 2005). Some applications of SA techniques relevant to ecological and environmental science include, e.g. atmospheric chemistry (Campolongo et al., 1999a, b), transport emissions (Kioutsioukis et al., 2004), geographic information systems (Crosetto and Tarantola, 2001), environmental management (EPA, 2003) and population dynamics (Zaldìvar and Campolongo, 2000; Fieberg and Jenkins, 2005). Some effort has been put into understanding the correct role of SA from an environmental regulatory point of view. Both the report on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (EPA, 2003) and the Guidance on the Development, Evaluation, and Application of Regulatory Environmental Models (IPCC, 2000) provide the information about application of UA/SA on environmental prediction. EPA (2003) also contains recommendations on good practices for UA/SA methods. In Europe, sensitivity analysis is mentioned in the guidelines for impact assessment (EC, 2005).

This paper aims to efficiently manage water resources in agriculture and improve the prediction of crop production under various environmental and water resources management conditions. For this purpose, an eco-hydrological model is developed by coupling a HYDRUS model with a WOFOST model. Based on the coupled modeling, we used UA/SA methods to evaluate the coupled model, predict the risk of a crop production loss as irrigation decreases and quantitatively study impact of coupled model parameters and environmental factors change on maize production. This method could be used as reference for predicting the crop production in regions with no or reduced data availability.

2 Study region and experimental field description

The Heihe river basin, located in semi-arid and arid region, is the second largest inland river basin in China. The region has a typical temperate continental climate, with the mean annual precipitation and evaporation ranging from 60 to 280 mm and 1000

HESSD
8, 3841–3881, 2011

to 2000 mm, respectively. The main crops of this region are maize and wheat, and water use efficiency is low. The key to solve water scarcity and ecological problems of this region is effective management of agricultural water resource and optimization irrigation. So, an agricultural experimental field (latitude 38°51′ N, longitude 100°25′ E, altitude 1519 m), which is shown in Fig. 1, is operated by CAS (Chinese Academy of Science) to study the impact of quantitative irrigation on maize growth. The station is managed according to agricultural practices in the Heihe river basin region, including crop rotations (maize and spring wheat) and flood irrigation.

2.1 Characterization of the soil properties

The experimental field was established on a clay loam soil (USDA classification system). To characterize the soil physical properties, five root zone soil samples were extracted from the ground to a depth of 85 cm. The samples were analyzed in the laboratory to determine soil bulk density (Grossman and Reinsch, 2002), volumetric water content (Topp and Ferré, 2002), and percentages of sand, silt, and clay (Gee and Or, 2002). The analysis' results are shown in Table 1.

2.2 Field experiment

The field was instrumented to monitor soil water dynamics in the root zone and the groundwater table. The instrumentation consisted of time-domain reflectometers (TDR) (CS616, Cambell Scientific, USA) for soil moisture measurements and groundwater observation wells. The depth of soil moisture measurements was 10 cm, 20 cm, 40 cm, 60 cm, 80 cm, respectively and the data were collected every hour.

The agricultural field was intensively monitored throughout the study period, which lasted from 20 April through 22 September 2009. The field was cultivated with maize and quantitatively irrigated. The field was irrigated 9 times throughout the period of crop growth. The water amount of irrigation is approximately 100 mm each time. The sowing date, emergence date and harvest date were 20 April, 6 May and 22 September respectively. Meanwhile, the data of Leaf area index (LAI) were measured once every 15 days by LAI-2200 instrument. Dry weight of storage organs, dry weight of total above-ground biomass and crop height were measured every 15 days by samples during crop growth.

Half-hourly meteorological data were recorded by the meteorological station (Milos520, Vaisala Co, Finland), located in the experimental field. Available data were net radiation, solar radiation, maximum air temperature, minimum air temperature, precipitation, wind speed, atmospheric pressure, and relative humidity. We measured actual evapotranspiration during crop growth using eddy covariance systems (EC) (Li7500 and CSAT3, Cambell Scientific, USA), which have been widely applied to measure the exchange of water vapor, energy and carbon between the earth's surface and atmosphere (Aubinet et al., 2000; Baldocchi et al., 2003).

3 Materials and methods

3.1 Crop growth model

WOFOST has been used to (Van Keulen and Wolf, 1986) simulate crop growth and production under various environments (soil, climate and fertilization), crop characteristics, and irrigation schemes. In WOFOST, the crop growth simulator (SUCROS) (Van Laar et al., 1997) approach for potential production conditions is used to simulate gross CO_2 assimilation, maintenance growth respiration. The CO_2 assimilation is obtained on a daily basis with Gaussian integration of the instantaneous CO_2 assimilation rates computed at three moments of a day and for three canopy depths. Maintenance respiration is assumed to be proportional to the dry weight of plant organs, considering that different organs have different respiration to weight ratios. Total dry matter production is partitioned among the different plant organs according to development-dependent coefficients. During early growth stages, leaf area is considered growing exponentially as a function of temperature. After canopy closure, leaf area index (LAI) is derived from leaf biomass using a development-dependent specific leaf area (SLA). In the water-limited situation, the soil water balance was calculated using a tipping bucket approach with three compartments, i.e., a root zone, a transmission zone, and a groundwater zone. The potential evapotranspiration was estimated with the Penman-Monteith equation (Monteith, 1965; Monteith and Unsworth, 1990). The actual crop uptake from soil was calculated as the product of the potential evapotranspiration, a crop factor and a water stress factor. A detailed model description can be found in van Ittersum et al. (2003).

The numerical software, WOFOST, is a very useful code for determining the production potential, optimizing crop management and quantifying yield gaps of various crops (e.g., wheat, maize, potatoes) (Van Laar et al., 1997; Bouman et al., 2001; Wolf, 2002). The code can also be used to study the effects of environmental variability and climatic change on crop production (Kropff et al., 1996; Berge et al., 1997; Tsuji et al., 1998; Matthews and Stephens, 2002).

3.2 Hydrologic model

HYDRUS-1D (Šimůnek et al., 2005) has an advantage in simulating water flow and root water uptake. The simulation is based on the following assumptions: (i) The soil is homogeneous and isotropic, (ii) The air phase does not affect liquid flow processes, and (iii) Moisture movement due to thermal gradients is negligible. So, the governing equation for water flow is the 1-D Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x}+1\right)\right] - S \quad (1)$$

where h is soil water pressure head (L); θ represents volumetric water content (L^3 L^{-3}); t is time (T); x is the vertical space coordinate (L); K is the unsaturated hydraulic conductivity ($L\ T^{-1}$); and S represents a sink term ($L^3\ L^{-3}\ T^{-1}$), defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake.

HESSD
8, 3841–3881, 2011

The sink term is specified in terms of a potential water uptake rate and a stress factor (Feddes et al., 1978):

$$S = \frac{\alpha(h)R(z)}{\int_0^{lr} \alpha(h)R(z)dz} T_P \quad (2)$$

where S is the root water uptake rate ($L^3\ L^{-3}\ T^{-1}$); $R(z)$ is the distribution function of the root; lr is the depth of root (L); T_P is potential transpiration (L); the dimensionless water stress response function $\alpha(h)$ ($0 \le \alpha(h) \le 1$) prescribes the reduction in uptake that occurs due to drought stress. For $\alpha(h)$, we used the functional form introduced by Feddes et al. (1978):

$$\alpha(h) = \begin{Bmatrix} (h-h_4)/(h_3-h_4) & h_4 < h \le h_3 \\ 1 & h_3 < h \le h_2 \\ (h-h_1)/(h_2-h_1) & h_2 < h \le h_1 \\ 0 & h \le h_4, h > h_1 \end{Bmatrix} \quad (3)$$

where h_1, h_2, h_3, and h_4 are threshold parameters. The uptake is at the potential rate when the pressure head is between h_2 and h_3. It drops off linearly when $h > h_2$ or $h < h_3$. The uptake rate becomes zero when $h < h_4$ or $h > h_1$. Crop-specific values for these parameters were chosen from the database contained in HYDRUS-1D (Šimůnek et al., 2005).

An atmospheric boundary condition was implemented at the soil surface. The atmospheric boundary condition required specifying daily irrigation and precipitation rates, as well as the potential evaporation and transpiration rates. To determine evaporation and transpiration, we calculated a reference evapotranspiration $ET_0(t)$ using the Penman-Monteith method (e.g., Kashyap and Panda, 2001). The potential evapotranspiration $ET_p(t)$ was then given by (Allen et al., 1998):

$$ET_p(t) = K_c(t) \cdot ET_0(t) \quad (4)$$

where $ET_0(t)$ was estimated in daily time steps and $K_c(t)$ is a crop-specific coefficient that characterizes plant water uptake and evaporation relative to the reference crop.

HESSD
8, 3841–3881, 2011
Modelling irrigated maize with a combination
Y. Li et al.

The potential evaporation $E_p(t)$ can be calculated according to (e.g., Kroes and Van Damm, 2003; Pachepsky et al., 2004):

$$E_p(t) = \mathrm{ET}_p(t) \cdot \exp^{-\beta \cdot \mathrm{LAI}(t)} \tag{5}$$

where β is the radiation extinction coefficient and LAI (t) is the leaf area index.

With ET_p an dE_p given by Eqs. (4) and (5), the potential transpiration $T_p(t)$ was specified by:

$$T_p(t) = \mathrm{ET}_p(t) - E_p(t)$$

The soil hydraulic properties were modeled using the van Genuchten-Mualem constitutive relationships (Mualem, 1976; van Genuchten, 1980):

$$\theta(h) = \begin{Bmatrix} \theta_r + \frac{\theta_S - \theta_r}{[1+|\alpha h|^n]^{1-1/n}} & h < 0 \\ \theta_S & h \geq 0 \end{Bmatrix} \tag{6}$$

$$K(h) = K_s S_e^l \left\{ 1 - \left[1 - S_e^{n/(n-1)} \right]^{1-1/n} \right\}^2 \tag{7}$$

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{8}$$

where S_e is effective saturation and θ_s is saturated water content ($L^3\ L^{-3}$); θ_r is residual water content ($L^3\ L^{-3}$); K_s is saturated hydraulic conductivity ($L\ T^{-1}$); α is the air entry parameter; n is the pore size distribution parameter; and l is the pore connectivity parameter. The parameters $\alpha, n,$ and l are empirical coefficients that determine the shape of the hydraulic functions. To reduce the number of free parameters, we took $l = 1$, a common assumption which is based on Mualem's study result (1976).

Running the model required specifying the hydraulic parameters $\theta_r, \theta_s, \alpha, n, K_s,$ and l. The soil profile is divided into three layers in vertical direction according to the soil

HESSD
8, 3841–3881, 2011

physical properties. The fist layer is from the ground to a depth of 30 cm. The second layer and the third layer are from a depth of 30 cm to a depth of 60 cm and from a depth of 60 cm to a depth of 100 cm, respectively. Meanwhile, a deep drainage condition was used at the bottom. The condition needs given initial reference groundwater depth (Šimůnek et al., 2005). We estimated the parameters of the three layers using SCE-UA algorithm (shuffled complex evolution algorithm) (Duan et al., 1993). The NSE (Nash-Sutcliffe coefficient) is chosen as the objective function,

$$\mathrm{NSE}=1-\left(\sum_{t=1}^{N}(\mathrm{Q}_{\mathrm{sim},t}-Q_{\mathrm{obs},t})^2 \middle/ \sum_{t=1}^{N}(\mathrm{Q}_{\mathrm{obs},t}-\overline{Q})^2\right) \tag{9}$$

3.3 Coupling of the model

The coupling has been performed at a daily scale. Coupling process is shown in the Fig. 2: (1) The irrigation and precipitation, the daily net radiation, the daily maximum and minimum temperatures, the daily wind speed and the daily relative humidity are the input terms in the HYDRUS model. (2) The potential evaporation and transpiration are calculated by the Penman-Monteith combination method in the HYDRUS model. (3) The water uptake is calculated according to Feddes equation in the HYDRUS model. (4) The soil water balance, soil moisture and groundwater depth are calculated using the HYDRUS model. (5) The root water uptake and actual transpiration on a daily basis are assumed the same, because the most root water uptake is consumed by crop transpiration. Therefore, the ratio between calculated actual water uptake based on Feddes equation and potential transpiration based on Penman-Monteith method is regarded as an indicator for the degree of water stress. (6) The potential daily total gross CO_2 assimilation of the crop, which is calculated according to the WOFOST model, is multiplied by the water stress ratio to calculate the actual daily CO_2 assimilation. Then, carbohydrate allocation among different crop parts is calculated according to the WOFOST model. (7) The calculated vegetation parameters from

HESSD
8, 3841–3881, 2011

the WOFOST model, more specifically rooting depth, height of the crop and LAI, are then used as inputs for the HYDRUS model at the next step.

4 Results and discussion

4.1 Model validation

The simulation time is during the cultivation of maize from sowing (20 April 2009) to harvest (22 September 2009), comprising day of year (DOY) 110–265. The computation time step is one day. Running the coupled model required atmospheric (minimum temperature, maximum temperature, irradiation, vapor pressure, wind speed and precipitation) and irrigation conditions at a daily scale, the parameters of crop characteristics (including parameters referring to, among other things, phenology, assimilation and respiration characteristics, and partitioning of assimilates to plant organs) and the soil hydraulic parameters (θ_r, θ_s, α, n, K_s).

The meteorological data were acquired by the meteorological station. The amounts and times of irrigation are recorded. The parameters of crop characteristics choose the maize data set provided by the European Community (Boons-Prins et al., 1993). An atmospheric boundary condition was implemented at the soil surface. The potential evaporation and transpiration rates are calculated by the meteorological data and the parameters of the crop growth (LAI and height of the crop), which are shown in Fig. 3. The optimized soil hydraulic parameters of the different soil layers were estimated using an SCE-UA algorithm. The NSE values of the fit to observed soil moisture for the three soil layers and the final optimized parameters are shown in Tables 2 and 3. The comparison between fitted soil moisture and observed soil moisture is shown in Fig. 4. The observed TAGP (total above-ground dry production), WSO (dry weight of storage organs) and the LAI (Leaf area index) are compared with the simulation results, which are shown in Figs. 5 and 6. The results show the simulated dry matter accumulation and partition between the various crop organs match the observations well. The related

HESSD
8, 3841–3881, 2011

parameter values are reasonable for local maize characteristics and soil properties in the study field. The coupled model can be used to quantitatively predict agricultural production under water-limited conditions. The dry matter accumulation and partition between the various plant organs, the final yield and harvest index are simulated by the coupled model, as shown in Table 4. The simulated evapotranspiration also match as well the evapotranspiration observed by eddy covariance systems (EC), which are shown in Fig. 7. The simulated evapotranspiration is divided into actual transpiration and actual evaporation. The cumulative simulated actual transpiration is 364 mm. The cumulative simulated actual evaporation is 203 mm. The result reveals that the crop‘s effective transpiration is approximately 1.79 times the soil evaporation during maize growth under realistic irrigation conditions.

4.2 Sensitivity analysis

Sensitivity analysis determines the contribution of each input factor to the uncertainty of the outputs. Sensitivity analysis was evaluated using a two-step method: the screening method proposed by Morris (1991) and a variance-based technique proposed by Sobol' (1993). The Morris method provides a qualitative assessment of the importance of each input factor, while the Sobol' method performs a quantitative analysis of sensitivity and uncertainty. This two-step methodology has been used in recent studies of input-output relationship and model evaluation (Fox et al., 2010; Jawitz et al., 2008; Muñoz-Carpena et al., 2010).

The one-factor-at-a-time Morris (Morris, 1991) method is particularly effective to screen a subset of relevant parameters among those contained in models with a large number of parameters or with time consuming simulations. The method calculate a set of incremental ratios (Δoutput/Δparameter) at various points of the parameters space and to obtain means (μ^*; calculated on absolute values) and standard deviations (σ) of these ratios. A large value of μ^* belongs to a parameter with an important overall influence (total effect), whilst a large value of σ indicates nonlinearities in model response or interactions with other parameters.

HESSD
8, 3841–3881, 2011

Modelling irrigated maize with a combination

Y. Li et al.

Sobol's method (Sobol, 1993) is a variance-based method. The method is modified by Saltelli (2002) by decomposing the output variance into terms of increasing dimensions (i.e., partial variances), representing the contribution of single parameters, and of groups of parameters to the overall uncertainty of the model output. This method allows the simultaneous exploration of the parameter space via a Monte Carlo method. Statistical estimators of partial variances are provided by quantifying the relevance of parameters and parameter groups through multi-dimensional integrals. The advantage of Sobol's method is that it allows the simultaneous computation of the first order and total order effect indices for a given parameter. A main sensitivity index (S_x) quantifies the first order effect of a parameter. A total sensitivity index (S_{Tx}) quantifies the overall effect of a parameter (i.e., including all the possible interactions).

Prior to performing sensitivity analysis, the ranges of the 34 input factors were defined (Table 5) based on values from literature review, experience, research objectives and default, minimum and maximum values of WOFOST and HYDRUS databases. Uniform distributions were assigned to input factors when only the base value was known, the range was considered finite, and no explicit knowledge of the distribution was available (McKay, 1995). This conservative assumption allows an equal probability of occurrence of the input factors along the probability range (Muñoz-Carpena et al., 2010). We divided the parameters into 13 groups according to physical properties and functions. The groups of parameters and the value ranges of all parameters are shown in Table 5.

One model output for weight of storage organs at physiological maturity (WSO) was considered in this analysis. WSO was selected as it determines the productity of maize and a synthetic representation of the culmination of numerous physical processes. The variation of WSO in response to variations of the crop and environment parameters were investigated using Morris and Sobol's sensitivity study methods, based on SimLab Dynamic Link Library (http://simlab.jrc.ec.europa.eu/), integrated in the coupled HYDRUS and WOFOST models.

HESSD
8, 3841–3881, 2011

For Morris method, the means and standard deviations of the sensitivity parameters (μ^*, σ) for each factor are obtained from 320 samples using the total range of trajectories (10) and levels (4) (Saltelli et al., 2004). For Sobol' method, Monte Carlo sample size was set to 5000 for each factor.

The guided irrigation scheme (Each time 100 mm of water is applied to maize, in total 9 times) was explored in this study. Figure 8 displays graphically the average strength (μ^*) and spread (σ) of model response (change of yield) to the variation of parameters according to their various functions of crop growth (phenology, assimilation, respiration, conversion, etc.) and environment factors (sowing date, groundwater depth, soil characteristics, etc.). The parameters were ranked in descending order of the μ^* values, which are shown Table 6. The screening carried out with the Morris method allowed identifying 13 out of 33 parameters (40%) as not relevant. Each parameter cause a yield change less than 500 kg ha^{-1}, which approximately accounting for 5% of the total output 10 777 kg ha^{-1}. The 12 out of 33 parameters (36%) are identified with an effect between 500 and 2000 kg ha^{-1}. The 8 out of 33 parameters (24%) have an effect greater than 2000 kg ha^{-1} (including HYDRUS parameters, ZIT, SLATB1, IDSOW, EFFTB, RDMCR, KDIFIB, CFET). Further, σ indicates that interaction, correlation and non-linearity are relevant for coupled model.

We also analyzed the distribution of simulated yields with Monte Carlo methods to gain information about the reaction of maize production to the variations of the parameters under various irrigation schemes. The Monte Carlo sample size was set to 5000. Four scenarios were proposed. In the four scenarios the single application of irrigation-water is respectively assumed to be 40 mm, 60 mm, 80 mm and 100 mm for a total of 9 irrigation times. The uncertainty analysis was performed. The results are shown in Fig. 9, which reveal the risk of crop production loss with decrease of irrigation. The average crop production increases from 4204.2 kg ha^{-1} in the case where each irrigation-water is 40 mm to 7781.2 kg ha^{-1} in the case where each irrigation-water is 100 mm. When each irrigation- water is more than 80 mm, the distribution of simulated yields is mainly between 5500 kg ha^{-1} and 11 000 kg ha^{-1}, which account for

85% realizations. This method can predict probability of crop production in uncertain range of crop parameters and environment parameters.

The Sobol' method is used to improve our understanding of the effect of parameter groups on crop production under various irrigation schemes. The results are shown in Table 7. In the above mentioned irrigation-water scenarios, summations of first-order indices of parameters are always close to 1, which suggests that the coupled model has not over-parameterization. Total-order indices of parameters were not significantly different in the coupled model, which may be attributed to the coupled model as being balance. Summation of total-order indices leads to values between 2.65¬3.8, suggesting that the simulated yield is always affected by more parameters acting in conjunction with each other. Table 7 reveals that the crop outputs were mainly influenced by physiological parameters (including CO_2 assimilation, green area, correction factor transpiration rate, the conversion of assimilates into the various organs compounds) and environment parameters (including sowing date, groundwater depth, soil hydraulic characteristic). Table 7 further shows that the effect of groundwater, soil hydraulic characteristic and correction factor transpiration rate on output increases as irrigation-water decreases. The effect of most physiological parameters on output decreases as irrigation-water decreases, owing to the fact that a shortage of transpiration supplied water uptake from the soil causes stomata closure and reduces assimilation and respiration of crops.

5 Summary and conclusions

The objective of this study was to develop a fully coupled hydrology–crop growth model which can optimize irrigation-water under different climatic and environmental conditions. A crop growth model (WOFOST) has been coupled to a hydrologic model (HYDRUS) for this purpose. The coupled model considers not only the physiological processes of the crop, but also the water balance during the crop growth process. Inverse modeling methods (SCE-UA algorithm) are used to identify the parameters of soil hydraulic properties and improve simulated accuracy of the soil moisture profile.

HESSD
8, 3841–3881, 2011

The coupled model was calibrated using field data collected at an experimental field in the middle reaches of northwest China's Heihe River, located in a semi-arid to arid region. The results show the good agreement was achieved between coupled model simulations and field measurements under water limited-conditions. The results show that the coupled model can have a higher precision than the WOFOST model alone owing to HYDRUS model's advantage in simulating soil moisture and root water uptake as a physical process. These applications illustrate the coupled model can be used for analysis of saving-water approach and also for the study on interaction between crop growth and the hydrological cycle.

The uncertainty analysis and the sensitivity analysis methods were used to improve prediction and evaluation of the coupled model beyond the simple quantification of the agreement between measured and simulated data. In conclusion, the study illustrates that the uncertainty method (Monte Carlo method) not only reveals the risk of facing a loss in crop production as irrigation decreases, but also can estimates the probability of crop production in the uncertainty range of crop parameters and environment parameters. The sensitivity analysis not only can test the coupled model behavior but also quantify the impact of the coupled model parameters and environment scenarios on crop output.

Synthetically, the method of integrating a coupled hydrologic and crop growth model with uncertainty analysis and sensitivity analysis can be used for guiding agricultural irrigation, saving water resources, predicting agricultural production and researching effects of the climatic and environmental change on agricultural production.

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HESSD
8, 3841–3881, 2011

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HESSD
8, 3841–3881, 2011

Modelling irrigated maize with a combination

Y. Li et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Measured soil textural and bulk density data.

Depth(cm)	Textural fractions			Bulk density (g cm^{-3})
	2–0.05 mm	0.05–0.002 mm	<0.002 mm	
5 cm	33.86	45.44	20.70	1.43
15 cm	37.60	42.53	19.87	1.379
30 cm	49.69	33.87	16.44	1.483
55 cm	24.56	48.65	26.79	1.571
85 cm	16.61	53.68	29.71	1.644

HESSD
8, 3841–3881, 2011

Table 2. Nash-Sutcliffe coefficient of the fit to observed data for the three layers.

	NSE (30 cm soil moisture)	NSE (50 cm soil moisture)	NSE (100 cm soil moisture)
After the seventieth steps	0.749775	0.698925	0.842211

HESSD
8, 3841–3881, 2011

Table 3. The estimated parameters of soil hydraulic properties of three layers by SCE-UA algorithm.

	θ_r(cm^3 cm^{-3})	θ_s(cm^3 cm^{-3})	α	n	K_s(cm day^{-1})
The first layer	0.05	0.41	0.08	0.13	569
The second layer	0.05	0.41	0.087	0.115	344.85
The third layer	0.05	0.41	0.11	0.10	91.62

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

8, 3841–3881, 2011

Modelling irrigated maize with a combination

Y. Li et al.

Table 4. The output variables of maize growth obtained by the coupled model.

DOY	TAGP	WLV	WST	WSO	WRT	LAI	HI
Day of year	Total above ground production	Dry weight of the leaves	Dry weight of the stems	Dry weight of storage organs	Dry weight of the roots	Leaf area index	Harvest index
–	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$m^2\,m^{-2}$	–
124	30	19	11	0	20	0.05	0
129	62	39	24	0	48	0.08	0
134	102	63	39	0	69	0.11	0
139	134	83	51	0	88	0.16	0
144	230	142	87	0	155	0.28	0
149	503	312	191	0	310	0.61	0
154	1197	740	456	0	616	0.93	0
159	2165	1285	875	0	1031	1.31	0
164	3587	2010	1570	0	1474	1.78	0
169	4055	2036	1824	0	1535	2.33	0
174	5476	2517	2739	0	1888	2.92	0
179	6759	2831	3651	0	2080	3.67	0
184	8080	3006	4702	0	2183	4.87	0
189	8877	3081	5380	0	2230	5.31	0
194	10081	3153	6256	164	2233	5.29	0.02
199	10218	2856	6325	217	2233	4.81	0.02
204	11385	2835	6457	1219	2233	4.64	0.11
209	12724	2808	6457	2558	2233	4.38	0.20
214	13674	2729	6457	3508	2233	4.27	0.26
219	14852	2678	6457	4686	2233	4.06	0.32
224	15874	2649	6077	5708	2059	4.04	0.36
229	16139	2419	5493	5973	1862	3.74	0.37
234	17169	2377	4965	7003	1683	3.65	0.41
239	18103	2377	4488	7937	1521	3.57	0.44
244	19112	2328	4057	8946	1375	3.43	0.47
249	19612	1693	3667	9446	1243	2.95	0.48
254	20013	1570	3315	9847	1123	2.68	0.49
259	20498	1486	2996	10432	1015	2.1	0.50
261	20743	1478	2878	10777	995	1.89	0.51

HESSD
8, 3841–3881, 2011

Table 5. The groups of parameters and the value ranges of parameters for UA/SA.

group	parameter	meaning	unit	values range
Sowing date	IDSOW	sowing date	(d)	U(103¬117)
Groundwater depth	ZIT	Initial depth of groundwater table	(cm)	U(50–500)
Soil hydraulic parameters (HYDRUS)	Parameters of HYDRUS model	soil hydraulic parameters	(cm cm^{-1}) (cm cm^{-1}) – – (cm day^{-1})	Θr U(0.01–0.1) Θs U(0.25–0.4) a U(0.02–0.14) n U(0.2¬0.6) Ks U(10¬800)
Emergence	TBASEM	Lower threshold temperature for emergence	(°C)	U(2¬5)
	TEFFMX	Maximum effective temperature for emergence	(°C)	U(20¬30)
Phenology	TSUM1	Thermal time from emergence to anthesis	(°C d^{-1})	U(700¬900)
	TSUM2	Thermal time from anthesis to maturity	(°C d^{-1})	U(800¬1200)
Initial	RGRLAI	Maximum relative increase in LAI	(ha ha^{-1} d^{-1})	U(0.01¬0.04)
	LAIEM	Leaf area index at emergence	(ha ha^{-1})	U(0.1¬0.2)
Green area	SPAN	Life span of leaves growing at 35 °C	(d)	U(30¬36)
	SLATB	Specific leaf area as a function of development stage	(ha kg^{-1})	U(0.002¬0.003)
	SLATB1	Specific leaf area as a function of development stage	(ha kg^{-1})	U(0.001¬0.002)

HESSD

8, 3841–3881, 2011

Table 5. Continued.

group	parameter	meaning	unit	values range
Assimilation	AMAXTB	Maximum leaf CO_2 assimilation rate at development stage of the crop growth	(kg ha^{-1} hr^{-1})	U(50¬70)
	AMAXTB1	Maximum leaf CO_2 assimilation rate at the first development stage of the crop maturity	(kg ha^{-1} hr^{-1})	U(50¬70)
	AMAXTB2	Maximum leaf CO_2 assimilation rate at the second development stage of the crop maturity	(kg ha^{-1} hr^{-1})	U(50¬70)
	AMAXTB3	Maximum leaf CO_2 assimilation rate at the third development stage of the crop maturity	(kg ha^{-1} hr^{-1})	U(30¬50)
	AMAXTB4	Maximum leaf CO_2 assimilation rate at the fourth development stage of the crop maturity	(kg ha^{-1} hr^{-1})	U(10¬20)
	EFFTB	Initial light-use efficiency of CO_2 assimilation of single leaves as function of daily temperature	((kg ha^{-1} hr^{-1})/ (Jm-^{2}s^{-1}); °C)	U(0.4¬0.5)
	KDIFTB	Extinction coefficient for diffuse visible light as function of development stage		U(0.5¬0.7)
Conversion of assimilates into biomass	CVO	Conversion efficiency of assimilates into storage organ		U(0.6¬0.8)
	CVS	Conversion efficiency of assimilates into stem	(kg kg^{-1})	U(0.59¬0.76)
	CVL	Conversion efficiency of assimilates into leaf	(kg kg^{-1})	U(0.61¬0.75)
	CVR	Conversion efficiency of assimilates into root	(kg kg^{-1})	U(0.62¬0.76)
Maintenance respiration	RMS	Relative maintenance respiration rate stems	(kg (CH2O) kg-1d^{-1})	U(0.013¬0.02)
	RML	Relative maintenance respiration rate leaves	(kg (CH2O) kg-1d^{-1})	U(0.027¬0.033)
	Q10	Relative change in respiration rate per 10 °C temperature change		U(1.6¬2)
	RMO	Relative maintenance respiration rate storage organs	(kg (CH2O)kg^{-1}d^{-1})	U(0.005¬0.015)
	RMR	Relative maintenance respiration rate roots	(kg (CH2O)kg^{-1}d^{-1})	U(0.01¬0.016)

HESSD
8, 3841–3881, 2011
Modelling irrigated maize with a combination
Y. Li et al.

Table 5. Continued.

group	parameter	meaning	unit	values range
Death rates due to water stress	PERDL	Maximum relative death rate of leaves due to water stress	$(kg\,kg^{-1}d^{-1})$.	U(0.02¬0.06)
Correction factor transpiration rate	CFET	correction factor transpiration rate		U(0.7¬1.2)
Root parameters	RRI	Maximum daily increase in rooting depth	(cmd^{-1})	U(2¬3)
	RDI	Initial rooting depth	(cm)	U(7¬14)
	RDMCR	maximum rooting depth	(cm)	U(90.5¬120)

HESSD
8, 3841–3881, 2011

Table 6. The Morris sensitivity measures μ^* and σ for 13 groups of parameters.

parameter	μ^*	σ	parameter	μ^*	σ
Soil characteristics (parameters of HYDRUS)	10731	6411.7	Q10	639	297.5
ZIT	6053	5172.5	TSUM2	562	359.6
SLATB1	3375	2650.9	CVS	562	598.6
IDSOW	3306	2304.1	PERDL	441	688.8
EFFTB	2970	1723.4	RMO	419	221.1
RDMCR	2775	3062	RMS	410	119.1
KDIFTB	2455	1389.9	RML	394	363.2
CFET	2127	2008.6	AMAXTB	351	326.1
CVL	1464	2801.4	AMAXTB1	343	159.7
SLATB	1458	1498.6	AMAXTB2	338	136.8
CVO	1452	745.1	AMAXTB3	268	212.4
RDI	1427	1505	AMAXTB4	232	82.9
TSUM1	1387	1245	SPAN	180	278.6
TBASEM	1385	1068.1	RMR	162	36.4
RRI	845	683.3	TEFFMX	0	0
CVR	802	815.4	LAIEM	0	0
RGRLAI	667	837.4			

HESSD
8, 3841–3881, 2011
Modelling irrigated maize with a combination
Y. Li et al.

Table 7. First effect and total effect indices of 13 groups of parameters.

	Irrigation 100 mm		Irrigation 80 mm		Irrigation 60 mm		Irrigation 40 mm	
Group of parameters	first	total	first	total	first	total	first	total
sowing date	0.1057	0.2686	0.0982	0.2228	0.1002	0.1887	0.0731	0.1376
groundwater depth	0.0817	0.2601	0.1257	0.3466	0.2588	0.4384	0.3469	0.651
Soil hydraulic parameters (HYDRUS)	0.1355	0.2805	0.1446	0.2997	0.1846	0.3627	0.2561	0.4034
emergence	0.0385	0.1383	0.0345	0.1843	0.0385	0.1956	0.0307	0.1246
phenology	0.0335	0.103	0.0276	0.1171	0.0195	0.1224	0.0056	0.1136
initial	0.0432	0.3609	0.0398	0.3541	0.0273	0.1161	0.027	0.0809
green area	0.0965	0.3596	0.0566	0.263	0.0247	0.1691	0.0054	0.0913
assimilation	0.1474	0.5965	0.1446	0.6634	0.0958	0.3577	0.0416	0.1421
conversion of assimilates into biomass	0.093	0.36	0.1023	0.3113	0.0642	0.2049	0.0144	0.1556
maintenance respiration	0.0441	0.2523	0.0407	0.306	0.0277	0.266	0.0193	0.1618
death rates due to water stress	0.0112	0.1429	0.0042	0.2882	0.0048	0.1632	0.0083	0.0924
correction factor transpiration rate	0.0907	0.2563	0.0764	0.2858	0.088	0.3538	0.096	0.404
root parameters	0.0569	0.2057	0.0382	0.1615	0.0293	0.1885	0.0164	0.0981
Total	0.9779	3.5847	0.9334	3.8038	0.9634	3.1271	0.9408	2.6564

HESSD
8, 3841–3881, 2011

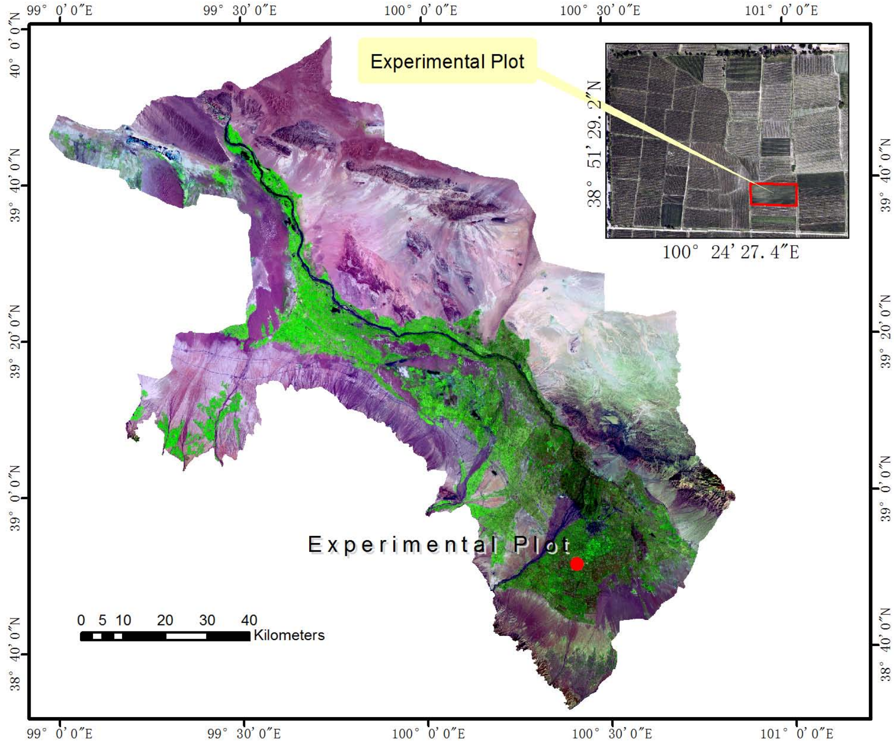

Fig. 1. The location of the experimental plot.

HESSD
8, 3841–3881, 2011

Modelling irrigated maize with a combination

Y. Li et al.

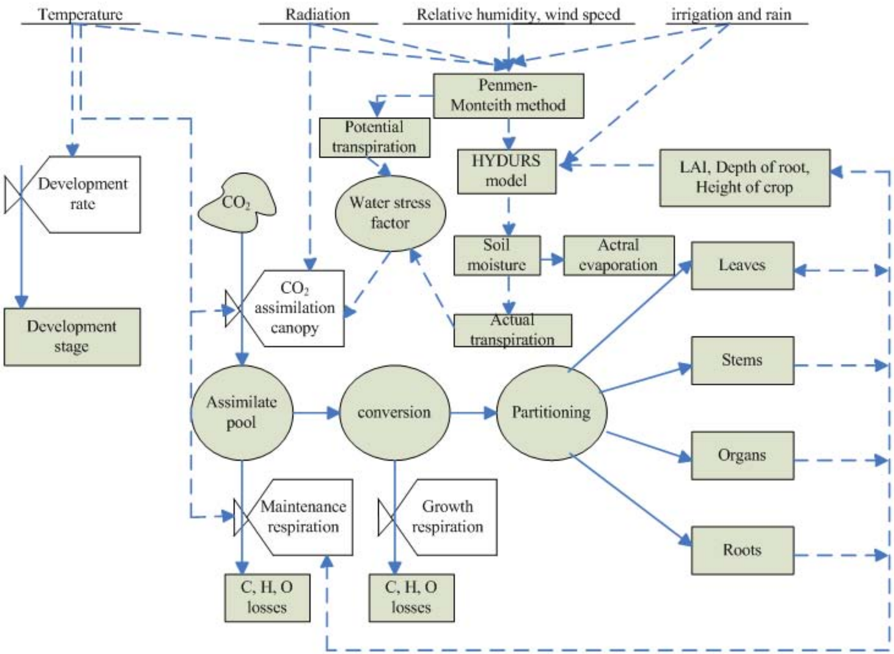

Fig. 2. Flow chart of the coupled HYDRUS and WOFOST models. (Boxes are state variables, valves are rate variables, circles are intermediates. Solid lines are flows of material, dotted lines are flows of information).

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8, 3841–3881, 2011

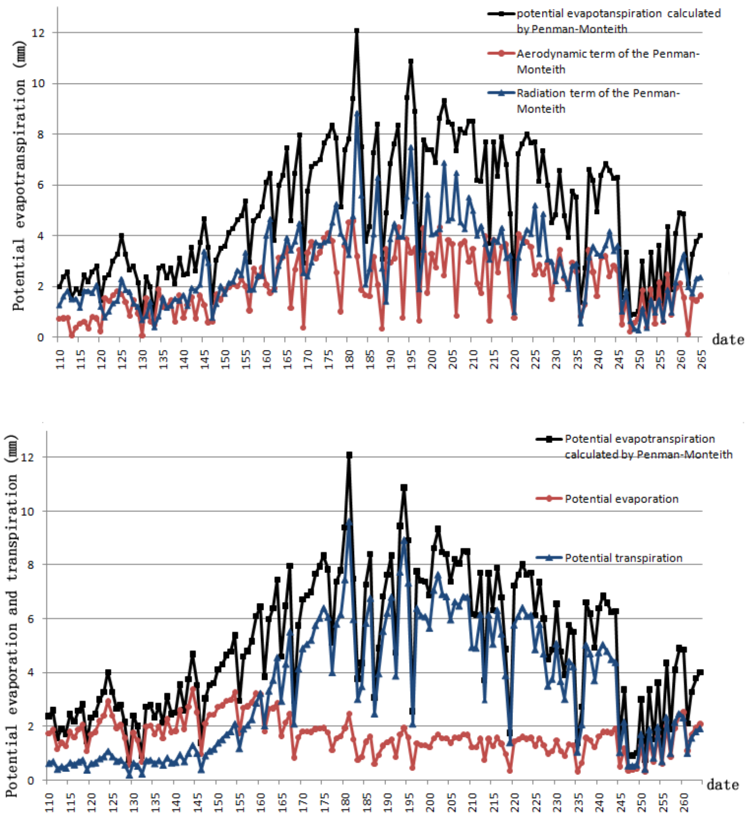

Fig. 3. The estimated potential evapotranspiration, potential evaporation and potential transpiration.

HESSD
8, 3841–3881, 2011

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

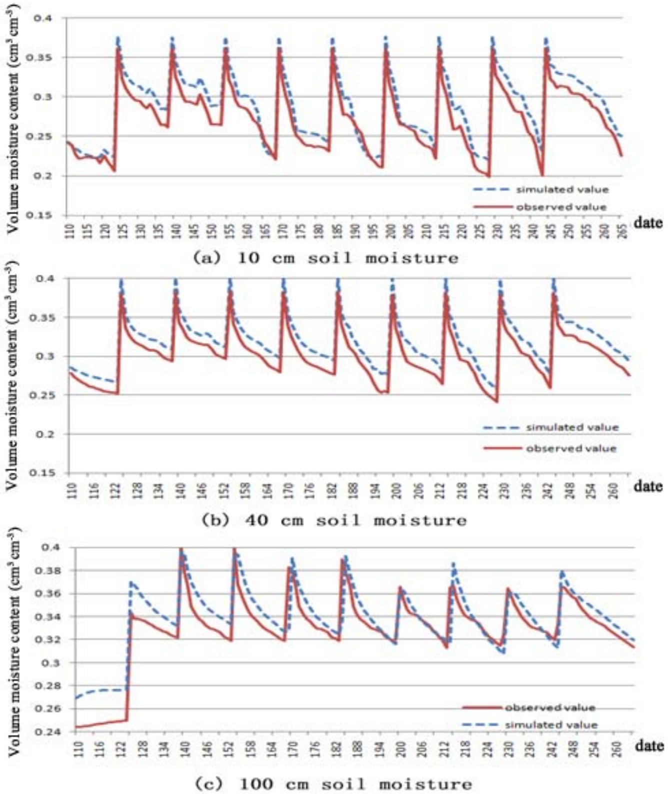

Fig. 4. Comparison between observed soil moisture and fitted soil moisture by SCE-UA algorithm.

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8, 3841–3881, 2011

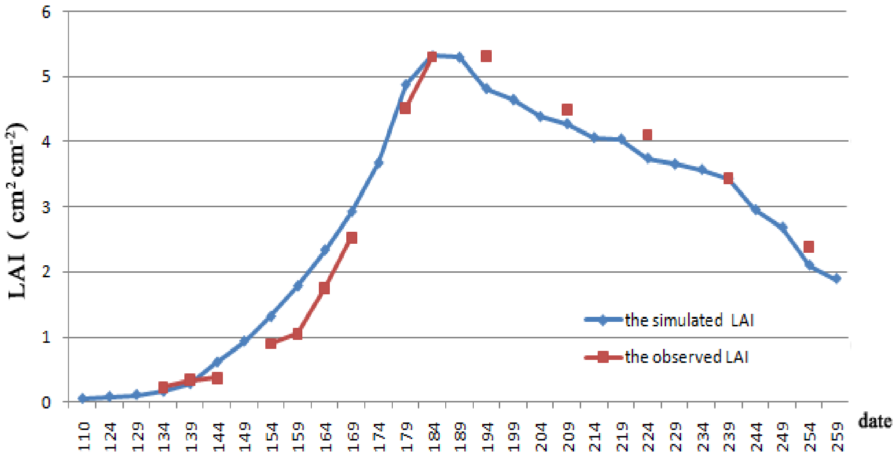

Fig. 5. Comparison between simulated and observed LAI.

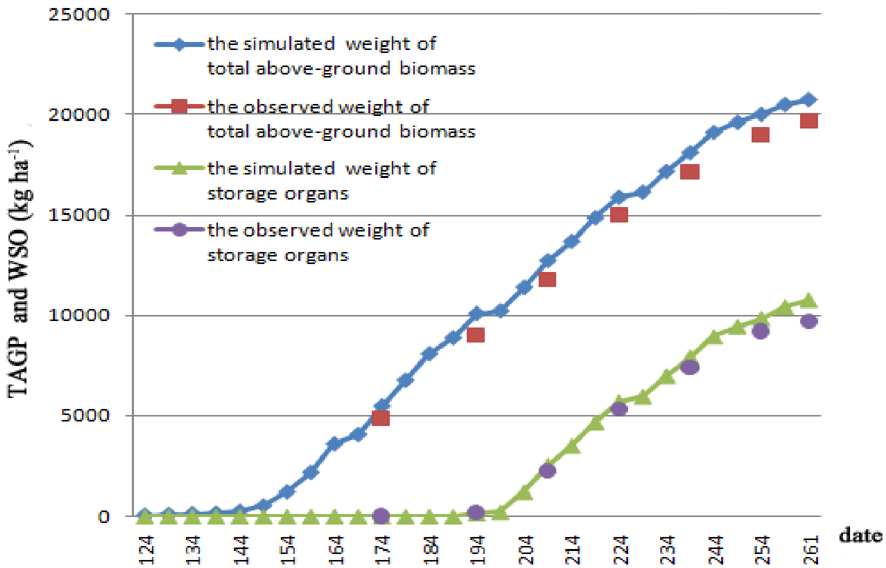

Fig. 6. Comparison between simulated and observed weight of total above-ground biomass and weight of storage organs.

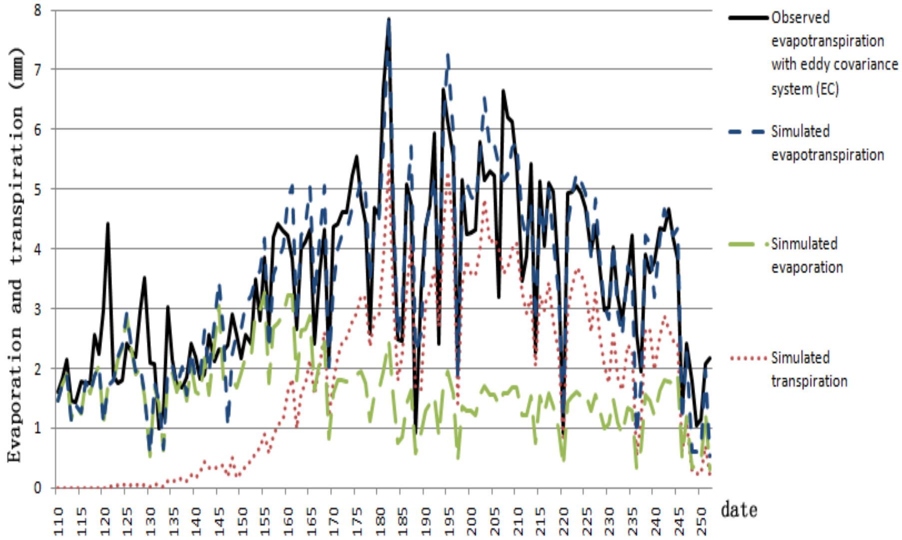

Fig. 7. Comparison between simulated and observed actual evapotranspiration.

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8, 3841–3881, 2011

Modelling irrigated maize with a combination

Y. Li et al.

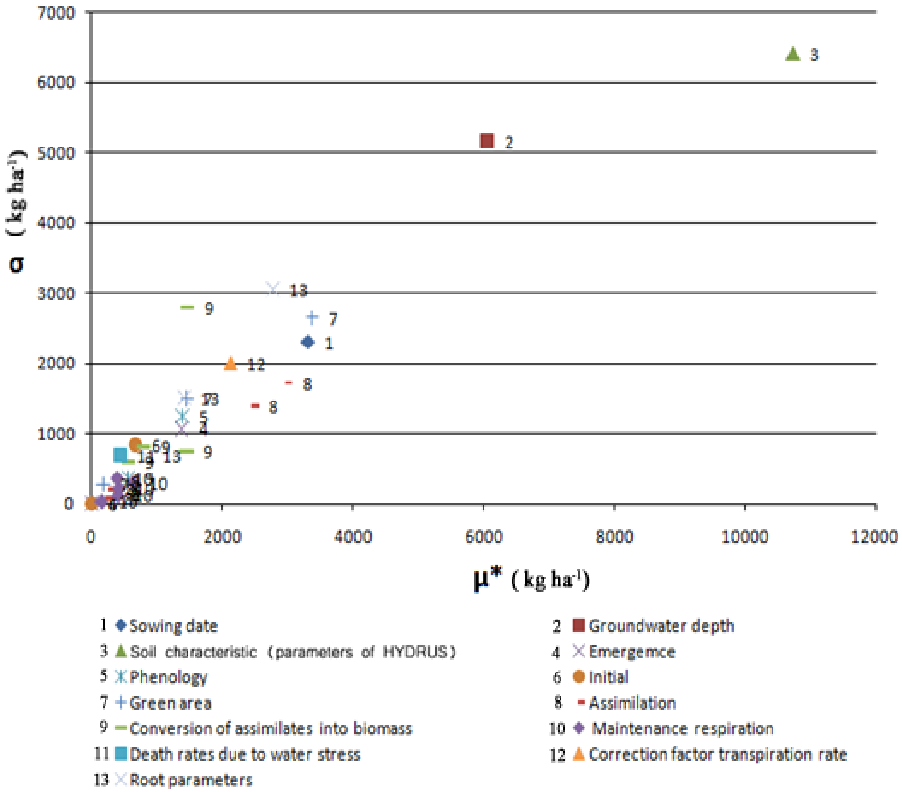

Fig. 8. Graph displaying the Morris sensitivity measures μ^* and σ for 13 groups of parameters.

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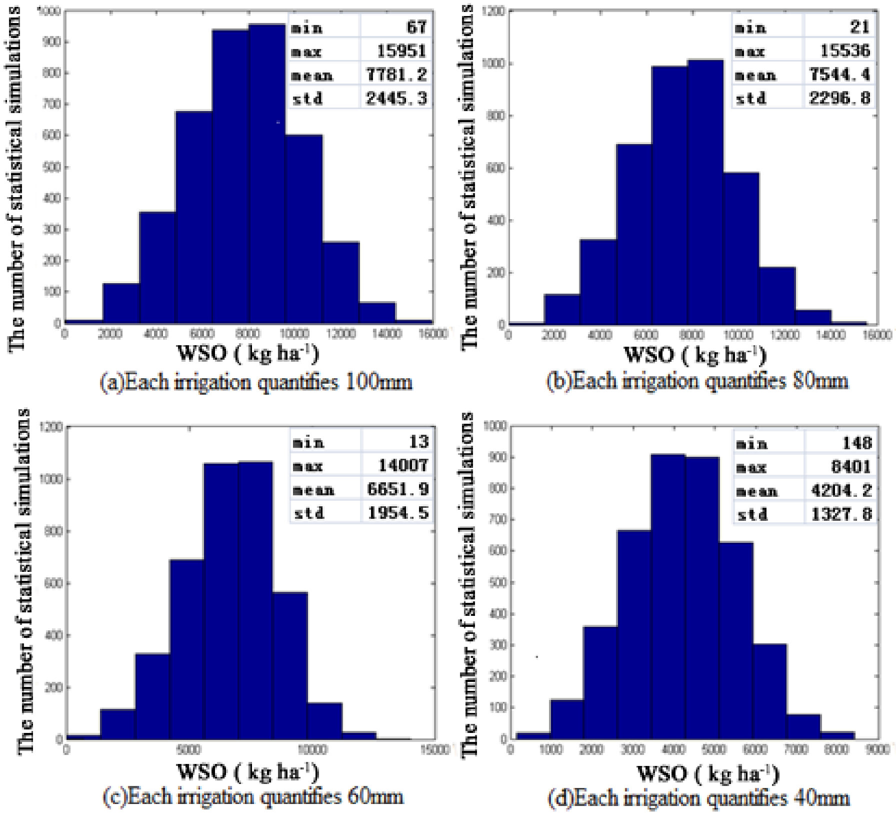

Fig. 9. Histograms of the output distributions in four different irrigation scenarios.

HESSD
8, 3841–3881, 2011

Modelling irrigated maize with a combination

Y. Li et al.