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Abstract. Winter wheat is mainly planted in water shortage area, such as North China and Northwest China. As a key field management measure, irrigation plays an important role in the production of winter wheat. This paper focuses on the improvement of regional winter wheat yield estimation technique in county scale by adjusting the irrigation management measure in crop growth model. The WOFOST (World Food Study) model was used by dividing the whole county into a number of EMUs(elementary mapping units) and then running the model in each unit in sequence. While running, the measured soil moisture and LAI were used to rate the irrigation parameters. Finally, the calibrated irrigation parameters were used to run the model again. The results showed that the simulated winter wheat growth process was normal. During the whole growing period of winter wheat, the change trends of the time series of soil moisture and LAI were basically consistent with that of the measured. The precision of simulated yield was between 87.26% and 98.68% among the 5 units, and the average of the precision was 94.56%. The precision of simulated winter wheat yield was well, and could meet the needs of winter wheat yield estimation in county-wide. This study may provide basis for estimating crop yield in regional area by using the crop growth model.

Keywords: WOFOST, Irrigation Parameter, Winter Wheat Yield

1 Introduction

Winter wheat, one of the main crops in northern China, is mainly planted in water shortage area, such as North China and Northwest China. As a key management measure, irrigation plays an important role in the production of winter wheat. Driving by the light, temperature, water, soil and other environmental variables, the crop growth dynamic model can daily simulate the photosynthesis, respiration, transpiration and evaporation process in crop growth period, and their relationship with meteorological, soil, and other environmental conditions, and can quantitatively describe the dynamic process of crop growth, development, and yield information. WOFOST model originated in the framework of interdisciplinary studies on world food security and on the potential world food production by the Center for World Food Studies in cooperation with the Wageningen Agricultural University[1]. WOFOST is a mechanism model, and had been successfully used in daily business of agro meteorological monitoring and yield forecasting in European Union[2].

Meanwhile, WOFOST was also widely used in board as follows. Wu Dingrong[3] evaluated the applicability of WOFOST in the North China Plain. Xie Wenxia[4] simulated and validated the rice potential growth process in Zhejiang Province by utilizing WOFOST. According to climate characteristic and ecologic type of winter wheat variety in North China, Ma Yuping[1] adjusted the parameters of WOFOST, and simulated phenological phase of overwinter in the region. Chen Zhenlin[5] simulated the integrated impacts of low temperature and drought on maize yield. The abovementioned applications were in field scale. Combining the GIS technology, the application of WOFOST can be extended to regional scale. Ma Yuping[6] simulated the winter wheat growth in regional scale in North China Plain by scaling-up WOFOST model. Li Xiufen[7] evaluated the suitability of meteorological conditions during growing period of Maize in northeast of China. Li Xiufen[8], Gao Yonggang[9-10], Du Chunying[11] respectively simulated the growth process of rice, wheat, maize, soybean, beet, potato and so on using WOFOST in Heilongjiang Province. Huang Jianxi[12] estimated the winter wheat yield in region by the method of optimizing the parameters of WOFOST based on assimilating simulated LAI and MODIS LAI at the re-greening stage of winter wheat. However, there were few reports about the method of simultaneously using the measured LAI and soil moisture to rate the irrigation parameters of model, and to simulate crop growth processing in regional scale.

In this paper, Yutian County, a water shortage region in Hebei Province, was selected as the research area. Both the measured LAI and soil moisture were used to rate the irrigation parameters. The adjusted irrigation parameters were used to run the model to simulate the winter wheat growth processing and to estimate the yield of winter wheat in county scale. All these would provide the basis for regional crop yield estimation by using crop growth model.

2 MATERIALS AND METHODS

2.1 STUDY AREA

Yutian county locates between 117° 31′ E～117° 56′ E and 39° 30′ N～39° 58′ N, at the south of Yan Mountains, the center of Eastern Hebei Plain. The terrain of the county slopes gently from northeast to southwest, the altitude in north is about 50~400 meters, in center and south under 25 meters, forming the views of the northern hills, central plains, the southern low-lying land pattern. According to the second national soil survey, there are 4 soil types, 9 subtypes in the county. The total area of the main 5 subtypes, leached cinnamon soil, meadow cinnamon soil, swamp alluvial soil, alluvial soil, salted alluvial soil, accounts for nearly 95%. The county belongs to warm temperate semi humid region in the eastern monsoon region, with the average annual rainfall 655.4 mm, the average temperature 11.6 degrees, and the annual frost free period 196 days. The main crops include winter wheat, spring maize, summer maize. The main varieties of winter wheat are Jingdong NO.8 and Lunxuan NO. 987, with average yield level 3750～6000 kg/hm^2.

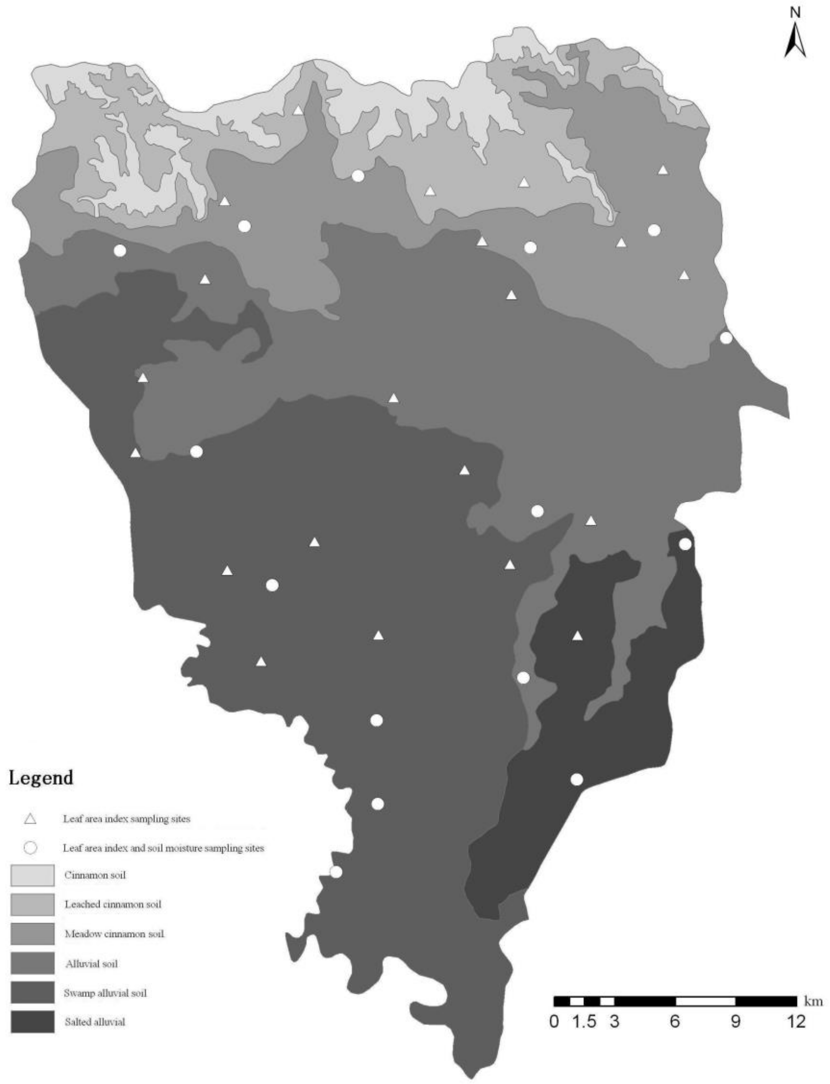

Fig. 1. Spatial distribution of experiment sites and soil types in study area

2.2 MEASURED DATA

According to the environmental condition and the spatial distribution of winter wheat, 36 sites were chosen to measure ground parameters in 2012. In order to ensure the purity of the remote sensing image pixels, the area of winter wheat must be not less than 200 m×200 m in each site. The distribution of the sites, shown in Fig.1, should be representative and homogeneous. Based on the phenological phase of winter wheat, some key stages from re-greening to mature were selected to measure soil moisture, LAI and other crop parameters. The three elements of yield, including the number of heads per hectare, grain number per head, and 1000 grain weight, were collected to estimate the yield from heading stage to mature stage. Dates were respectively April 9-12 re-greening stage, May 2-6 jointing stage, May 16-19 heading stage, June 4-6 grain filling stage, and June 13-17 mature stage. Only soil moisture was measured in grain filling stage, and only crop parameters were measured mature stage.

Method of measuring LAI is as follows. Three subareas about 20 m^2 for each one were homogeneously chosen in each site. Five values of LAI from different locations in each subarea were measured by LAI2000 which was produced by U.S. LI-COR Company. The average of the five values is read as the LAI value of the subarea, and the average of three subareas is written as that of the site. The measurement is done between 09:00 am and 17:00 pm.

Method of measuring soil moisture is as follows. Fifteen representative sites whose area of winter wheat beyond 500m×500m were selected as soil moisture measuring sites from the LAI measuring sites. The soil volume moisture of winter wheat field in the four angles of the site was measured respectively at the depth of 0～10、10～20、20～40、40～60cm by the TSC-Ⅰsoil moisture measuring instrument which was produced by Chinese Agricultural University.

The winter wheat yield is calculated by the method called three agricultural elements estimating yield algorithm, which is gained from the number of heads per hectare, grain number per head, and 1000 grain weight multiplication[13-14]. The detailed steps are as follows. In each site, three 1m^2 rectangular areas were selected randomly. The number of heads in the three rectangular areas during heading stage and grain filling stage are counted respectively. The average of heads in the three rectangles at the same stage is used to calculate the number of heads per hectare at that stage. The average of the number of heads per hectare of the two stages is the number of heads per hectare of the site. At mature stage, total 50～80 heads wheat were randomly selected as the sample from the above three rectangular areas in each site. After drying, threshing, counting, weighing, grain number per head, and 1000 grain weight were calculated.

2.3 STUDY IDEAS

Based on the spatial discretization and irrigation parameters rating, the purpose of estimating winter wheat yield in county scale by using the WOFOST model was implemented. The steps were shown as Fig. 2 in follows. First, overlaying the county boundary and the map of soil type spatial distribution, dividing the whole county into several EMUs in which the combination of meteorology and soil type was homogeneous. Then, the parameters of weather, soil, crop, field management measures including initial irrigation management measures extracted from local management habits were prepared in each unit. After that, the model was run. The ground sites in each unit were selected, and the measured LAI and soil moisture in these sites were averaged as that of the unit. With the help of measured LAI and soil moisture, the initial irrigation operations were calibrated. Finally, the calibrated irrigation parameters were used to run the model again.

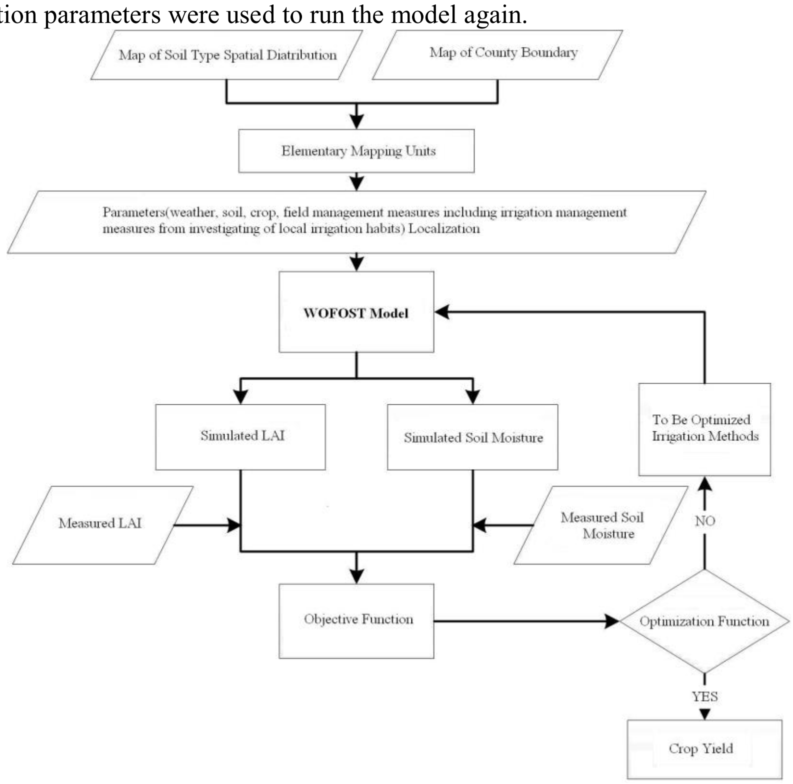

Fig. 2. Flow chart of study

2.4 WOFOST

MODEL LOCALIZATION WOFOST needs parameters of meteorology, soil, crop, management and so on. Both the daily and monthly meteorology parameters can be accepted by the model[15]. The format of daily meteorological parameter is CABO, which contains the maximum and minimum temperature(℃), precipitation(mm), average wind speed(m/s), water vapor pressure at 08:00 am(kPa), solar radiation (MJ/m2• d). The daily measured meteorological data from January 1st, 2010 to June 30th, 2012, including the maximum and minimum temperature, precipitation and sunshine duration, was got from Yutian Meteorology Office(117° 44′ E、39° 53′ N，Altitude 14.4 m). The period covered two whole growth stages of winter wheat, 2010/2011, and 2011/2012. The measured data from neighboring Tangshan Meteorology Observation Station（118° 9′ E、39° 40′ N）from January 1st, 1957 to June 30th, 2012, including daily average atmosphere pressure, maximum atmosphere pressure, minimum atmosphere pressure, average temperature, maximum temperature, minimum temperature, average relative humidity, minimum relative humidity, precipitation, average wind speed, sunshine duration and so on, was also downloaded on the internet as additional information[16]. The wind speed parameter needed by the model could be replaced by the observed data from Tangshan. The other needed parameters, water vapor pressure and solar radiation, which had no observed data, could be calculated. The water vapor was calculated by relative humidity multiplying the saturation vapor pressure. The saturation vapor pressure was calculated by the formula recommended by China Meteorological Administration[17]. The solar radiation was calculated by sunshine duration, the maximum and minimum temperature[18-19]. Harmonized World Soil Database from Food and Agricultural Organization of the United Nations[20] and the data from the Second National Soil Survey were also collected. The map of soil spatial distribution was extracted from the soil database of FAO. The cinnamon soil distributed in non cultivated land area, the northern mountainous area, was eliminated firstly. The smaller proportion soil types in cultivated land area were combined to the adjacent bigger types. The main five types, leached cinnamon soil, meadow cinnamon soil, swamp alluvial soil, alluvial soil, salted alluvial soil, were finally extracted. The most physical and chemical properties referred to that in model, and the important parameters, such as field capacity, saturated water content, wilting coefficient, were calculated by SPAM（soil-plant-atmosphere-water）using the texture, organic matter content from the soil database of FAO[21]. Some crop parameters such as the temperature sum from sowing to emergence(TSUMEM), the temperature sum from emergence to anthesis(TSUM1), and the temperature sum from anthesis to maturity(TSUM2), was calculated by the long time-series observed temperature data in Tangshan and the surveyed long-time phenology of winter wheat in local. The other parameters for crop were confirmed by looking up papers and documents[1,3,15,22-23] or debugging the model. The detailed crop parameters were listed in table1 as bellow. The needed filed management parameters were gained by surveying the planting and managing habit of winter wheat in local. In general, the winter wheat is sowing in early October, harvesting in the second or third ten-days in June. So, when running, the variable sowing date was selected, with the earliest Oct 1st and the latest Oct 10th, the harvesting date was calculated automatically by the model and the longest duration was less than 300 days.

Table 1. Crop parameters settings for WOFOST model

Parameters	Description	Value
TBASEM	lower threshold temperature for emergence	0
TEFFMX	maximum effective temperature for emergence	30.0
TSUMEM	temperature sum from sowing to emergence	113.0
TSUM1	temperature sum from emergence to anthesis	1150.4

TSUM2	temperature sum from anthesis to maturity	900.4
LAIEM	leaf area at emergence	0.1365
RGRLAI	maximum relative increase in LAI	0.00917
SPAN	life span of leaves growing at 35℃	31.3
TBASE	lower threshold temperature for aging of leaves	0
EFFTB	light-use efficiency of single leaf	0.45
CVL	efficiency of conversion into leaves	0.685
CVO	efficiency of conversion into storage organs	0.709
CVR	efficiency of conversion into roots	0.694
CVS	efficiency of conversion into stems	0.662
Q10	relative increase in respiration rate per 10℃ temperature increase	2
RML	relative maintenance respiration rate of leaves	0.03
RMO	relative maintenance respiration rate of storage organs	0.01
RMR	relative maintenance respiration rate of roots	0.015
RMS	relative maintenance respiration rate of stems	0.015
TBASEM	maximum relative death rate of leaves due to water stress	0.03

RATING IRRIGATION PARAMETERS The irrigation parameters, including irrigation date and irrigation volume, were initially set on the base of surveying local irrigation condition. In general, there is 4 times irrigation during the winter wheat growth period. The volume of irrigation for each time is about 50～100 mm. The first time of irrigation often occurs before overwintering period in early December. The second time of irrigation will be implemented after re-greening period in middle ten-days in March next year. The third irrigation may occur before jointing stage, in middle or late April. The fourth time irrigation will be done in heading-anthesis stage in middle May. The times of irrigation may be reduced to three according to the actual weather condition. In the paper, the irrigation parameters were initiated four times, 70mm for each time, and the dates of which were respectively in November 30th, March 14th the next year, April 14th, and May 14th.

The assumed irrigation parameters were used to run the model firstly. While running, the parameters were rated with the measured LAI and soil moisture by using the trial-and-error method. The initial irrigation volume as the center, 10mm as the step size, irrigation volume was adjusted between 50～100 mm. The initial irrigation date was determined as the center, and 1 day as the step size. The irrigation date was changed from -5 to 5 days, and avoided the rainy day. The parameters which make the error of simulated and measured LAI and soil moisture minimum and the irrigation amount lowest were chosen as the best value. Overlaying the map of soil type distribution and boundary, the whole county was divided into 5 EMUs, which were respectively leached cinnamon soil unit, meadow cinnamon soil unit, swamp alluvial soil unit, alluvial soil unit, and salted alluvial soil unit. The irrigation parameters for each unit were shown as table2.

Table 2. Calibrated irrigation parameters

Soil Type	First Irrigation	Second Irrigation	Third Irrigation	The 4th Irrigation

	Date	Volume（mm）	Date	Volume（mm）	Date	Volume（mm）	Date	Volume（mm）
Leached Cinnamon Soil	11-11-30	70	12-3-19	80	12-4-18	80	12-5-17	70
Meadow Cinnamon Soil	11-11-30	70	12-3-19	70	12-4-18	80	12-5-17	60
Swamp Alluvial Soil	11-11-30	70	12-3-14	70	12-4-10	70	12-5-13	70
Alluvial Soil	11-11-30	70	12-3-14	70	12-4-9	70	12-5-13	70
Salted Alluvial Soil	11-11-30	70	12-3-19	70	12-4-18	50		

3 RESULTS AND ANALYSIS

The WOFOST model was run in each unit in sequence. Both the no irrigation and rated irrigation were run respectively to simulate soil moisture, LAI, and winter wheat yield.

3.1 SOIL MOISTURE SIMULATION

The simulation results shown as in Fig 3 showed that the precipitation cannot meet the needs of winter wheat. The soil moisture kept at low level during the whole growth stage. After irrigation, the simulated soil moisture was similar with that of measured. The peak of time-series curve could reflect the irrigation. In general, the average percentage error of the simulated and measured among twenty values, which were measured during the four field experiments for all five soil types, was -17.56%. For some values, the error of absolute value between the simulated and measured was large. But during the whole growth stage, the trends of simulated and measured soil moisture were basically similar.

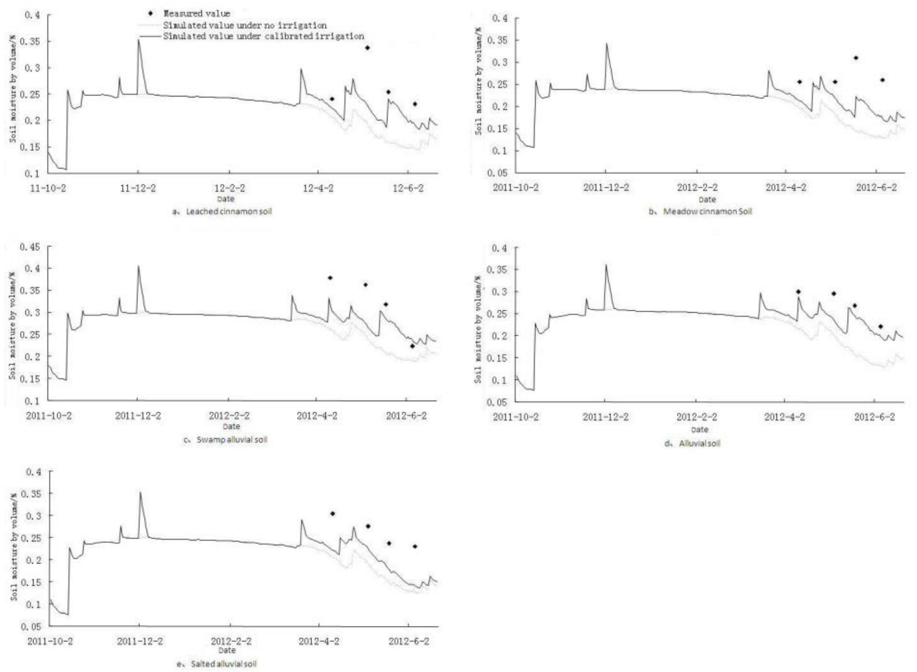

Fig. 3. Comparison of simulated and measured soil moisture under different irrigation methods

3.2 LAI SIMULATION

Under no irrigation, the results of the LAI simulation(shown as Fig4) showed that it is basically normal for the simulated LAI before heading stage of winter wheat. But, after heading stage, the LAI decreased quickly, leading the winter wheat died too early. After irrigation, the change trends of simulated and measured LAI were same. But in the early re-greening stage and lately maturity stage, there were relatively larger deviations between them. In the re-greening stage, the value of simulated was higher than that of measured, which might be caused by ignoring the influence of ‘winter loss’, a phenomenon that some leaves of winter wheat may be died in overwintering period. The simulated leaf might grow more quickly than the actual leaf in re-greening stage which affected by ‘winter loss’. In the lately maturity stage, the simulated LAI was lower than that of measured. The measured LAI might be wrongly added by the dead leaves whose influence were difficulty to be eliminated while measuring. The maximum LAI values in the five units were respectively 4.64，4.64，4.46，4.81，3.69，and the corresponding simulated value were respectively 4.57，4.57，4.59，4.57，4.57. The RMSE(root-mean-square error) of the simulated and measured maximum LAI was 0.41, occurring 1.86% of the average maximum LAI. The date of the simulated maximum LAI was earlier about 10 days than that of the measured. This difference between them might be influenced by the different time step size of them. LAI would be measured only during the key stage, and the average time interval is about 20 days. But the model was simulated day by day. The different temporal resolution between the simulated and measured LAI might lead the difference of date.

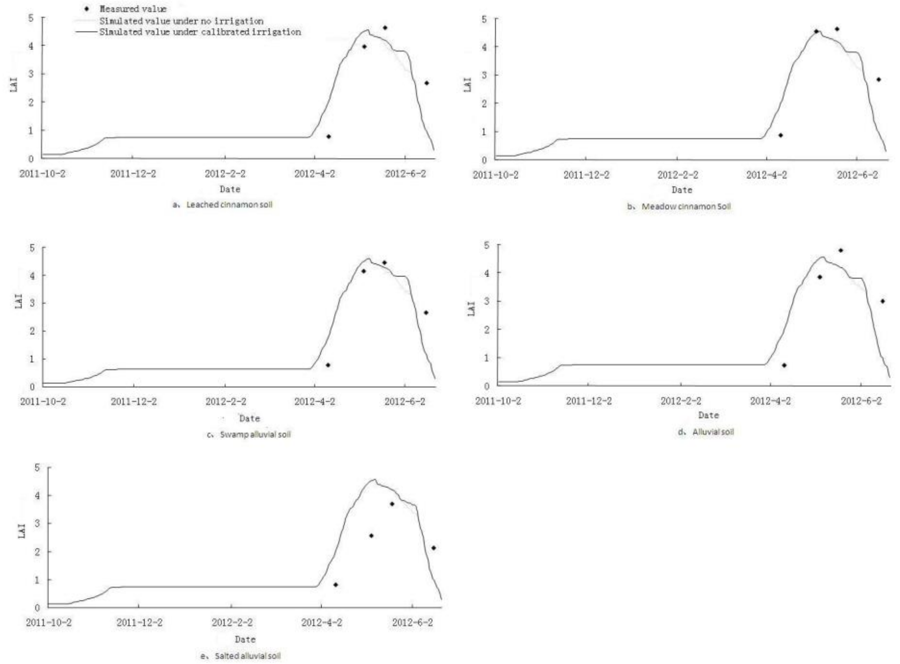

Fig. 4. Comparison of simulated and measured winter wheat LAI under different irrigation methods

3.3 YIELD SIMULATION

While no irrigation, the winter wheat died too early, and the yield was too little. Added irrigation in the model, the simulated growth process was normal, and the yield was also reasonable. The precision equals 1- abs(percentage error), which was used to express the effect of simulation. The measured yields were respectively 4614.29, 4852.65, 5537.62, 5170.72, 4302.24 kg/hm^2 in the five EMUs, and that of simulated were respectively 4943, 4857, 4832, 4970, 4359 kg/hm^2. The precisions for the five EMUs were respectively 92.88%, 97.85%, 87.26%, 96.12%, 98.68%. Averaging all the units, the measured yield was 4895.5 kg/hm^2, the simulated yield was 4812.20 kg/hm^2, and the precision was 94.56%. The difference of simulated yields among the EMUs was obviously lower than that of observed. For example, the minimum measured yield was 4302.24 kg/hm^2, the maximum measured yield was 5537.62 kg/hm^2, the difference between them was 1235.38 kg/hm^2. Simultaneously, the simulated value were respectively 4359 kg/hm^2, 4970 kg/hm^2, 611 kg/hm^2. It had a lot to do with the considered parameters in model and the method of model localization. The considered parameters in model included meteorology parameters, soil parameters, crop parameters and irrigation parameters. But in the farm, the factors that influencing yield were more complex, not only containing the above mentioned factors, but also soil fertility condition, local climate, field terrain, plant diseases and insect pests and so on. During the localization process, being limited by the data acquisition conditions, only soil and irrigation parameters were considerd in different EMUs. But the crop and meteorology parameters were same in the whole county. It was not consistent with the actual situation. For example, the precipitation may be different in the whole county, in the region of 55km from north to south, 36km from east to west. But there is only one weather observing station in the whole county. Using the same meteorology parameters in all EMUs reduce the difference of simulated yield among the EMUs. But totally, the precision of simulation can meet the estimating yield in county scale.

Table 3. Comparison of simulated and measured winter wheat yield

Soil Type	Measured Yield （kg/ha）	Simulated Yield No Irrigation （kg/ha）	Precision	Simulated Yield Calibrated Irrigation （kg/ha）	Precision
Leached Cinnamon Soil	4614.29	1954	42.35%	4943	92.88%
Meadow Cinnamon Soil	4852.65	2352	48.47%	4957	97.85%
Swamp Alluvial Soil	5537.62	2390	43.16%	4832	87.26%
Alluvial Soil	5170.72	3413	66.01%	4970	96.12%
Salted Alluvial Soil	4302.24	1954	45.42%	4359	98.68%
Average	4895.5	2412.60	49.08%	4812.20	94.56%

4 CONCLUSION

As an example, Yutian County in Hebei Province was selected to divide into five EMUs, in which the combination of soil type and meteorology was same. The assumed irrigation parameters from surveying local irrigation condition were used to run the model firstly. Then, run the model, rated the irrigation parameters with the help of measured LAI and soil moisture by using the trial-and-error method. Finally, the rated irrigation parameters were used to run the model again, and completing the estimating yield in county scale. The conclusions were as follows.

1) The simulated growth process of winter wheat was basically normal. The change trends of the time-series of simulated soil moisture and LAI were basically consistent with the measured in the whole growth period of winter wheat. In the numerical, the difference between the simulated LAI and the measured LAI in the early re-greening stage and lately maturity stage was greater than that of in jointing stage and heading-

anthesis stage. The simulated maximum LAI values in the whole stage in all EMUs were close to that of measured. But the date had an error about 10 days which might be affected by the different time scale between simulation and measure.

2) The simulated results could meet the needs of winter wheat yield estimation in county-wide. The precision of simulated yield was between 87.26% and 98.68% among the 5 units, and the average of the precision is 94.56%.

Because being limited by the difficulty in obtaining parameters in large range, and ignoring some affected factors such as soil fertility condition, local climate, field terrain, plant diseases and insect pests and so on, the simulated difference among the EMUs was obviously lower than that of observed. In the more fine application, in order to improve the precision, the more parameters should be considered in the model and the more detailed input parameters should be used in the simulation.

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