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Research Paper

Developing a water and nitrogen management model for greenhouse vegetable production in China: Sensitivity analysis and evaluation

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A B S T R A C T

Excessive water and fertilizer inputs have led to a series of environmental problems in vegetable production areas in China. Identifying the fates of water and nutrients is crucial to develop best management strategies in intensive vegetable production systems. The objectives of this study were to (i) develop a scientific water and nitrogen (N) management tool for intensive greenhouse vegetable production in China, and (ii) evaluate the model performance in the simulating the fate of water and N, and vegetable growth under different water and N management practices in China. A vegetable growth component was added to the field soil-crop system model WHCNS (soil Water Heat Carbon Nitrogen Simulator), named WHCNS_Veg. Parameters for the model were estimated and a sensitivity analysis was conducted by coupling the model with the model-independent parameter estimation program (PEST). Data used to test the model came from two years of cucumber and tomato experiments with various water and N combinations in Shandong province, China. The results of sensitivity analysis showed that the soil hydraulic parameters and vegetable genetic parameters had a relatively higher sensitivity compared with those of N transformation parameters. The saturated soil water content had the highest sensitivity among soil hydraulic parameters, and the total available accumulated temperature, crop coefficient and maximum root depth had higher sensitivity for both vegetable crops. Among the N transformation parameters, the parameters related to nitrification had the highest sensitivity. The automatic optimization algorithm performed well in adjusting soil hydraulic parameters, vegetable genetic parameters and N transformation parameters. The normalized root mean square error for soil water content, soil nitrate concentration, marketable fresh yield and vegetable N uptake were 5.7%, 28.0%, 2.7% and 8.3%, respectively, and indices of agreement were 0.727, 0.730, 0.997 and 0.832, respectively. The results indicated that the WHCNS_Veg model has great potential to simulate and analyze water and N fates, and vegetable growth for the intensive greenhouse vegetable production in China.

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1. Introduction

Greenhouse vegetable production in China developed rapidly over the last 30 years. In 2014, the cultivated area of greenhouse vegetables reached 3.7 million ha and accounted for 17.6% of the total national vegetable planting area (Chinese Ministry of Agriculture, 2015). Compared to field crops, nutrients (especially nitrogen and potassium) in vegetable production are more prone to leaching due to its shallow root system. Excessive water and fertilizer inputs is common in many greenhouse vegetable areas in China, which has led to a series of environmental problems such as groundwater pollution, soil acidification and salinity etc. (Zhu et al., 2005; Shi et al., 2009; Du et al., 2011). For example, Zhu et al. (2005) surveyed the groundwater quality in greenhouse vegetable production areas in Shandong province and found that the nitrate concentration of more than half of 94 local wells exceeded the WHO's public drinking water limit of 10 mg L^{-1}. Du et al. (2011) investigated the groundwater pollution in the Beijing area, and also found that the nitrate concentration of groundwater (13.8 mg L^{-1}) in vegetable fields was 2.8 times greater than in crop land. Furthermore, some researchers reported that excessive N fertilizer inputs leads to groundwater pollution and also causes acidification and salinity of soils (Shi et al., 2009).

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In recent years, many studies aimed to achieve a balance between vegetable production yields and environment pollution. For example, Min et al. (2012) reported that nitrate leaching was reduced by 39.6% without vegetable yield loss when the traditional N fertilizer rate decreased by 40%. Fan et al. (2014) found that the yield of tomato increased 9% and nitrate leaching was significantly reduced when water and N fertilizer inputs of drip irrigation treatments were decreased by 78% and 43%, respectively compared with furrow irrigation. Li et al. (2015a) also found that the amount of ammonia volatilization decreased by 37.2% when the N application rate was reduced from the traditional 1200 kg N ha^{-1} to an optimal rate of 600 kg N ha^{-1} without reducing tomato yield. These studies were based on the water and N fertilizer controlled experiments in the greenhouse, which are time-consuming and costly. More importantly, the results from the experiments are often only relevant to a specific climate condition, management practice, and soil type, which greatly restrict their application under other conditions.

Soil-crop models have been widely used to extend point based experimental results to other locations for problems such as crop production management (Hansen et al., 1990; Greenwood, 2001), water and fertilizer optimal management (Nendel, 2009; Rahn et al., 2010), and environment impact assessment (Nolan et al., 2010), etc. Two existing vegetable decision support models are the N Expert (Fink and Scharpf, 1993) and N_ABLE models (Greenwood, 2001). The N_ABLE model was widely adopted in Europe, and based on this model, many vegetable models were developed such as the WELL_N (Rahn et al., 2001), NPK model (Zhang et al., 2007), SMCR_N (Zhang et al., 2009), EU-Rotate_N model (Rahn et al., 2010), etc. Among these models, the EU-Rotate_N model is the most widely used to simulate vegetable growth under different water and N management practices (Nendel, 2009; Guo et al., 2010; Sun et al., 2012; Sun et al., 2013; Soto et al., 2014; Suárez-Rey et al., 2016). The EU-Rotate_N model has also been tested with various open field and greenhouse vegetables (over 24 vegetables), and researchers have established a complete vegetable parameter database (Greenwood, 2001; Rahn et al., 2010).

Guo et al. (2010) first introduced the EU-Rotate_N model into China to analyze the N loss in a greenhouse, and found that the N mineralization was the key process influencing N leaching, but it was strongly underestimated in previously studies for the greenhouse vegetable production system. Sun et al. (2012, 2013) used this model to simulate N fate and optimize the water and N management for greenhouse cucumber and tomato, and suggested that the drip irrigation with straw incorporation can effectively reduce N leaching while maintaining vegetable yield. However, the soil water movement and solute transport in EU-Rotate_N model used a simple capacitance approach, which greatly limits the use of this model under complex bottom boundary conditions. Yang et al. (2009) proposed an alternative dynamic method (Richards equation) to simulate soil water movement, but this method has not been implemented in the current EU-Rotate_N model (Rahn et al., 2010). In addition, this model could not separate the processes of denitrification and ammonia volatilization, for example, since the gas emission of NH_3 and N_2O were calculated together and output as one item of N gas.

To overcome the limitation of the above models, Liang et al. (2016a) developed a water and N management model (soil Water Heat Carbon Nitrogen Simulator, WHCNS) for intensive cropping system. This model was inspired by the widely validated modules and models around the world, including soil water movement module from RZWQM model (Ahuja et al., 2000), heat transfer and solute transport processes from HYDRUS-1D model (Simunek et al., 2008) carbon (C) and N cycles routines from DAISY model (Hansen et al., 1990), and crop growth from EPIC model (Williams et al., 1989). The model has been successfully applied to water and N management for the major staple crops in North China (Li et al., 2015b; Liang et al., 2016b). However, the original crop growth module of WHCNS was a simplification of the EPIC crop model, which is not suitable for simulation of vegetable growth (Nendel et al., 2009). In this study, we developed a vegetable growth module for the WHCNS model based on EU_Rotate-N model to improve water and N management for greenhouse vegetable production in China. At the same time, a Model-Independent Parameter Estimation (PEST) (Doherty, 2004) program was coupled with the model to conduct the sensitivity analysis and parameter auto-estimation for the newly coupled WHCNS_Veg model.

The objectives of this study were to (i) develop a vegetable growth module for the WHCNS model, (ii) conduct a sensitivity analysis and parameter auto-optimization using the model-independent parameter estimation program (PEST), and (iii) evaluate the performance of the model in the simulation of soil water movement, N transport and vegetable growth under different water and N management practices.

2. Materials and methods

2.1. WHCNS model

The key processes described in WHCNS model include soil evaporation, crop transpiration, soil water movement, soil temperature, mineralization of fresh crop residue and soil organic N, soil inorganic N immobilization in biomass, nitrification, ammonia volatilization, denitrification, and crop growth. In the model, the reference evapotranspiration is estimated using the grass-based Penman-Monteith method (Allen et al., 1998). The infiltration of rainfall or irrigation is computed by a modified Green-Ampt approach (Green and Ampt, 1911). Water redistribution is simulated by the Richards equation in a soil profile in which surface evaporation and plant uptake are considered as sinks (Simunek et al., 2008). Meanwhile, soil heat transport simulation is directly imported from the HYDRUS-1D model (Simunek et al., 2008). Soil C and N cycling concepts are drawn from the DAISY model (Hansen et al., 1990). The model runs on a daily time step and is driven by inputs including weather data and crop biological parameters. The model inputs include: site latitude and elevation, basic soil properties, field management, initial conditions, and daily weather data. A detailed model description is available in the literature (Liang et al., 2016a).

2.2. Model development

2.2.1. Plant dry matter accumulation

The main vegetable growth processes are based on the methods proposed by Greenwood (2001) and Rahn et al. (2010). This approach uses total dry matter yield at harvest as a target yield. While this approach requires fewer input parameters which facilitates use, it does require the user to provide a target yield. The crop development stage was calculated by Eqs. (1) and (2).

$$RDS_i = RDS_{i-1} + \Delta RDS_i \tag{1}$$

$$\Delta RDS_i = \begin{cases} 0 & T_i < T_{base} \\ (T_i - T_{base})/Tsum & T_{base} \le T_i \le T_{crit} \\ (T_{crit} - T_i)/Tsum & T_i > T_{crit} \end{cases} \tag{2}$$

where T_i is average daily temperature on the day i (°C), T_{base} is the threshold temperature for crop development (°C), T_{crit} is critical temperature for crop development (°C), set to 20 °C (Rahn et al., 2010), T_{sum} is total heat unit requirement from emergence or transplant to maturity (°C), RDS_i is the crop relative development stage

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