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Modification of maize simulation model for predicting growth and yield of winter wheat under different applied water and nitrogen

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ABSTRACT

Model WSM (Wheat Simulation Model) was developed based on the previous model (MSM, Maize Simulation Model). The planted cultivar was Shiraz with five irrigation treatments (1.2, 1.0, 0.8, and 0.5 ratios of the potential irrigation requirement under surface irrigation system and rain-fed) and four applied nitrogen treatments (0, 46, 92, 136 kg N ha^{-1}). The irrigation water requirements were estimated by measuring the differences between soil field capacity and measured soil water content at root depth in the full irrigation treatment before irrigation. In the WSM model, dynamic flow of water, nitrogen, and heat through the soil were simulated numerically in an unsteady state condition at soil profile. Water and nitrogen transfer in the soil are governed by the Richard's equation and the diffusion convection equation, respectively. Emergence time of seed after sowing was simulated using soil water content, temperature, sowing depth, and soil particle diameters using beta function. Plant growth stages were simulated considering photoperiod, vernalization and air temperature. Hourly simulation of actual evaporation from soil surface and transpiration were simulated using the Penman–Monteith method based on atmospheric conditions and soil water content at root depth. Nitrogen uptake was simulated through mass flow and diffusion processes during the growing season. Produced dry matter was simulated as a function of hourly corrected intercepted radiation (based on air temperature) by plant leaves, maximum and minimum plant top N concentration and the amount of N uptake. Wheat grain yield was simulated by the ratio of grain N uptake and grain N concentration that were estimated by an empirical equation as a function of simulated top N uptake. Obtained experimental data in 2009–2010 were used to calibrate the model. The experimental results from 2010 to 2011 validated favorably the proposed model.

1. Introduction

Wheat is one of the major cereal crop that is strategic for food security across the world (FAOSTAT, http://faostat.fao.org). Soil moisture deficit during the growing period (from double ridge to anthesis) and around the anthesis causes yield and top dry matter losses (Cossani et al., 2009). Similarly, nitrogen (N) nutrition deficiency has been found responsible for cereal yield loss (Passioura, 2002). The understanding of the interactive effects of water and N availability, along with the crop ability to efficiently use these resources is of crucial importance for management of cereal production (Albrizio et al., 2010). Many investigators indicated that proper fertilizer, crop, water and soil management can minimize leaching of nitrates and increase crop yields (Perego et al., 2012).

Crop simulation models have widely been used to assess and understand the effects of environmental parameters, fertilizer application, and irrigation regimes on plant growth and yield. They also help to manage resources, maximize returns to producer and reduce impacts on water quality. They can be used to optimize sowing time, fertilizer rate and water application in a way with maximum yield and minimum environmental pollution. These models differ in the complexity and the theory that have been used in their development (Hoogenboom, 2000).

Many crop simulation models like STICS (Brisson et al., 2003) use water balance methods and non-dynamic water flow through soil for prediction of evapotranspiration and grain or relative yields. Water balance and soil water content is without doubt one of the crucial points in the application of any crop simulation model. Crop models including water balance calculations should be tested prior to application in different sites and environments (Eitzinger et al., 2004). Some models use Richards' equation to simulate soil water flow and consequently soil water pressure head, water content, and root water uptake. In these models crop dry matter production,

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grain and relative grain yield is simulated based on light interception by crop canopy, photosynthesis, water and nutrient stress effects (Kiniry et al., 1992; Pang and Letey, 1998; Stockle et al., 2003; van Dam et al., 1997; Lafolie, 2007). These models differ in types and complexity of the involving biological processes.

The effects of water and nitrogen on plant growth are considered in some models such as: ENVIRO-GRO (Pang and Letey, 1998), CERES-Wheat (Godwin et al., 1989), LEACHM (Hutson and Wagenet, 1992), RZWQ (Great Plains System Research, 1992), EPIC (Williams et al., 1989), WOFOST (van Ittersum et al., 2003), SWAP (van Dam et al., 1997), CropSyst (Stockle et al., 2003), AFRCWHEAT2 (Porter, 1993), NWHEAT (Keating et al., 2001), Sirius (Jamieson et al., 1998). In ENVIRO-GRO, CERES-Wheat, LEACHM, RZWQ, EPIC models, N demand that is determined from previous experiments, is used to determine plant-N uptake.

In AFRCWHEAT2, the crop N demand is calculated as the difference between current nitrogen concentration in the shoots and roots and their maximum value for the current development stage. In NWHEAT model denitrification and ammonia volatilization are not taken into account. In Sirius model, the nitrogen subroutine is very similar to the NITCROS model (Hansen and Aslyng, 1984). In this model, maximum nitrogen uptake is determined by using dry matter production and maximum nitrogen concentration which is a function of the age of the crop. Actual nitrogen uptake depends on both maximum nitrogen uptake and the available amount of inorganic nitrogen in the soil. The mineral N budget in CropSyst, and crop N uptake is modeled by adapting the approach presented by Godwin and Jones (1991), where N uptake is determined as the minimum of crop nitrogen demand and potential nitrogen uptake. Crop nitrogen demand is the amount of nitrogen that the crop needs to meet growth N requirements plus its deficiency demand. The deficiency demand is the difference between the crop maximum and actual nitrogen concentration.

Mechanistic models in simulating soil water flow and soil nitrogen balance like PASTIS (Lafolie, 2007) was based on daily time step. Air temperature and solar radiation vary during a day. Usually daily minimum and maximum air temperatures occur before the sunrise and after the noon, respectively. When the mean value of daily air temperature was nearly optimal, its hourly values before sunrise and after noon would be lower or higher than the optimal value. Therefore, using the daily values of environmental parameters like air temperature and solar radiation might not determine the effects of these parameters on crop growth accurately. Zand-Parsa et al. (2006) developed a simulation model (MSM) for maize growth and yield under variable irrigation water and nitrogen with 1 h time step. In MSM, the following items were considered: (1) one-dimensional flow of water, heat, and nitrogen were simulated in unsteady state conditions by numerical analysis for estimation of volumetric water content, temperature, nitrate and urea concentration at different layers of soil at every hour during the growing period of the plant, (2) nitrogen uptake was simulated by considering mass flow and diffusion processes, (3) maximum and minimum maize top N concentrations were related to the growth stages, (4) leaf area index (LAI) at every time step was simulated by the value of aboveground dry matter (DM) by a function that was obtained from measured values of *LAI* and DM, (5) potential and actual evapotranspiration were calculated hourly then, evaporation and transpiration were separated based on some meteorological and plant data, and (6) estimating grain N uptake and grain N concentration by aboveground N uptake with two empirical functions that were obtained from measured data. Zand-Parsa et al. (2006) validated the MSM model, and their results indicated the favorable validation of the model. Majnooni-Heris et al. (2011) modified MSM model (called MSM2) for N uptake and predicting yield based on plant stover N uptake. Their results validated the modified model fairly well. Abedi (2011) modified MSM model for drip irrigation and indicated that the modified model predicted growth and yield of maize with good accuracy. Considering wide applications of crop simulation models and importance of wheat in the world due to its nutrition value, the objectives of this study were:

1. To develop a wheat simulation model (WSM) by modifying MSM model for simulation of winter wheat growth considering the simulation of plant emergence, rosette stage, anthesis and maturity times.
2. To calibrate and validate the modified model (WSM) with an experimental field data.

2. Theory of WSM model

In the following section a brief theory of WSM model is presented. For further information the related studies were referred to readers along the article. However, the parts of WSM considering the growth of winter wheat were described in detail.

2.1. Soil water

In WSM model, the hourly soil water content and soil water pressure was simulated by numerically solving Richards' equation as described by Zand-Parsa (2001). Depth of soil profile was 1.8 m and the thickness of each layer was 0.05 m. The relationships between $h-\theta$ and $K-\theta$ were determined from van Genuchten (1980) as follows:

$$Se=\left[\frac{1}{1+(\alpha_v|h|^{n_v})}\right]^{m_v} \quad (1)$$

$$K=K_sSe^{0.5}[1-(1-Se^{1/m_v})^{m_v}]^2 \quad (2)$$

$$S_e=\frac{\theta-\theta_s}{\theta_s-\theta_r} \quad (3)$$

$$m_v=1-\frac{1}{n_v} \quad (4)$$

where θ, θ_r and θ_s are the volumetric soil water content, volumetric water content at soil saturation and residual soil water content, respectively, Se is the effective saturation degree, K and K_s are the soil hydraulic conductivity (as a function of h) and saturated hydraulic conductivity, (m s^{-1}), respectively, α_v, n_v and m_v are the coefficients of van Genuchten's equation.

The relationship between crop potential evapotranspiration (ETc) was estimated by direct Penman–Monteith method as described by Allen et al. (1998). Two important parts of Penman–Monteith are the aerodynamic resistance (r_a) and bulk canopy resistance (r_c) that refer to air flux over vegetative surfaces and resistance of plant stomata and soil, respectively (Shahrokhnia and Sepaskhah, 2012). According to FAO-56 manual (Allen et al., 1998), r_a is determined as follows:

$$r_a=\frac{\ln[(z_m-d)/z_{om}]\ln[(z_h-d)/z_{oh}]}{k^2u_z} \quad (5)$$

where z_m is the wind speed measurement height (m), z_{om} is the momentum roughness length (m), z_h is the relative humidity measurement height (m), z_{oh} is the vapor roughness length (m), u_z is the wind speed at height of z (m s^{-1}), which is considered to be 2 m above the ground and d is the zero displacement height (m). Different parameters in Eq. (5) are estimated as follows (Allen et al., 1998):

$$d=\frac{2}{3}h_c \quad (6)$$

$$z_{om}=0.123h_c \quad (7)$$

$$z_{oh}=0.1z_{om} \quad (8)$$