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Coupling and testing a new soil water module in DSSAT CERES-Maize model for maize production under semi-arid condition

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ABSTRACT

Process-oriented crop simulation models are valuable tools for representing our understanding of the current and future states of a cropping system. The main objective of this research was to couple the Cropping System Model-(CSM)-Crop-Environment Resource Synthesis (CERES)-Maize (CSM-CERES-Maize) with the Soil, Water, Atmosphere, and Plant (SWAP) model in order to benefit from the advantages of both models. A new model was developed by replacing a simplified version of the SWAP with WatBal and SPAM modules of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.0. In this hybrid model, the CERES-Maize supplied the SWAP model with plant growth variables. Meanwhile, the SWAP model provided the CERES-Maize model with daily evapotranspiration, soil water content, and root water uptake. The model was then validated with a dataset including four irrigation levels (two deficit levels along with one full and one over-irrigation level), and three nitrogen levels (0, 150, and 200 kg/ha nitrogen) obtained from a field experiment in 2003 and 2004. The root mean square errors (RMSE) across all treatments in the simulation of final biomass were, respectively, 1175 and 2148 kg/ha in the first year and 1274 and 1514 kg/ha in the second year for the hybrid and original version of CERES-Maize model. Average RMSE for two non-water stress treatments was 1.29 and 1.35 cm in the simulation of soil water content for hybrid and original models, respectively. In general, our findings indicated that the new hybrid model was fairly successful in biomass simulation, which was due to better soil water simulations of all four irrigation levels except severe deficit irrigation.

1. Introduction

Crop models facilitate the clarification and evaluation of multi-dimensional relationships between factors affecting crop growth, development, and yield. These factors include planting date, cultivar selection, seeding rates, soil type, fertilizer and irrigation strategies, and seasonal weather patterns (Yang, 2008). For the past several decades, researchers have applied crop models to understand, organize, and develop new ideas and to analyze different management practices (Jiang et al., 2011; Dogan et al., 2006). Due to their proven value in environmental and agricultural resource management and policy-making, these models currently play a critical role in agricultural systems (Ma et al., 2005). Crop models employ simple or complex approaches to simulate environmental processes based on their objectives and data availability. The Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003; Hoogenboom et al., 2012), the Agricultural Production Systems sIMulator (APSIM) (McCown et al., 1995; Keating et al., 2003), the Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2002), and the Soil, Water, Atmosphere, and Plant (SWAP) (Van Dam et al., 1997) are examples of popular simulation models worldwide. While SWAP model is an agrohydrological model mainly focusing on soil water (Van Dam and Feddes, 2000), the Crop Environment Resource Synthesis-Maize (CERES-Maize) model from the

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DSSAT platform mostly deals with plant-related processes (Miao et al., 2006).

SWAP model simulates water transfer in the saturated/unsaturated zones by considering crop development (Van Dam et al., 1997). The Richards equation and van Genuchten–Mualem model are used to calculate soil water flow and soil hydraulic functions, respectively. SWAP model provides a numerical solution to the Richards equation through an implicit, backward, finite difference scheme (Van Dam and Feddes, 2000). It delivers the chance to use measured evapotranspiration (ET) in combination with crop factors. It also computes actual transpiration by considering soil moisture status and salinity conditions in the root zone (Kroes et al., 2008). Moreover, the crop module present in the SWAP model can predict crop development regardless of external stress factors. SWAP model mainly seeks to determine a proper upper boundary condition for soil water movement by taking leaf area index, root growth, biomass accumulation, and other variables as inputs (Kroes et al., 2008).

Unlike SWAP model, the CERES-Maize model does not assume plant processes to be fixed and tries to simulate them all (Jones et al., 2003). It calculates daily dry matter accumulation based on its relationships with daily intercepted radiation and radiation use efficiency. Light interception is computed as a function of plant population, row spacing, and leaf area index. Potential dry matter production is converted to attainable production using stress indexes for water, nitrogen, temperature, and atmospheric CO_2 concentration (Jones et al., 2003; Ritchie et al., 1998).

SWAP model has been extensively employed for soil water simulation (Crescimanno and Garofalo, 2005; Eitzinger et al., 2004; Gusev and Nasonova, 2003; Bonfante et al., 2010; Marinov et al., 2005; Van Dam et al., 2008), water management (Noory et al., 2011; Ma et al., 2011), and saline water application (Verma et al., 2012; Su et al., 2005; Jiang et al., 2011; Droogers, 2000). It has also been popular in studies on groundwater (Anuraga et al., 2006; Xu et al., 2012) and ET (Droogers, 2000; Utset et al., 2004). In contrast, the CERES crop model family is extensively used and improved (DeJonge et al., 2012; Sau et al., 2004) all over the world. These models have been applied to investigate yield and crop growth by considering genotypic factors (Garcia y Garcia et al., 2009; López-Cedrón et al., 2005; Dogan et al., 2006; Pang et al., 1997; Thorp et al., 2007; Saseendran et al., 2008), nitrogen uptake, and management factors (Gungula et al., 2003; Pang et al., 1997; Garrison et al., 1999; Dokoohaki et al., 2015). It is also useful in evaluating different management practices (Soler et al., 2007; Dogan et al., 2006; Panda et al., 2004; DeJonge et al., 2011; Fang et al., 2010) and long-term assessment studies (Popova and Kercheva, 2005; Jagtap et al., 1999).

A number of researchers have used combinations of various models or tried to benefit from the components of other existing models to save the development time (Ma et al., 2005). Ma et al. (2005, 2006) coupled the RZWQM model, which uses a comprehensive soil water module and Richards equations, with CROPGRO and CERES crop models in two different studies. Some studies have also incorporated soil organic carbon and nitrogen module from the CENTURY model in the DSSAT (Gijsman et al., 2002; Jones et al., 2003). In a study to investigate the shallow water table, Xu et al. (2012) found a link between SWAP and MODFLOW 2000 models for modeling groundwater dynamics.

In the current study, attempts have also been made to combine the Cropping System Model (CSM)-CERES-Maize and SWAP model to extend their applicability under different irrigation regimes. In contrast to its earlier versions, the new compound CERES-Maize model (hereafter, called CSM-CERES-Maize-hbased) works based on soil water potential. It benefits from the ability of SWAP model to simulate soil water content and reduction in root water uptake due to saline water stress and tiled drainage. It also exploits the ability of CERES-Maize model and the shared components of DSSAT in crop growth simulation. However, no other studies have been published about the combination of CERES-Maize model and one agrohydrological model, particularly the SWAP model. Hence, the present study aimed to link the CERES-Maize and the SWAP models and to compare their performances mostly in terms of biomass and yield simulation under different levels of water and nitrogen application in a semi-arid environment.

2. Materials and methods

The field site was located in the Agricultural Research Center in Varamin (Tehran Province, Iran). Its longitude, latitude, and elevation are 51°38′E, 35°20′N, and 973 m, respectively. Since the site contained clay loam soil (typical Torriorthents) and a groundwater level of less than 10 m, soil drainage was easily practicable. A 2-ha field was planted with the silage maize hybrid 704 single-cross during 2003 and 2004. The experimental treatments consisted of four different irrigation levels including two deficit irrigation levels (0.7 and 0.85 soil moisture depletion referred to as W1 and W2, respectively), a full irrigation level (1.0 soil moisture depletion, referred to as W3), and an over-irrigation level (1.13 soil moisture depletion, referred to as W4). Three nitrogen fertilizer levels containing 0, 150, and 200 kg/ha nitrogen (referred to as N0, N150, and N200, respectively) were also applied (Gheysari et al., 2009a).

Each treatment was planted in three replicates and data were collected from all plots over two years. Overall, 12 treatments were arranged in a strip-plot design using a randomized complete blocks design. Phenological indices such as leaf area index (LAI) and weight of biomass were measured during the maize growing season in 2003 and 2004. A leaf area meter was used to measure LAI at 25, 45, 58, and 70 days after planting (DAP) in 2003 and at 22, 34, 47, 63, and 80 DAP in 2004. Weight of biomass was determined at 25, 45, 58, 70, 90, and 98 DAP in 2003 and only at 34 and 87 DAP in 2004.

In 2004, a neutron probe was used to measure daily soil water content at the center of each plot, where a 2-m long polyvinyl chloride (PVC) access tube was installed. Detailed descriptions of field measurements have been presented by Gheysari et al. (2009a,b, 2015). The RETention Curve (RETC) computer program was used to obtain the soil–water characteristic curve and van-Genuchten coefficients based on soil moisture values under six different soil moisture potentials, from 0.01 to 1.5 MPa (Van Genuchten et al., 1991) (Table 1).

2.1. Evapotranspiration measurement

Measured crop evapotranspiration (ET_{ac}, mm/$(t_2 - t_1)$ days) was estimated by water balance approach for both years using the following equation:

$$ET_{ac} = I_n + BP - D + \int_0^Z \int_{t_1}^{t_2} \frac{\partial \bar{\theta}}{\partial t} \partial Z \partial t \quad (1)$$

where I_n (mm) is irrigation-water depth, BP is bulk precipitation (mm), D is deep percolation (mm), t is time (day), Z is soil depth and θ is soil water content ($m^3\,m^{-3}$). Deep percolation or percolation deeper than 60 cm was assumed to be negligible due to capillary rise and other effects. Using ET_{ac} measured in the field, crop coefficient was also estimated as the ratio of the actual ET to the reference crop evapotranspiration (ET_0):

$$K_C = \frac{ET_{ac}}{ET_0} \quad (2)$$