SIMULATION OF SALINITY STRESS ON GROWTH OF WINTER WHEAT BY SOIL WATER ATMOSPHERE PLANT MODEL IN LOESS PLATEAU
/
用 SWAP 模拟盐分胁迫对黄土高原冬小麦生长的影响

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Abstract: *The sustainable development of efficient water-saving agricultural irrigation in Loess Plateau requires reasonable and quantitative planning, design, management, and strategies based on crop-water-salt response relationship. In the present paper, data were measured by using the soil-water-salt sensor CS655 to modify the simulation of root uptake in the original Soil Water Atmosphere Plant (SWAP) model. Spring wheat field experiment data in the salinized irrigation district of Fuping County, Shaanxi Province, China were used to test the feasibility of using the SWAP model in irrigation districts of Loess Plateau. The comparison of soil moisture and salt concentration in the root system, along with simulated and measured values of partial above-ground biomass showed the following results: the average relative error and root-square error of soil moisture in the root layer were close to 0; model R^2 tended to be 1; simulation accuracy of water module was high; salt concentration in the simulation varied, but the overall simulation consistency was good; crop growth parameters matched well; and simulated yield was close to the actual value with a relative error of 3.6%. The SWAP model can be well applied to simulate soil, water and salt transfer at field scale in salinized districts of Loess Plateau.*

Keywords: *SWAP; soil moisture; soil salt; agricultural crops*

摘要: *黄土高原农业可持续发展的高效节水灌溉需要依据作物-水-盐响应关系来合理定量规划设计和管理决策。本文以 SWAP（soil water atmosphere plant）模型为工具，通过土壤水盐传感器 CS655 实测数据以修正原 SWAP 模型对根系吸水的模拟。采用陕西省富平县盐渍化灌区春小麦田间试验数据，对 SWAP 模型在黄土高原灌区适用性进行了检验。对比分析植物根系层土壤水分与盐分浓度、作物地上部分生物量的模拟值与实测值，结果表明，根系层土壤水分的平均相对误差 MRE 和均方根误差 RMSE 均接近于 0 且模型 R^2 值趋于 1，水分模块模拟精度较高，盐分浓度模拟存在差异但总体模拟一致性较好，且作物生长指标匹配良好，模拟产量较接近实际值相对误差为 3.6%。综上所述，该模型可良好地应用于黄土高原盐渍化区田间尺度土壤水盐运移的模拟。*

关键词: *SWAP; 土壤含水量; 土壤含盐量;农作物*

INTRODUCTION

Because of poor soil, sparse vegetation, great surface evaporation, severe water and soil loss, and frequent drought, the Fuping district of Loess Plateau in Shaanxi Province is under severe soil salinization. This district is known for agriculture; hence, the salinity stress on crop growth has attracted the attention of local and foreign researchers [10]. Salinity stress is a growth adversity for crops and most commonly exists under field conditions. The reasonable adjustment of crops and agricultural management initially requires an understanding of crops' responses to such adversity [12]. Salinity stress affects crops' internal and external responses physiologically, biochemically, and morphologically. Many studies have investigated salinity stress, and Hsiao described salinity stress in detail [7]. Famous agro-ecological models around the world that could simulate crop growth include Dutch World Food Study (WOFOST), Crop and Environmental Research Synthesis (CERES) series developed by United States Department of Agriculture, Root Zone Water Quality, Daisy developed by Denmark and other countries, and Semiarid Prairie Agricultural Research Center (SPARC)-Wheat and PARC-Barley developed by SPARC, which localized CERES [3].

Dutch Soil Water Atmosphere Plant (SWAP) model simulates water amount and provides many options

引言

陕西富平黄土高原区由于土壤贫瘠、植被稀疏、地表蒸发量大、水土流失严重，加之气候特征十年九旱，从而导致土壤盐渍化严重，而作为以农业生产为主要产业的地区，盐分胁迫对作物生长的影响已经成为目前国内外同行研究的热点[10]。盐渍化胁迫是田间条件下存在最广泛的一种作物生长逆境，了解作物对该逆境的响应，是对作物进行合理调控、实现农业管理的前提[12]。盐渍化胁迫使作物从内到外发生一系列生理、生化及形态上的响应，这方面已有大量研究，Hsiao 曾对此做过详细综述[7]。目前国际上比较著名的农业生态模型都能够模拟作物的生长状况。例如荷兰的 WOFOST（World Food Study）模型，美国农业部研究开发的 CERES（Crop and Environmental Research Synthesis）系列模型，RZWQ（Root Zone Water Quality）模型，丹麦等国共同研制的 DAISY 模型，加拿大农业部半干旱草原农业研究中心（Semiarid Prairie Agricultural Research Center，SPARC）对 CERES 模型进行本地化形成的 SPARC-Wheat 和 SPARC-Barley 模型[3]。

relating to field moisture [2]. This model has definite physical mechanisms for different districts and conditions and can predict the changes of soil moisture content. SWAP can simulate the transfer of field moisture, solute, and heat quantity between saturated and unsaturated soils during the entire growth period of crops; with SWAP, irrigation can be planned according to various standards [4]. SWAP can be used to solve problems in the study of agriculture, water resource management, and environmental protection. After considering the abovementioned applications of this model, we used SWAP to study winter wheat growth under salinity stress.

荷兰的 SWAP（Soil Water Atmosphere Plant）模型将模拟重点放在水量过程上，提供了多种和田间水分相关的模拟选项[2]。另外该模型有明确的物理机制，适合在不同地区、不同条件下移植应用，同时还有预测土壤含水量变化过程的功能。SWAP 模型可以模拟作物整个生长期内田间水分、溶质和热量在饱和/非饱和土壤中的移动，还可根据各种标准制定出灌溉计划[4]。该模型可用以解决农业、水资源管理和环境保护等几个领域的研究与实践问题。所以本研究采用该模型来对盐分胁迫下的冬小麦生长问题进行研究。

Fig.1- Channel networks arrangement plan of ditch for water storage.

MATERIAL AND METHOD

Study area

Experiments were performed at the Shaanxi Estate Development Service Corporation and Xi’an University of Technology, China. The study area is located in Shaanxi Province, China, as shown in figure 1 (101°21′ to 101°26′E, 34°47′ to 34°49′N). The regional climate is semiarid, with a mean annual precipitation of approximately 437 mm and evaporation of 1,000 mm to 1,300 mm; these values for precipitation and evaporation mostly result in intense storms from June to September [5]. The mean annual air temperature is approximately 13.4 °C, with a pH of 8.3 to 8.6. A salinity level in the range 2.8 g/L to 3.2 g/L was found in the semiarid zone. Corn, wheat, and cotton are the main crops cultivated in fields in this area. Fields are irrigated by using ditch systems. The study area consisted of a number of fields covering a piece of land 40 m long and 10 m wide, with a total area of 400 m^2. The salinity of groundwater affected the distribution and variability of salinity in the topsoil and was also the main limiting factor for crops because high salinity resulted in high mineral concentration in the groundwater.

材料与方法

研究区域

本试验的研究是在陕西地产开发服务公司和西安理工大学共同努力下进行的。研究区位于中国的陕西省如图 1 所示位置（101° 21′ 101° 26′ E，34° 47′ 34° 49′ n）。陕西气候干旱年平均降水量约 437 毫米，蒸发量 1000-1300 毫米，降雨大多集中在六月到九月[5]。年平均气温约为 13.4°C，研究区土壤 pH 值为 8.3～8.6，含盐量 2.8-3.2 g / L。在这个区域主要种植玉米，小麦，棉花采取渠系灌溉方式。研究区由一个长 40 米，宽 10 米的田块组成，用地面积 400 平方米。高盐分的地下水影响着表层土壤含盐度的分布与变化。高矿化度的地下水也是限制了作物生长的主要因素 。

Model introduction

In salinized farmlands, dissolved salt moved with the water. The core of SWAP is related to the simulation of water movement, thereby defining the water source, destination, and changes in soils. Water mostly came from rain and artificial irrigation. After canopy interception, rain reaches the ground. Part of the rain water becomes runoff, and the rest infiltrates the soil. Some of the rain water in the soil evaporated and disappeared, but most of it went back to the air via plant transpiration; thus, salt is left on the soil surface [8]. Water in soil moved according to the description of the Richards equation, and key factors influencing the process include soil property and moisture content.

模型介绍

在盐渍化的农田中，溶解在水分中的盐分会随着水分运移。SWAP 模型的核心部分是对水分运动的模拟，即确定水的来源、去向以及在土壤中的变化过程。水的来源主要是降雨以及人工灌溉。降雨经过冠层截留后到达地面，一部分形成径流，其余则渗入土层。土壤中较少部分的水通过蒸发散失，大多数则是通过植物的蒸腾作用返回大气，盐分就被留在了土壤表层[8]。土壤中的水分按 Richards 方程的描述运动，影响这一过程的关键因素是土壤性质和

Water infiltrating downward turned into deep phreatic water, and water that moved to the lateral sides would flow into drainage systems (rivers and drain pipes) [6]. The movement of solute depended on soil property, whereas crop growth can be considered as dry matter accumulation determined by radiation and transpiration; solute was then allocated into different crop tissues in proportion [11]. Crops consisted of canopy and roots, which function differently. For winter wheat, development revolved around canopy growth in general; thus, canopy dry matter accumulation is an in decreasing function of time [9]. Root system growth determined the water uptake of the crops, and gradually reached the maximum with crop development. In this period, crop growth was an increasing function of time. Afterward, matter accumulation decreased because of fading and the output of dry matter to canopy. Thus, growth became a decreasing function of time. Therefore, studying the dynamic changes of crops' above-ground biomass and root uptake under water and salinity stress is important [1].

土壤含水量。水分向下入渗会成为深层地下水，向侧向运动则会从排水系统（河道、排水管网等）流走[6]。溶质的运动取决于土壤特性，而作物生长则可认为是由辐射和蒸腾作用决定干物质积累，再按一定比例分配到不同组织[11]。作物整体由冠和根两种功能不同的器官组成。就冬小麦而言, 大部分时间是以冠生长为中心, 因此冠部干物质积累是时间的单调不减函数[9]。根系生长决定着作物对水分的吸收，并随作物不断发育而快速生长并达到最大值, 此期间其生长是时间的递增函数, 此后由于衰老和干物质向冠部输出, 物质积累量开始下降, 生长为时间的递减函数。那么研究在水盐胁迫下作物地上部分生物量的动态变化，以及水盐胁迫下作物根部对水分的吸收状况具有十分重要的意义 [1]。

Root water uptake module under water and salinity stress

To calculate water stress in SWAP, the sectional linear water stress function proposed by Feddes et al. was used; calculating salinity stress required the corresponding linear function suggested by Maas and Hoffman. The function was constructed based on the relationship between soil saturation extract conductivity (EC_e) and root uptake. Actual root uptake rate S_{act} (h, EC, z) (cm/d) can then be expressed as follow:

水盐胁迫下根系吸水模块

SWAP 中水分胁迫的计算采用了 Feddes 等提出的分段线性水分胁迫函数。盐分胁迫则采用 Maas 和 Hoffman 建议的线性相应函数，该函数是基于土壤饱和浸提液电导率（EC_e）与根系吸水关系构建的。故 Actual root uptake rate S_{act} (h, EC, z) (cm/d)可表示为：

$$S_{act}(h,EC,z)=a_{rw}(h)a_{rs}(EC)S_{Pot}(z) \tag{1}$$

Where, a_{rw} (h) - the water stress reduction factor (fig.2);
a_{rs} (ECe) - the salinity stress reduction factor, as shown in figure 3;
S_{pot} (z) - the potential root uptake rate, cm/d;
EC - the electrical conductivity (smcm-1);
H - the soil water pressure head (cm).

式中，a_{rw}(h) - 水胁迫折减系数，见图 2；
a_{rs}(EC_e) - 盐胁迫折减系数，见图 3；
S_{pot}(z) - 根系实际吸水 速率；
EC - 电导率 smcm^{-1}；
H - 土壤压力水头；

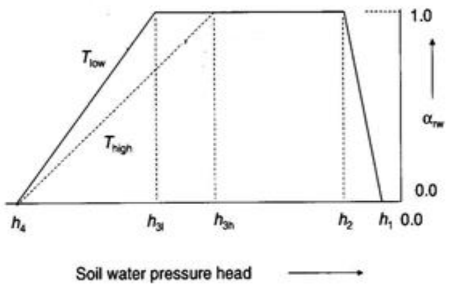

Fig. 2 - Water stress reduction factor

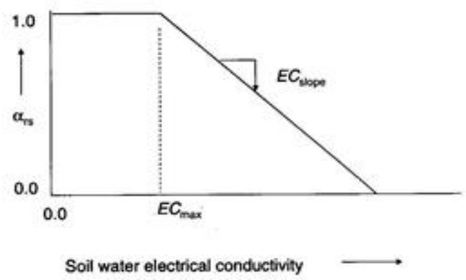

Fig. 3 - Salinity stress reduction factor

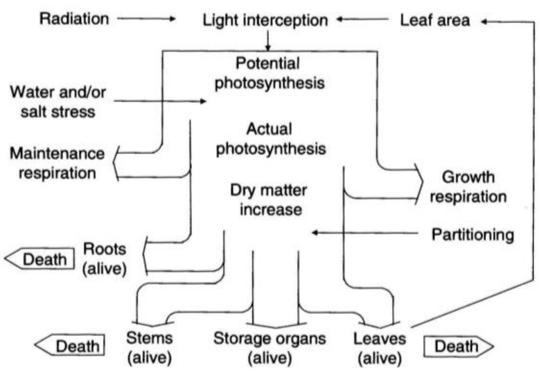

Fig. 4 - Crop growth processes

Crop growth module

The module used in SWAP to simulate crop growth was WOFOST 6.0, as shown in Fig.4. WOFOST was used to determine the radiation absorbed by crop canopy as a function of incident radiation and leaf area and to calculate potential photosynthesis with the feature of photosynthesis in leaves. Potential photosynthesis would be reduced due to water and salinity stress, and some of the radiation was used for maintaining respiration. Thus, the actual photosynthesis is achieved. Furthermore, the amount of CO_2 that was assimilated into carbohydrates CH_2O was obtained. After obtaining the amount of respiration required for growth, the increased amount of dry matter was determined. The dry matter was allocated to different tissues in proper proportions, and the amount that reached the leaves determined leaf growth. The crop growth model at simplified field scale refers to formula (2), simple model (field scale), as follows:

作物生长模块

SWAP 模拟作物生长模块所用的是 WOFOST 6.0 程序见图 4。WOFOST 将作物冠层吸收的辐射能看成入射辐射和作物叶面面积的函数，并考虑叶片发生光合作用的特性，计算得出潜在光合作用。潜在光合作用会因水分和盐分压力有所消减，而且还有一部分要用于维持呼吸作用，由此得到实际光合作用，进而得出 CO_2 同化为碳水化合物 CH_2O 的量。这一部分扣除用于生长的呼吸作用后就可得出干物质的增加量，产生的干物质再按一定的因子分配到作物的各个组织。划分到叶片的那部分干物质又会决定叶片生长。可以将其简化田间尺度的作物生长模型见公式（2），简化模型（田间尺度）：

$$\frac{Y_a}{Y_p}=\prod_{k=1}^{N}\frac{T_{a,k}}{T_{p,k}} \tag{2}$$

Where: Y_a - actual crop yield;
Y_p - potential crop yield;
$T_{a,k}$ - actual transpiration at stage k;
$T_{p,k}$ - potential transpiration at stage k;
N - number of growth stages.

式中：Y_a - 实际产量；
Y_p - 潜在产量；
$T_{a,k}$ - 在 k 田块的实际蒸发；
$T_{p,k}$ - 在 k 田块的潜在蒸发；
N - 田块总数.

RESULTS

Model verification and discussion

In the present paper, the field experimental data of winter wheat irrigated with Yellow River water were obtained in the salinized irrigation district of Fuping County, Shaanxi Province in 2014. The field plot area was 40 m × 10 m = 400 m^2, and the soil was mostly loess. The typical local field irrigation and fertilization systems were used. Soil moisture content and conductivity were detected daily by real-time forecast using the soil-water-salt sensor CS655. During harvest, a variety study and a yield test were conducted. Inspection wells were available around experimental plots for detecting ground water level, and an automatic water level detector was used to measured groundwater level once daily. The initial conditions of the model were determined by measuring groundwater level and salt concentration. The upper boundary was the flux formed by rain, interception, evaporation, and transpiration, or variable waterhead boundary, and the lower boundary was the variable waterhead boundary defined by measuring ground water level.

结果

模型验证与讨论

本文分别采用在陕西富平盐渍化灌区开展的 2014 年冬小麦引黄渠灌田间试验数据。试验田间小区面积为个 40m×10m=400m^2，土壤质地以黄土为主，采用当地典型田间灌溉及施肥制度，通过土壤水盐传感器 CS655 实时测报的方法每天测定土壤含水率和土壤电导率。收获时进行考种测产。试验小区附近布设有地下水位观测井，自动水位计每天进行 1 次地下水位监测。模型的初始条件根据实测地下水位与盐分浓度确定，上边界由降雨、截留、蒸散发组成的通量或变水头边界，下边界条件采用由实测地下水位确定的变水头边界。

Table 1

Calibrated values of primary crop biological parameters in SWAP crop growth module

Parameters	2014 winter wheat
Light use efficiency of crops RUE ([kg hm^{-2}].[MJm$^{-2)-1}$]	36
Curve shape parameter ab1	13.15
Curve shape parameter ab2	62.27
Controlling value of root uptake weakening curve because of the water condition	-15
Controlling value of root uptake weakening curve because of the salt condition	6.0
crop resistance r_{crop}	70
Canopy's rainfall interception coefficient cm	0.25

Winter wheat was sown and harvested on 20 December 2013 and 30 May 2014, respectively. In Fuping, Shaanxi, soil is usually thawed by middle January and melted by late February or early March. Accordingly, the simulation of winter wheat's growth period considered the soil thawing process. Table 1 lists the corresponding definite values of parameters of winter wheat modules. The comparison of simulated and observed values of soil moisture in different layers indicated that these values matched well. The overall the average relative error (MRE) and root-square error (RMSE) tended to be 0, whereas R^2 was close to 1, as shown in Fig. 5, thereby proving that the simulated and measured values of soil moisture matched well. Meanwhile, the sudden increase of water in the upper soil layer was closely linked with concentrated rainfall. The lower soil layer had high moisture content and underwent relatively little changes because of the effect of shallow groundwater level. Fig. 6 shows the simulated and measured values of water-salt concentration in root soil, and these values differed slightly with consistent overall tendency. The statistics of overall simulated and measured salt concentrations were MRE = -0.037, RMSE = 0.227, and R^2 = 0.806, which indicated good consistency. The low simulated value R^2 of salt concentration may be due to a system error in the soil water model generalization. For instance, average values of irrigation and rainfall were obtained in one day. After irrigation or concentrated rainfall, water salt concentration in root soil significantly declined, which enhanced crop growth. Increased water consumption by crops led to the gradual rise of salinity accumulation and concentration in the root zone.

Fig. 7 shows that the simulated value was close to the measured value of above-ground biomass, thereby indicating the accuracy of simulation results. Nash-Sutcliffe efficiency was approximately 0.96, but MRE and RMSE values were large, which may be related to the small size of measured data. In existing studies, above-ground biomass of wheat tended to follow a mono-linear growth trend in the middle and late growth periods. The measured values of biomass in this research, however, covered only one growth cycle of wheat. Therefore, we still adopted SWAP biomass calculation and allocation formulas, and we will focus on simulation of above-ground biomass in future studies to further improve the model. The simulated yield was 0.86 kg/m^2, which was slightly smaller than the observed value of 1 kg/m^2. As the actual field conditions were complex, crops might be affected by other factors during growth. For this reason, differences in simulation of growth parameters were acceptable. The comparison of soil moisture, soil salinity, simulated values, and measured values of growth parameters indicated that SWAP simulated the dynamic changes of field water and salinity and growth coupling process of spring wheat in Loess Plateau.

冬小麦播种和收获日期分别为 2013 年 12 月 20 日和 2014 年 5 月 30 日，陕西富平自 1 月中旬开始解冻，至 2 月底或 3 月初融通。因此，冬小麦生育期模拟需考虑土壤融化过程，冬小麦所对应的作物模块参数率定值列于表 1. 比较各层土壤水分的模拟值与观测值，二者吻合结果较好。总体的 MRE 和 RMSE 趋于 0，R^2 则接近于 1 如图 5，进一步表明了土壤水分模拟值与实测值匹配良好。同时，上层土壤水分的突增与灌溉和集中降雨密切相关，而下层土壤又同时受到浅地下水位的影响，其维持着较高的含水率且变化相对较小。根系层土壤水盐分浓度的模拟值与实测值，如图 6 所示，二者差异较小，且总体趋势一致。总体的模拟与实测盐分浓度统计值 MRE=-0.037、RMSE=0.227、R^2=0.806，表明二者具有较好的一致性。但土壤盐分浓度模拟统计值 R^2 值较小。可能是由于土壤水模型概化中的系统误差所致，如对采用了灌溉、降雨的日内平均化处理。同时，根系在灌溉或集中降雨后，根区土壤水盐分浓度呈现明显下降趋势，这有利于作物生长；其后随着作物耗水的增加又引起根区盐分积累和浓度逐步上升。

如图 7 所示，地上部生物量的模拟值与实测值较为接近，模拟效果基本可以接受， NSE 值约为 0.96，但 MRE 和 RMSE 值则相对较大，这可能与实测数据的数量过少有关。考虑到已有研究中小麦地上部生物量在生长中后期多呈现单一的近似线性增长趋势，且本研究中生物量观测值仅为小麦一个生长周期，因此，本文仍采用 SWAP 生物量计算及分配公式，并将在后续研究中关注与地上部生物量的模拟，以求进一步改进模型。产量模拟值为 0.86kg/m^2，略小于观测值 1 kg/m^2。考虑到田间实际状况复杂，作物生长可能还会受到其他因素影响，因此，上述作物生长指标的模拟差异是可以接受的。综合以上土壤水分、土壤盐分、作物生长指标模拟值与实测值的对比结果，表明 SWAP 模型可以良好的模拟黄土高原春小麦田间土壤水盐动态及作物生长耦合过程。

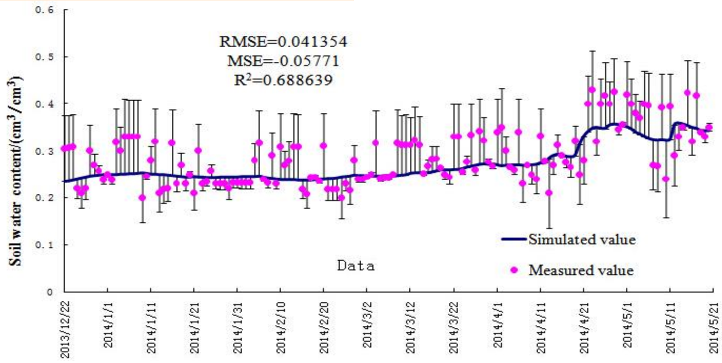

Fig. 5 - Soil water content of root layer

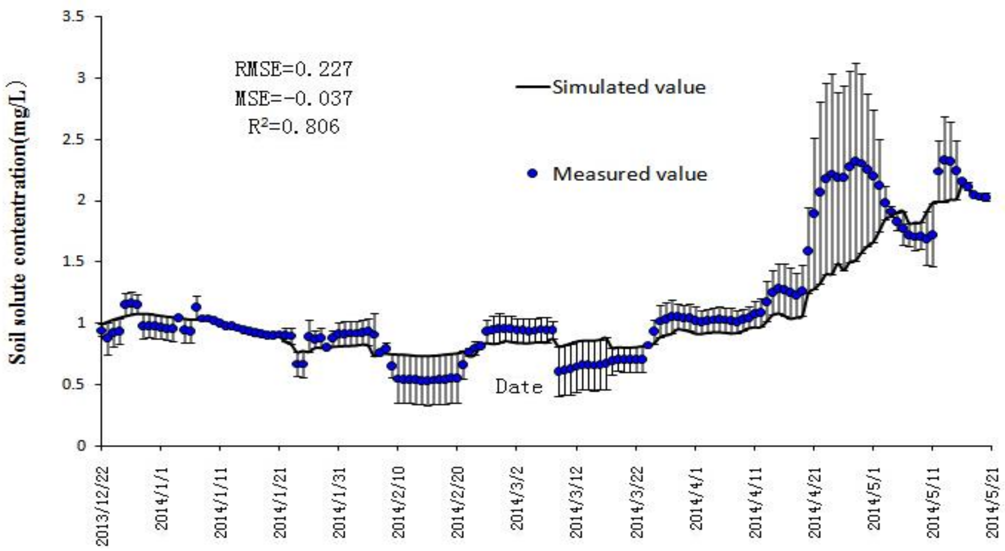

Fig. 6 - Soil salinity content of root layer

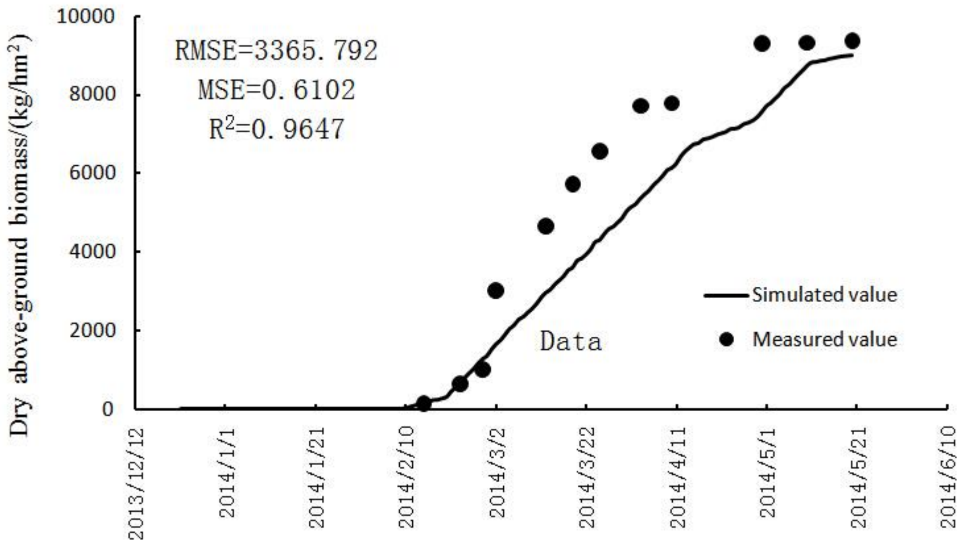

Fig. 7 - Above-ground biomass

CONCLUSIONS

Based on SWAP, we used the field data of winter wheat in the salinized irrigation district of Fuping, Shaanxi to test field applicability and to compare soil water, soil salinity, and the simulated and measured values of above-ground biomass. We also analyzed the parameters based on SWAP. The simulation results demonstrated the following:

1) Crop growth module of SWAP described the details of crops' physiological process and morphology in a simple manner. Simulation of the growth and distribution of the root system and the increase of plant height or group leaf distribution was not achieved using the model. However, the model was able to simulate the process of crop growth and yield. Thus, the simulation of the dynamic changes of soil water salinity and daily crop growth was still achieved.

2) SWAP required detailed physical processes and many rare formulas, which resulted in the unreasonable generalization of the initial growth period of crops. Thus, distorted simulation was achieved.

结论

本研究以 SWAP 模型为基础，采用陕西富平盐渍化灌区冬小麦田间试验数据进行了田间适用性检验，分别对土壤水分、盐分浓度、作物地上部生物量的模拟值与观测值进行了对比与指标统计分析。模拟结果表明：

1）SWAP 模型的作物生长模块，对作物生理过程与形态特征的细节描述仍较为简单，尚不能模拟作物根系生长动态及分布、株高的增长动态及群体叶片分布等，其主要适用于模拟作物生长与产量形成的主要过程。但实现了以日为时间步长的土壤水盐动态及作物生长的模拟。

2）由于 SWAP 考虑的物理过程十分详细，用到了很多公式，而且其中很多都是不常见的，使得作物生长初期概化不合理而导致的模拟失真。

3) MRE and RMSE of soil moisture in winter wheat experiment were close to 0, and model R^2 value was close to 1. Thus, the water module showed high simulation accuracy. The simulation of salinity concentration differed slightly, but was generally consistent.

3）冬小麦试验中土壤水分的平均相对误差 MRE 和均方根误差 RMSE 均接近于 0，且模型 R^2 值趋近于 1，水分模块模拟精度较高，盐分浓度模拟存在略微差异但总体上一致性较好。

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