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Developing and normalizing average corn crop water production functions across years and locations using a system model

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ABSTRACT

Crop water production functions (CWPFs) are often expressed as crop yield vs. consumptive water use or irrigation water applied. CWPFs are helpful for optimizing management of limited water resources, but are site-specific and vary from year to year, especially when yield is expressed as a function of irrigation water applied. Designing limited irrigation practices requires deriving CWPFs from long-term field data to account for variation in precipitation and other climatic variables at a location. However, long-term field experimental data are seldom available. We developed location-specific (soil and climate) long-term averaged CWPFs for corn (*Zea mays* L.) using the Root Zone Water Quality Model (RZWQM2) and 20 years (1992–2011) of historical weather data from three counties of Colorado. Mean CWPFs as functions of crop evapotranspiration (*ET*), *ET* due to irrigation (ET_{a-d}), irrigation (*I*), and plant water supply (*PWS* = effective rainfall + plant available water in the soil profile at planting + applied irrigation) were developed for three soil types at each location. Normalization of the developed CWPF across soils and climates was also developed. A Cobb–Douglas type response function was used to explain the mean yield responses to applied irrigations and extend the CWPFs for drip, sprinkler and surface irrigation methods, respectively, assuming irrigation application efficiencies of 95, 85 and 55%, respectively. The CWPFs developed for corn, and other crops, are being used in an optimizer program for decision support in limited irrigation water management in Colorado.

1. Introduction

With increasing human population, the demand for fresh water for both urban consumption and crop production is increasing. Consequently, the water available for irrigation is declining while the demand for food is increasing. Providing crops with the right amount of water at the right time to optimize water productivity of food crops holds the key to addressing this challenge. Water is the most important natural resource limiting corn production in the semiarid Great Plains of USA (Halvorson et al., 2004). With competing demands for water (agriculture vs. urban needs), the practice of 'limited irrigation' is gaining attention in irrigated agriculture (Payero et al., 2006). In the evolving scenario, 'limited irrigation' is viewed as a system of managing water supply to impose periods of predetermined 'water stress' that can result in the most economic benefit for the water available (Klocke et al., 2004; Fereres and Soriano, 2007; Geerts and Raes, 2009).

Many experiments have shown that when other factors are not extremely limiting, the biomass produced and the water consumed (CWPF, crop water production function) by a given plant species are linearly related—this is often true of the grain yield as well (e.g., Briggs and Shantz, 1917; Stewart and Hagan, 1969, 1973; Hanks,

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1974, 1983). De Wit (1958) developed the first analytical approach to formalize the CWPF. Tanner and Sinclair (1983) presented a systematic analysis that provided a theoretical basis and confirmed the linear relationship for a given species in a given environment. Steduto et al. (2007) provide an excellent review and synthesis of the above studies and more recent developments on the crop biomass-water productivity relation.

It has been observed that when only water is limiting, grain yield response of most crops (CWPF) rises initially to a maximum then falls off with further application of water (Stewart and Hagan, 1973; Geerts and Raes, 2009). Hence, quantitative yield response to water available to the crop (soil water, effective rainfall and applied irrigation water) is required to predict yield when less than the maximum water requirement of the plant is available. Further, as water stress tolerance of crops varies considerably by soil and climate, specific CWPFs are prerequisites for planning and managing water needs and allocation during the crop growth period for analysis of economic outcomes (Martin et al., 1989; Geerts and Raes, 2009). For such applications, the CWPFs are normally used in computations of the potential grain yield that can be produced per unit of water consumed.

The measured CWPFs of crop yield vs. *ET* or irrigation may vary annually due to variation of weather factors (e.g., precipitation, temperature, and solar radiation, especially with the extremely high precipitation variability in the Great Plains). Therefore, for use in planning limited irrigation, we need CWPFs for yield vs. irrigation water that are averaged and take into account the risks over longer-term weather conditions. Such long-term average functions for irrigation, based on measured experimental data at a specific location are very expensive to obtain, and hence not readily available in the Great Plains. Comprehensive, process-oriented agricultural systems models provide a systems approach and a fast alternative method for extrapolating results from short-term experiments across long-term weather and soils (from one soil to another) (Hoogenboom et al., 1991; Ahuja et al., 2000; Saseendran et al., 2008). Once calibrated and tested for simulation of crop response for the climate and soil of the location, the models can be combined with soil and long-term weather data collected at the location to obtain the average CWPFs for crop yield vs. *ET* or consumptive water use for limited irrigation management. The actual irrigation water applied to meet the needed ET will vary with the irrigation method and its water application efficiency in the field. The CWPFs representing grain yield responses to irrigation can vary considerably from one soil to another soil and locations (Stewart and Hagan, 1973). Therefore, in order to make use of the CWPF developed using experimental data at one location across soils and climates in other locations (we designated this problem as 'normalization' of the CWPF) in the region, a scientifically sound procedure that makes use of the available information at the locations of interest needs also to be developed.

The objectives of this study were first to develop long-term average corn CWPFs for three different locations and three soil types at each location in eastern Colorado, USA using the calibrated and validated Root Zone Water and Quality Model (RZWQM2). The locations were Greeley, Weld County; Akron, Washington County, and Rocky Ford, Otero County in Colorado in the Central Great Plains of USA. The three locations were selected as they are spatially separated and had experimental data for model calibration. The perfect efficiency model results were then extended to three irrigation methods (drip, sprinkler and surface irrigation). A simple normalization method was tested on the nine average model CWPFs to explore their transferability across locations using minimum location-specific parameters (Maximum yield and maximum *ET*).

2. Materials and methods

2.1. RZWQM2 model

RZWQM2 is a process-oriented agricultural system model that was developed to simulate the impacts of water, tillage, crop residue, fertilizers, pesticides, and crop management practices on crop production and water quality (Ahuja et al., 2000; Ma et al., 2009). It contains the CSM-CERES-Maize v4.0 model for simulation of corn (Ma et al., 2005, 2006, 2009; Hoogenboom et al., 1991; Jones et al., 2003; http://arsagsoftware.ars.usda.gov/agsoftware/). Several studies tested the model on field research conducted in the Great Plains and extended the results for managing dryland and irrigated cropping systems (Ma et al., 2003; Saseendran et al., 2005, 2008, 2009). Recently, Saseendran et al. (2014) modified the water stress factor for processes related to photosynthesis (SURFAC) in RZWQM2-CERES using the daily potential root water uptake (TRWUP) calculated by the approach of Nimah and Hanks (1973) and accounted for stress due to additional heating of canopy from unused energy of potential evaporation. The modified water stress factor in RZWQM2 was found to be superior to other stress factors in simulations of grain yield, biomass and LAI in various experiments across soils and climates. The modified model was used for simulating yield responses to irrigation in this study.

Model inputs include weather (driving variables), soil physical and hydraulic parameters, crop and soil management information and soil initial conditions. RZWQM2 is a daily time-step model and the minimum weather variables needed for the simulations are daily solar irradiance, maximum and minimum temperature, wind speed, relative humidity (RH), and precipitation (as break point rainfall or water equivalent in the case of snowfall) representing the experimental location.

Soil physical properties required are: soil profile depth and horizons (layers); soil texture, bulk density, and organic matter content. Soil hydraulic properties required are: water retention curves and saturated hydraulic conductivity of each soil horizon represented in the form of the Brooks and Corey equations. Crop management data necessary are: tillage dates and methods; planting date, density, depth, and row spacing; and dates and amounts of irrigation; and amount and type of fertilizer applications. The model requires soil water, N, and carbon content by soil layer at the start of the simulation.

In the order of importance, experimental data needed for calibrating the model for simulating a crop cultivar are grain yield and biomass at maturity; crop biomass and leaf area index (LAI) at different growth stages; phenology dates, rooting depth and distribution in the profile; and frequent soil water content measurements. To simulate a specific corn hybrid, the CERES-maize 4.0 model requires six cultivar parameters (Jones et al., 2003).

Simulating cropping systems requires careful iterative calibration of the soil water component, followed by the nitrogen (N) component, and finally the plant growth component (CSM-CERES-Maize 4.0 model). If the simulation of crop growth at a calibration step is not satisfactory, the whole sequence of calibration is repeated to obtain more accurate simulations. In this study, RZWQM2 was calibrated manually following the comprehensive procedure laid out by Ma et al. (2011).

2.2. Site characteristics and experiments used in calibration and evaluation of RZWQM2

Data for calibration and evaluation of the model for simulating corn in the three counties of Colorado came from field experiments conducted near: (1) Greeley (40.45°N, 104.64°W, 1.43 km amsl), Weld county, (2) Rocky Ford (38.04°N, 103.70°W, 1.27 km amsl),