DISSERTATION

ENHANCEMENT OF AGRICULTURAL SYSTEMS MODELS FOR LIMITED IRRIGATED CROPPING SYSTEMS RESEARCH

Submitted by

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ABSTRACT

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Dwindling water supplies for irrigated crop production is the most limiting factor facing agriculture in the world today. In the evolving scenario, there is a need for making agricultural water use more efficient by bringing in up-to-date science based technologies in the irrigation field. In this context, crop water production functions (CWPFs, expressed as crop yield vs. consumptive water use or water applied) are helpful for optimal management of limited water resources for irrigation. However, they are site specific and vary from year to year, therefore for planning and managing limited irrigation, the CWPFs should be based on long-term field experiments to take into account the variations in precipitation and other climatic variables at the location. These problems can be addressed by using data from short term irrigation trials to calibrate and evaluate agricultural systems models that can subsequently be used for developing various irrigation water management strategies and thus extend the results across temporal and spatial dimensions. The primary objective this dissertation was to develop a methodology and use it to develop location (soil and climate) specific long-term averaged CWPFs for corn (*Zea mays* L) using available experimental data, long-term climate data, and a cropping system model, Root Zone Water Quality Model (RZWQM2), for various locations in the Great Plains of USA.

A paramount prerequisite for a system model to be qualified for such applications is its ability to accurately simulate crop responses to water deficit stresses (WS). In the RZWQM2, WS were calculated as the ratio of potential plant water uptake to potential transpiration to modify carbon assimilation (SWFAC) and leaf expansion (TURFAC) processes. Nonetheless,

inadequate simulations of crop responses to limited irrigations using these WS factors were reported.

To begin with, several ways of quantifying WS based on soil water measurements and their relationship with grain yield, biomass and canopy cover of corn, winter wheat (T*riticum aestivium* L.) and dry (pinto) bean (*Phaseolus vulgaris* L.) were investigated. There were six irrigation treatments for each crop, designed to meet 100 to 40% of potential crop ET (ETc) requirements during the growing season. Experiments were conducted from 2008 to 2011 near Greeley, Colorado in a sandy loam soil (LIRF, Limited irrigation Research Farm experiments). Water available for plant uptake (PAW, plant available water) and the maximum PAW (MAW) in the soil profile over the growing season were estimated from the soil water measurements. Daily tall reference crop ET (ETr) was calculated using Allen et al. (2005) method. Daily water deficit stress (WS) factors were calculated as ratios of (1) PAW to ETr (WSF1), (2) PAW to MAW (WSF2), and (3) WSF2 to ETr (WSF3). Average WSF1, WSF2 and WSF3 over the growing season were related to grain yield, biomass, and fraction canopy cover measurements. Results showed that in both experiments and simulations using RZWQM2 the responses of yield, biomass and canopy cover were explained most by WSF3, followed by WSF2 and WSF1.

However, accurate quantifications of the soil water based WS factors in RZWQM2 for simulation of specific crops will demand accurate measurements and specification of water in the root zone soil profile at planting, sometimes limiting its applications in experiments where these are not measured. Therefore, three additional WS factors (WSI1, WSI2 and WSI3) were developed as modifications of the default WS factors in the RZWQM2 using potential root water uptake (TRWUP) calculated by Nimah and Hanks (1973) approach and with accounting for stress due to heating of canopy from unused energy, when soil evaporation falls below the potential evaporation. These were incorporated in RZWQM2 and tested for simulation of corn in the LIRF experiments using CSM-CERES-Maize (v 4.0) module. Corn grain yield, biomass and leaf area index (LAI) data from the 1) LIRF experiments, 2) irrigated (1984 to 1986) and rainfed (1993 to 1997) experiments at Akron, Colorado (Akron experiments) and 3) two irrigation experiments in two contrasting soils (a sandy loam soil at, Zaragoza, Spain; and in a sandy soil at Gainesville, Florida, USA) distributed with DSSAT v4.5 were used for testing.

Simulations with the new stress factors showed that the simulations of crop responses to water can be substantially improved by incorporation of soil evaporation in both the supply and demand terms in the water stress quantifications in the model. Out of the three water stress factors tested, WSI2 was found to be better than others in simulations of corn grain yield, biomass and LAI. It was noteworthy, in the simulations with the WSI2 stress factor, that grain yield and biomass were improved simultaneously and the magnitudes of the errors were reasonable for model applications in water management. When WSI1 and WSI2 gave comparable grain yield simulations, WSI2 gave better accuracies in biomass and LAI as well. Superior simulations of RZWQM2 enhanced with WSI2 over other WS factors of corn under both rained and irrigated conditions at Akron, Colorado, USA; and two irrigation experiments in two contrasting soils, a sandy loam soil at, Zaragoza, Spain and a sandy soil at Gainesville, Florida, USA, verified the capability of the enhanced model for simulations across soils and climates.

Lastly, the RZWQM2 model was calibrated and validated for simulations of corn at two additional locations: Akron, Washington County and Rocky Ford, Otero County in Colorado, USA. Corn grain yield responses to different levels of irrigations at the three locations (Greeley, Akron and Rocky Ford) were simulated for multiple years, using available measured weather data (1993-2011) in RZWQM2. Mean CWPFs as functions of ET and applied water were developed for the soil types at the locations. 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 irrigations methods, assuming irrigation application efficiencies of 95, 85 and 55 %, respectively. The above procedure was repeated for a silt loam, clay loam and a sandy loam soil at the location to obtain soil-specific CWPFs. The CWPFs developed for corn are being used in an optimizer program to help farmers manage limited water for optimizing farm profitability in Colorado. Generalization of the developed CWPF across soils and climates was explored. We were able to generalize the CWPFs across the soils and locations through a linear relationship between relative grain yield (Y/Ymax) and relative ET (ET/ETmax). Linear relationships were found to exist between dryland ET (ETd) and PWS (plant water supply = effective precipitation + plant available water in the soil profile at planting), and relative dryland grain yield (Y/Ymax) and ETd. The estimated value of dryland yield and ETd also allowed us to develop the CWPFs for irrigation from knowledge of the long-term average fully irrigated maximum corn yield and the corresponding maximum ET and maximum irrigation. The method developed can be adapted for development of similar CWPFs for other crops of interest in different soils and climates across the world.

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DEDICATION

To my loving children, Vishnu and Durga, and my companion, Nirmala.

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CHAPTER I

GENERAL INTRODUCTION

AGRICULTURAL SYSTEM MODELS

Much of our detailed scientific knowledge of plant behavior has been reported in the special languages of various disciplines and published in scientific journals. At the same time, many scientists in the mid-to-late 20th century came to question the reductionist approach that sought to reduce complex systems to simple components. Scientists saw that it was necessary to synthesize, to a whole systems level, the quantitative knowledge obtained from numerous component experiments so that their research results could be transferable to other soils and climates. In this context, crop models were developed to effectively integrate and synthesize knowledge from different disciplines encompassing the plant, soil, water and atmosphere and simulate the impact of management and the environment on crop production (Ahuja et al., 2000). In general, system models quantify the interacting cycles of carbon, nutrients and water in the soil-plant-atmosphere continuum, making it possible to forecast the behavior of the system in response to changes in component variables and environmental factors. Crop models provide a vehicle for delivering our detailed knowledge on a systems level directly to users.

One hundred years ago, in the first issue of the Agronomy Journal (then known as the ‘Proceedings of the American Society of Agronomy), Lyon (1907) recognized and reported the intense influence of climate and soil on wheat (*Triticum aestivium* L) development and growth, and quality. This article probably was inspirational to many later researchers because it identified predictors and related them with prospective predictands in the system through statistical regression relationships (e.g., prediction of grain yield from weather information collected at climate stations). Regression relationships between yield of grain and straw in oats is an example of one of such earliest attempts to quantify relationships between different aspects of crop characteristics in variety trials in agronomy (Love, 1914; Hopkins, 1937). Crop modeling, starting with simple statistical relationships between crop yield and weather elements a century ago, has now developed into detailed dynamic simulations of most of the known physical, chemical, biological, biochemical and biophysical processes in the agricultural system and their response to management (Stockle et al., 1994; McCown et al., 1996; Ahuja et al., 2000; Stockle and Nelson, 2003; Jones et al., 2003). Advent of high speed computers and advances in computing technology are largely responsible for these explosive advances. The enormous amount of time and effort scientists invested in the simulation of agricultural systems is reflected in the number of models cited in review articles (Peart and Barrett, 1976; Hodges, 1982; Joyce and Kickert, 1987; Sinclair and Seligman, 1996; Anbumozhi et al., 2003). Today, system models are being used for decision support in agriculture in a variety of ways. Cultivar selection, water and nutrient input optimization, planting date selection, climate change impact analysis and water quality management are some of the promising areas of applications of the models in field level farm management (e.g., Lee et al., 1996; Haskett et al., 1995; Schomberg and Steiner, 1997; Ma et al., 1998; Franko and Mirschel, 2001; Mathews et al., 2002; Saseendran et al., 1998).

Early efforts for simulating crop growth required quantifying the factors that limited crop yields (D.N. Baker, personal communication). Particular emphasis focused on measuring environmental variables such as light, carbon dioxide and temperature at fine spatial and temporal scales. A few early papers in the Agronomy Journal laid out the theoretical background for measurement and analysis of solar radiation (Tanner and Lemon, 1962; Yocum et al., 1964; Sinclair and Lemon, 1974). In order to measure photosynthesis, Musgrave and Moss (1961) developed infrared gas analyzers to measure CO_2. The interest in building crop simulation models was an outcome of the ability to measure all the environmental and biological information that is needed to calculate accumulation of carbon by plants. Early research concentrated on light interception and photosynthesis.

Papers also began to address more complex processes in plants such as nitrogen dynamics and partitioning. Sinclair and deWitt (1976) found that an increase in photosynthesis in soybean (*Glycine max* L.) without increasing N supply will decrease seed yield because the additional fixed carbon will tie up available N to make leaves instead of seed. Carbon partitioning became of interest once scientists gained experience in simulating carbon assimilation (Goenaga and Irizarry, 1994; Vanderlip and Arkin, 1977). Vanderlip and Arkin (1977) developed a mechanistic partitioning method for sorghum that was related to substrate concentrations in the plant. They found that this increased the models' sensitivity to timing of events. This underlines the problems than can arise from interactions when the complexity of models increases.

Radcliffe et al. (1980) recognized the importance of the detailed description of distribution and movement of soil water in the root zone of crops for increasing the usefulness of models in watershed management, and in research on the transport of soil nutrients and pollutants. They developed a model that would calculate the infiltration, evaporation, transpiration, and deep drainage of soil water in the root zone of a corn (*Zea mays* L.) crop throughout a growing season, using readily obtainable climatic data as daily inputs. A mechanistic approach, similar to that used by Nimah and Hanks (1973), considered root distribution, hydraulic conductivities, plant resistance, and root-soil contact resistance. A characteristic of many of the models developed in this direction is the use of a potential limit due to genetics and the effect of environment to determine if that limit is reached.

Boote et al. (1980) conducted field experiments to determine canopy photosynthesis and characteristics of peanut foliage layers in response to leafspot, defoliation, and combinations of disease and defoliation. With this pioneering work, scientists started looking at simulating management effects using models (Tuleen et al., 1981; Fick, 1982). Other studies included weed interactions with soybean (Wilkerson et al., 1990), and yield responses to plant density in sorghum (Huda, 1988) and, tillage systems and winter wheat production (Davidoff et al., 1992). Retta et al. (1991) found that accurate estimates of parameters known to be affected by weeds and insect pests are important if a model is to be used for this purpose.

In Europe, the development of mechanistic process oriented models in plant biology began with the pioneering work of de Wit (1959) on quantitative relationships in the photosynthetic process, through development of a formula for calculation of photosynthesis of a closed crop surface. Further works to model light interception and photosynthesis in the plant canopies followed (e.g., de Wit, 1965; Duncan et al., 1967).

Several reviews of crop modeling exist (e.g., Peart and Barrett, 1976; Hodges, 1982; Joyce and Kickert, 1987; Sinclair and Seligman, 1996; Anbumozhi et al. 2003). Peart and Barret (1976) opined that crop ecosystem modeling was still in its early stages as of the mid-70's. They identified the Wageningen group of scientists lead by de Wit as pioneers with their first model of a grass crop, ELCROS (elementary crop simulator; de Wit and Gourdian, 1975). Sinclair and Seligman (1996) visualized the crop modeling science as being born in the 1960's, and has subsequently gone through the developmental stages of infancy, juvenility and maturity, similar to living organisms. In their opinion, the crop models in the infancy stage promised to provide a sound scientific surrogate for cumbersome field experimentation. In the following stages, the models gained more complexity and computation sophistication. Anbumozhi et al. (2003) in their presentation of the historical perspectives of crop simulation models, classified and grouped crop models into three generations. Component process models built from 1960 to 1980 belonged to the first generation, more comprehensive and complex models belonged to the second generation, and models with universality in their application belonged to the third generation crop models that emerged from 1990 onwards.

In general, before 1970s, many modeling works were devoted to building theories and equations of various individual processes of the agricultural system. The 1980s saw the beginning of the development of whole agricultural system models. Much of this work began at Wageningen, Netherlands. System models of added complexity and level of detail continue to develop in the 1990s and 2000s [e.g., SHOOTGRO (McMaster et al., 1991), DAISY (Hansen et al., 1990, 1991), ALMANAC (Kiniry et al., 1992), TOMGRO (Dayan et al., 1993), ORYZA (Kropff et al., 1994), OZCOT (Hearn, 1994), DSSAT (Jones et al., 2003), CropSyst (Stockle et al., 2003), WEPP (Flanagan and Nearing, 1995), MODWht3 (Rickman et al., 1996), APSIM (McCown et al., 1996), SWAT (Arnold et al., 1998), WAVES (Zhang and Dawes, 1998), FASSET (Jacobsen et al., 1998), Sirius (Jamieson et al., 1998), RZWQM (Ahuja et al., 2000), GPFARM (Shaffer et al., 2000), Hybrid-maize (Yang et al., 2004), PESTFATE (Bera et al., 2005), and InfoCrop (Aggarwal et al., 2006)].

Over the years, models grew in complexity, new applications were found, and the scope of applications widened. Models began to address carbon sequestration (e.g., Lee et al., 1996; Franko and Mirschel, 2001), global climate change (e.g., Saseendran et al., 2000; Tubiello et al., 2000; Chavas et al., 2009; Daccache et al., 2011; Ko et al., 2012; Islam et al., 2012), litter decomposition simulation for erosion prediction (e.g., Schomberg and Steiner, 1997; Ma et al., 1998). Research to fill knowledge gaps in our understanding of plant and soil processes has continued to the present providing much better insight into agricultural systems. More recently, the emphasis has been on applying crop models in more comprehensive systems. The goal has been to simulate the soil plant system and account for tillage effects, water availability, nutrient leaching, rotations and weed competition (Grenz et al., 2005; Saseendran et al., 2005a; Miao et al., 2006; Basso et al., 2010; Saseendran et al., 2010).

Quite a few studies also were focused on applying models for simulating water management effects in irrigated cropping systems. Using the SORKAM model, Baumhardt et al. (2007) showed that, when limited amount of water was available, sorghum yield was higher when irrigation was only applied to half or two-thirds of the field keeping the remaining rainfed in Texas, USA. Lyon et al. (2003) applied the APSIM model to evaluate best corn plant population with a given initial soil water content at planting in the semiarid climate of western Nebraska and recommended a plant population of 3 plants m^{-2} and initial soil moisture of 240 mm to reduce risk. Saseendran et al. (2008b) employed RZWQM2 model and 97 yr weather records to explore different options for optimal management of limited irrigation water for growing corn in the Central Great Plains. Optimum allocation of limited irrigation between vegetative and reproductive growth stages, along with optimum amount of N to apply, and optimum soil water depletion level for initiating limited irrigation, over the long term were developed. Fang et al. (2010) evaluated the RZWQM2 model for simulation of wheat (*Triticum aestivum* L.) and corn double cropping systems in the North China Plain (NCP), and combined it with long-term weather data (1962-1999) and investigated various irrigation strategies for high yield and water use efficiency (WUE). He et al. (2012) used the CERES-Maize model and developed irrigation and nitrogen best management practices (BMPs) for sweet corn production on sandy soils in Florida.

In the studies presented in this dissertation, the CSM-CERES-maize 4.0 model within the agricultural system model, RZWQM2 (Root Zone Water Quality Model; Ma et al., 2009) was used for simulation of corn. The RZWQM2 is process-oriented and combines the biological, physical and chemical processes for simulation of impacts of agro-management practices (tillage, water, agricultural chemical and crop) on crop production and water quality (Ahuja et al., 2000). Potential evapotranspiration in the soil-residue-canopy system is modeled using the 'extended Shuttleworth-Wallace ET model' (Farahani and Ahuja, 1996). Water infiltration is calculated with the Green-Ampt equation (Green and Ampt, 1911) and water redistribution is calculated by solving the Richards' equation (Ahuja et al., 2000). Soil hydraulic properties are estimated using the Brooks-Corey equation (Brooks and Corey, 1964). The OMNI computer program drives the organic matter/nitrogen cycling in RZWQM (Shaffer et al., 2000). RZWQM has a generic crop model that can be parameterized to simulate a specific crop (Hanson, 2000). In addition to a generic crop model that can be parameterized to simulate specific crops, it contains the CSM (Cropping System Models) crop modules of DSSAT 4.0 (Decision Support System for Agrotechnology Transfer; Ma et al., 2009; Hoogenboom et al., 1991; Jones et al., 2003) (http://arsagsoftware.ars.usda.gov/agsoftware/). A number of studies verifying the potential of applying RZWQM2 for managing dryland cropping systems in the Great Plains have been reported (e.g., Ma et al., 2003; Saseendran et al., 2004; 2005a; 2005b, 2008b, 2009). The CSM-CERES-Maize v 4.0 model which was originally distributed with DSSAT (Decision Support System for Agrotechnology Transfer) v4.0 cropping system package and as available for simulation of corn in RZWQM2 is a process oriented model that simulates phenological development of the crop; growth of leaves, stems and roots; biomass accumulation based on light interception and environmental stresses; and water and nitrogen uptake (Ritchie, 1998; Jones et al., 2003). Advantages of using RZWQM2 come from combining the detailed simulations of soil surface residue dynamics, tillage and other soil management practices, and detailed soil water and soil carbon/nitrogen processes of RZWQM with the detailed crop specific plant growth models of the DSSAT.

BACKGROUND AND SCOPE OF THE DISSERTATION

With the competing demands for water (agriculture vs. urban needs) as well as grains (food vs. fuel) in the semiarid Great Plains region of USA, the practice of 'limited irrigation' is gaining importance in irrigated agriculture. 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 some economic benefit (Schneekloth et al., 1991, 2001; Klocke et al. 2004; Hergert, 2010). However, it has been observed that when water only is limiting, grain yield response of most of the crops 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) or the complete crop water production functions (CWPF) are required to predict yield when less than the maximum water requirement of the plant is applied. In this context, CWPF are critical for management decisions in limited water irrigation. The CWPF are expressed as crop yield vs. consumptive water use or water applied. As water stress tolerance of crops varies considerably by genotype, robust crop, soil and climate specific CWPF are pre-requisites for planning and managing water needs and allocation of water during the crop growth period, and for analysis of economic outcomes (Martin et al., 1989; Geerts and Raes, 2009).

The measured CWPF of crop yield vs. ET or irrigation may vary from year to year due to the observed wide variations in the severity and timing of the water and other biotic and abiotic stresses controlled by location specific climate variability characteristics, especially when yield is expressed as a function of irrigation water applied. The actual irrigation water applied to meet the needed irrigation water will also vary with the method of irrigation, with its water application efficiency in the field. As such, like any other agro-management practice, the transfer of location specific limited irrigation technologies across locations has been confronted with practical difficulties owing to different precipitation regimes, soils and landscapes (Hergert, 2010). Therefore, for use in planning limited irrigation, location specific CWPF of yield vs. irrigation water needed that are averaged over longer term weather conditions are prerequisites. Such long-term average CWPF, based on measured experimental data at a specific location are very expensive to obtain, and hence not readily available in the Great Plains. In this context, Martin et al. (1984, 2010) used a simple crop model based on a soil water balance procedure and long-term weather data to develop long-term average CWPFs for average expected relative yield estimates as functions of T or ET, for different crops and soil types in Nebraska, USA. Klocke et al. (2006) developed a 'Crop Water Allocator', also a water balance based model for limited irrigation on a farm, in which yield for crops were estimated from relationships with irrigation amount for annual rainfall and silt loam soils with loess origins derived from research in the High Plains of western Kansas.

In this perspective, comprehensive process oriented agricultural systems models provide a systems approach and a fast alternative method for extrapolating short-term experiments across climates and soils (Hoogenboom et al., 1991; Ahuja et al., 2000; Saseendran et al., 2008b). Once calibrated and tested for simulation of crop responses in the climate and soil of a location, the model can be combined with soil and long-term weather data collected at the location to obtain the average CWPFs for crop yield vs. needed irrigation water for limited irrigation management. So, there is a need for developing a methodology for developing robust soil and climate (location) specific long-term averaged CWPF for various crops and irrigation methods using the limited available experimental data, long-term climate data, and a detailed agricultural system model (e.g., RZWQM2). Nevertheless, adequacy of agricultural system models for limited irrigation water management depends upon how accurately they simulate the imposed soil water stresses due to limited water application and their impact on crop growth and yield.

Water stress decreases plant growth primarily by reducing cell division and expansion growth. Other known processes modulated by water stress are plant developmental rates, leaf initiation, photosynthesis, carbon allocation and partitioning, and root length and density in soil layers resulting in reduced biomass and grain yield (Passioura, 1994; Saini and Lalonde, 1998; Chaves et al., 2002; Saseendran et al., 2008a). Primarily, plants experience water stress when water supply in the soil fails to meet the evapotranspiration demand. Notwithstanding, quantification and representation of a 'water stress factor' in crop models have been a challenge in system modeling (Ritchie, 1981; Saseendran et al., 2008a). Ritchie (1981) analyzed practical difficulties in using several plant parameters (stomatal conductance and leaf water potential) as 'water stress factors' in the system models, and felt that the empirical quantifications of crop growth and development processes as related to the soil water deficits such as fraction of plant available water in the root zone of the crop as a viable option but difficult to simulate accurately.

In general, water stress effects are accomplished in the current cropping system models by describing a ‘water stress factor’ to modify other simulated plant growth and development processes. The RZWQM2 uses the water stress functions of DSSAT based on the ratio of potential root water uptake (TRWUP) to potential transpiration (EP_o) to represent water stress for modulating dry matter synthesis and expansion growth in crop simulations (Ritchie, 1998). Under well-watered conditions, TRWUP is higher than EP_o and there is no water stress. As the soil dries out due to root water uptake, TRWUP decreases. At a certain stage, a threshold is reached where the first WS factor or turgor factor to modulate expansive leaf growth, called TURFAC, is activated. In both C3 and C4 plants, this point corresponds to the situation when the root water uptake combined with osmotic adjustments and wall extension in plant leaf cells (meristematic) fail to maintain enough turgor pressure to sustain expansion and cell division (mitosis) growth (Boyer, 1970; Cosgrove and Cleland, 1983; Cosgrove, 1998). The TURFAC is defined as:

$$TURFAC = \frac{TRWUP}{RWUEP1 * EPo} \quad \text{............ (1)}$$

where, *RWUEP*1 is a species-specific parameter, used for emulating the water level in the plants below which turgor pressure in the plant leaves fail to sustain expansion growth at the potential level, which is currently set to 1.5 for corn.

When *EPo* demand equals or exceeds the TRWUP, a second stress factor, called *SWFAC,* is activated :

$$SWFAC = \frac{TRWUP}{EPo} \quad \text{............ (2)}$$

SWFAC mainly affects photosynthesis and other dry matter assimilation related processes. In plants, this stress sets in at a leaf water potential level, which is significantly below the TURFAC level, when the photosynthesis and other carbon assimilation processes get compromised due to water shortage. Reduction in photosynthesis can occur mainly due to stomatal closure but also from photoinhibition and reduction in metabolic potential to a lesser extent in C3 plants (Boyer, 1970: Chaves et al., 2009). Reduction in photosynthesis due to stomatal closure is more complex in C4 plants due to the initial CO_2 concentration mechanism in operation in the mesophyll cells that are physically separated from the site of actual carbon fixation in the Calvin cycle (common to both C3 and C4 plants) located in the bundle-sheath cells. However, water stress effects on carbon fixation other than the direct effects of stomatal conductance (i.e. effects on metabolic potential and photoinhibition) are common for both C3 and C4 crops (Chaves et al., 2009; Ghannoum, 2009). In the model, for both C3 and C4 crops, both stress factors are used as a direct multiplier on growth or dry matter accumulation rate that ranges from 1 for no stress to 0 for complete stress.

Inadequate crop growth simulations and the need for enhancing the water stress quantifications in CERES-Maize model (in DSSAT and RZWQM2) have been reported in the literature (Castrignano et al., 1998; Nouna et al., 2000; Faria and Bowen, 2003; Sau et al., 2004; Saseendran et al., 2008a). In 2008, a field study was initiated at the limited irrigation research farm (LIRF) at Greely in the Great Plains of Colorado, USA to collect information on response of commonly grown crops [winter wheat, field corn, oil-type sunflower (*Helianthus annuus* L.), and dry (pinto) beans (*Phaseolus vulgaris* L.)] to limited irrigation (Trout et al., 2010; Bausch et al., 2011; McMaster et al., 2012). A wide range of irrigation levels from fully irrigated (100% of ET demands) to about 40% of full irrigation is being tested. The data collected are useful to evolve deficit irrigation practices for optimum yields, and also to develop effective stress factors for improved simulation of crop response to water in RZWQM2 and extension of results across soils and climates in the region.

OBJECTIVES

(1) Quantify crop water stress factors in limited irrigation experiments under corn, winter wheat and dry beans at Greeley, Colorado (LIRF).

(2) Study the impacts of the above stress factors in RZWQM2 for simulations of corn in the LIRF experiments.

(3) Apply the calibrated and evaluated RZWQM2 model with the best stress factor for development of crop water production functions for corn.

DISSERTATION ORGANIZATION

In this dissertation, three manuscripts either submitted or intended for submission to peer reviewed journals are presented. The three manuscripts address the three objectives presented above.

In Chapter I, a general introduction and review of crop modeling science and water stress quantifications in current agricultural system models are presented.

In Chapter II, quantification of crop water stress factors in limited irrigation experiments under corn, winter wheat and dry beans are presented. Impacts of the stress factors in simulation of corn using CSM-CERES-Maize in RZWQM2 are also presented.

In Chapter III, formulation and impacts of three non-soil water based stress factors in simulation of corn using the CSM-CERES-Maize model in RZWQM2 are presented.

In Chapter IV, development of crop water production functions using the model developed in Chapter III is presented.

In Chapter V, a summary of all the major conclusions obtained from the three journal manuscripts presented in the dissertation (Chapters II, III and IV) are highlighted followed by my vision for future works needed for improving agricultural system models for limited irrigation management applications.

REFERENCES

Aggarwal, P.K., N. Kalra, S. Chander, and H. Pathak. 2006. InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. Agricultural Systems 89:1–25.

Ahuja, L.R., K.W. Rojas, J.D. Hanson, M.J. Shaffer, and L. Ma. (ed.). 2000. Root Zone Water Quality Model. Water Resources Publication, Englewood, CO. p2-360.

Anbumozhi, V., V.R. Reddy, Y.C. Lu, and E. Yamaji. 2003. The role of crop simulation models in agricultural research and development: A review. Agricultural Engineering Journal 12:2-18.

Arnold, J. G., R. Srinavasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. J. American Water Resources Assoc. 34:74-89.

Basso, B., D. Cammarano, A. Troccoli, D. Chen, and J.T. Ritchie. 2010. Long-term wheat response to nitrogen in a rainfed Mediterranean environment: Field data and simulation analysis. European Journal of Agronomy 33:133-138.

Baumhardt, R.L., J.A. Tolk, T.A. Howell, and W.D. Rosenthal. 2007. Sorghum management practices suited to varying irrigation strategies, a simulation analysis. Agron. J. 99:665-672.

Bausch, W., T. Trout, and G. Buchleiter. 2011. Evapotranspiration adjustments for deficit-irrigated corn using canopy temperature: a concept. Irrig. and Drain. 60: 682–693.

Bera, P., S. O. Prasher, A. Madani, J. D. Gaynor, C. S. Tan, R. M. Patel, and S. H. Kim. 2005. Development and field validation of the PESTFATE model in Southern Ontario. Transactions of the ASAE 48: 85−100.

Boote, K. J., J. W., Jones, G. H. Simerage, C. S. Barfield, and R. D. Berger. 1980. Photosynthesis of peanut canopies as affected by leaf spot and artificial defoliation. Agron. J. 72:247-252.

Boyer, J.S. 1970. Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiol. 46:234-235.

Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. Hydrology Paper No. 3, Colorado State Univ., Fort Collins.

Castrignano, A., N. Katerji, F. Karam, M. Mastrorilli, and A. Hamdy. 1998. A modified version of CERES-Maize model for predicting crop response to salinity stress. Ecological Modeling 111:107–120.

Chavas, D.R., R.C. Izaurralde, A.M. Thomson, and X. Gao. 2009. Long-term climate change impacts on agricultural productivity in eastern China. Agricultural and Forest Meteorol. 149:1118–1128.

Chaves, M.M., J.S. Pereira, J. Maroco, M.L. Rodrigues, C.P.P. Ricardo, M.L. Osorio, I. Carvalho, T. Raria, and C. Pinheiro. 2002. How plants cope with water stress in the field? Photosynthesis and growth. Annals of Botany 89:907-916.

Chaves, M.M, J. Flexas, and C. Pinheiro. 2009. Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. Annals of Botany 103: 551–560.

Cosgrove D.J. 1998. Cell wall loosening by expansins. Plant Physiology 118**:** 333–339.

Cosgrove, D.J., and R.E. Cleland. 1983. Solutes in the free space of growing stem tissues. Plant Physiology 72**:** 326–331.

Daccache, A., E.K. Weatherhead, M.A. Stalham, and J.W. Knox. 2011. Impacts of climate change on irrigated potato production in a humid climate. Agricultural and Forest Meteorology 151:1641– 1653.

Davidoff, B., W. W. Wilhelm, and J. Skopp. 1992. Simulating winter wheat production in three tillage systems using the nitrogen tillage residue management model. Agron. J. 84:516-523.

Dayan, E., H. van Keulen, J.W. Jones, I. Zipori, D. Shmuel, and H. Challa. 1993. Development, calibration and validation of a greenhouse tomato growth model: I. Description of the model. Agricultural Systems 43: 145-163.

de Wit, C.T. 1959. Potential photosynthesis of crop surfaces. Netherlands Journal of Agricultural Sciences 7:142-149.

de Wit, C.T. 1965. Photosynthesis of leaf canopies. Inst. Biol. Chem. Res. Field Crops Herb. Agric. Res. Rep. 663. Wageningen, The Netherlands.

de Wit, C.T., and J. Gourdian. 1975. Simulation of ecological processes. PUDOC – Centre for Agricultural Publishing and Documentation. Wageningen, The Netherlands.

Duncan, W.G., R.S. Loomis, W.A. Williams, and R. Hanau. 1967. A model for simulating photosynthesis in plant communities. Hilgardia 38: 182-205.

Fang, Q., L. Ma, Q. Yu, L.R. Ahuja, R.W. Malone, and G. Hoogenboom. 2010. Irrigation strategies to improve the water use efficiency of wheat–maize double cropping systems in North China Plain. Agricultural Water Management 97:1165–1174.

Farahani, H.J., and L.R. Ahuja. 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Trans. ASAE 39:2052-2064.

Faria, R. T., and Bowen, W. T. 2003. Evaluation of DSSAT soil-water balance module under cropped and bare soil conditions. Brazilian Archives of Biology and Technology 46 (4): pp. 489-498.

Fick, G.W. 1982. Simulating alfalfa weevil effects by defoliation. Agron. J. 74: 5: 835-840.

Flanagan, D. C., and M. A. Nearing (ed.). 1995. USDA−water erosion prediction project: Hill slope profile and watershed model documentation. NSERL Report No. 10. West Lafayette, Ind.: USDA−ARS−NSERL.

Franko, U., and E. Mirschel. 2001. Integration of a crop growth model with a model of soil dynamics. Agron. J. 93: 666–670.

Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96: 1275–1284.

Goenaga, R. J., and H. Irizarry. 1994. Accumulation and partitioning of dry matter in water yam. Agron. J. 86: 1084-1087.

Ghannoum, O. 2009. C4 Photosynthesis and water stress. Annals of Botany 103:635-644.

Green, W.H., and G.A. Ampt. 1911. Studies on soil physics. 1. Flow of air and water through soils. J. Agr. Sci. 4:2-24.

Grenz, J.H., A.M. Manschadi, P. DeVoil, H. Meinke, and J. Sauerborn. 2005. Assessing strategies for orobanche sp. control using a combined seedbank and competition model. Agron. J. 97:1551–1559.

Hansen, S., H.E. Jensen, N.E. Nielsen, and H. Svendsen. 1990. DAISY — Soil plant atmosphere system model. Miljøstyrelsen, Copenhagen Report No. A10.

Hansen, S., H.E. Jensen, N.E. Nielsen, and H. Svendsen. 1991. Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. Fert. Res. 27:245–259.

Hanson, J.D. 2000. Generic plant production. p. 82-118. *In* L.R. Ahuja, K.W. Rojas, J.D. Hanson, M.J. Shafer, and L. Ma. (ed.). Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resources Publications, LLC, Highlands Ranch, CO.

Haskett, J. D., Y. A. Pachepsky, and B. Acock. 1995. Estimation of soybean yields at county and state levels using GLYCIM: A case study for Iowa. Agron. J. 87:926–931.

He, J., M. D. Dukes, G.J. Hochmuth, J. W. Jones, and W. D. Graham. 2012. Identifying irrigation and nitrogen best management practices for sweet corn production on sandy soils using CERES-Maize model. Agricultural Water Management 109: 61–70.

Hearn, A.B. 1994. OZCOT: A Simulation model for cotton crop management. Agricultural Systems 44:257-299.

Hergert, G. W. 2010. Limited irrigation of conventional and biofuel crops. Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney, NE., February 24-25, 2010. Available from CPIA, 760 N. Thompson, Colby, Kansas.

Hodges, T. 1982. Second generation crop yield models review. Missouri University, Columbia. Lyndon B. Johnson Space Center. Houston, Texas p2-33.

Hoogenboom, G., J.W. Jones, and K.J. Boote. 1991. A decision support system for prediction of crop yield, evapotranspiration, and irrigation management. In: Proc. 1991 Irrig. and Drainage. ASCE, Reston, VA, pp. 198–204.

Hopkins, J.W. 1937. Agricultural meteorology and crop forecasting in Western Canada. Journal American Society of Agronomy 30(4): 314-322.

Huda, A.K.S. 1988. Simulating growth and yield responses of sorghum to changes in plant density. Agron. J. 80: 542-547.

Islam, A., L.R. Ahuja, L.A. Garcia, L. Ma, S.A. Saseendran, and T.J. Trout. 2012. Modeling the impacts of climate change on irrigated corn production in the Central Great Plains. Agricultural Water Management 110:94–108.

Jacobsen, B.H., J.E. Olesen, B.M. Petersen, J. Berntsen, and C. Boye. 1998. FASSET—a dynamic whole farm simulation model. p.23-89. *In*: van Keulen, H., Lantinga, E.A., van Laar, H.H. (ed.) Proceedings of an International Workshop on Mixed Farming Systems in Europe, Dronten/Wageningen, The Netherlands, 25–28 May. Ir. A.P.

Jamieson, P.D., M.A. Semenov, I.R. Brooking, and G.S. Francis. 1998. Sirius: a mechanistic model of wheat response to environmental variation. Euro. J. Agron. 8:161–179.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping system model. Europ. J. Agron. 18:235-265.

Joyce, L. A., and R. N. Kickert. 1987. Applied plant growth models for grazing lands, forests, and crops. p142-156 *In* Wisiol, K., and J. D. Hesketh (Eds.). Plant growth modeling for resource management: current models and methods. Boca Raton: CRC Press.

Kiniry, J.R., R.R. Williams, P.W. Gassman, and P. Debaeke. 1992. A general process oriented model for two competing plant species. Transactions of the ASAE 35:802-810.

Klocke, N.L., J.P. Schneekloth, S.R. Melvin, R.T. Clark, and J.O. Payero. 2004. Field scale limited irrigation scenarios for water policy strategies. Applied Engineering in Agriculture 20: 624-631.

Klocke, N.L., L. R. Stone, G. A. Clark, T. J. Dumler, and S. Briggeman. 2006. Water allocation model for limited irrigation. Applied Engineering in Agriculture 22:382-389.

Ko, J., L.R. Ahuja, S.A. Saseendran, T.R. Green, L. Ma, D.C. Nielsen, and C.L. Walthall. 2012. Climate change impacts on dryland cropping systems in the Central Great Plains, USA. Climatic Change 111:445–472.

Kropff, M.J., H.H. Van Laar, and R.B. Matthews. 1994. ORYZA1: an ecophysiological model for irrigated rice production. SARP Research Proceedings. DLO-Research Institute for Agrobiology and Soil Fertility, Wageningen, WAU-Department of Theoretical Production Ecology, Wageningen and International Rice Research Institute, Los Banos, Philippines.

Lee, J.J., D.L. Phillips, and R.F. Dodson. 1996. Sensitivity of the U.S. Corn Belt to climate change and elevated CO_2: II. Soil erosion and organic carbon. Agricultural Systems 52: 504-521.

Love, H.H. 1914. Relation of yield of straw and grain in oats. Journal American Society of Agronomy 6: 97-108.

Lyon, D.J., G.L. Hammer, G.B. McLean, and J.M. Blumenthal. 2003. Simulation supplements field studies to determine no-till dryland corn population recommendations for semiarid western Nebraska. Agron. J. 95:884–891.

Lyon, T.L. 1907. The relation of wheat to climate and soil. Journal American Society of Agronomy 1: 108-125.

Ma, L., G. Hoogenboom, S. A. Saseendran, P. N. S. Bartling, L. R. Ahuja, and T. R. Green. 2009. Estimates of soil hydraulic properties and root growth factor on soil water balance and crop production. Agron. J. 101:572–583.

Ma, L., D.C. Nielsen, L.R. Ahuja, R.W. Malone, S.A. Saseendran, K.W. Rojas, J.D. Hanson, J.G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. Trans. ASAE 46:39-49.

Ma, L., M. J. Shaffer, J. K. Boyd, R. Waskom, L. R. Ahuja, K. W. Rojas, and C. Xu. 1998. Manure management in an irrigated silage corn field: experiment and modeling. Soil Sci. Soc. Am. J.62:1006-1017.

Martin, D. L., D.G. Watts, and J.R. Gilley. 1984. Model and production function for irrigation management. J. Irrig. and Drain. ASCE 110:149-164.

Martin, D.L., J. R. Gilley, and R.J. Supalla. 1989. Evaluation of irrigation planning decisions. Journal of Irrigation and Drainage Engineering 115: 58-77.

Martin, D.L., R.J. Supalla, C.L. Thompson, B.P. McMullen, G.W. Hergert, and P. A. Burgener. 2010. Advances in deficit irrigation management. Paper Number: IRR10-9277. ASABE Conference Presentation**.** 5th National Decennial Irrigation Conference Sponsored jointly by ASABE and the Irrigation Association Phoenix Convention Center Phoenix, Arizona. 10p.

Mathews, R., W. Stephens, T. Hess, T. Middleton, and A. Graves. 2002. Applications of crop/soil simulation models in tropical agricultural systems. Adv. Agron. 76:32-124.

McCown, R.L., G.L. Hammer, J.N.G. Hargreaves, D.L. Holzworth, and D.M. Freebairn. 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research. Agric. Syst. 50: 255-271.

McMaster, G.S., B. Klepper, R.W. Rickman, W.W. Wilhelm, and W.O. Willis. 1991. Simulation of aboveground vegetative development and growth of unstressed winter wheat. Ecological Model. 53:189-204.

McMaster, G.S., G.W. Buchleiter, and W.C. Bausch. 2012. Relationships between Sunflower Plant Spacing and Yield: Importance of Uniformity in Spacing. Crop Sci. 52:309–319,

Miao, Y., D. J. Mulla, W.D. Batchelor, J.O. Paz, P.C. Robert, and M. Wiebers. 2006. Evaluating Management Zone Optimal Nitrogen Rates with a Crop Growth Model. Agron. J. 98:545–553.

Musgrave, R.B., and D.N. Moss. 1961. Photosynthesis under field conditions. I. A portable closed system for determining net assimilation and respiration of corn. Crop Sci. 1:37-41.

Nimah, M.N., and R.J. Hanks. 1973. Model for estimating soil water, plant and atmospheric inter relations: I. description and sensitivity. Proceedings Soil Sci. Soc. of America 37:523-527.

Nouna, B.B., N. Katerji, and M. Mastrorilli. 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance. Europ. J. Agron. 13:309–322.

Passioura, J.B. 1994. The yield of crops in relation to drought. p. 344-359. *In* K.J. Boote (ed.) Physiology and determination of crop yield. Madison, Wisconsin, USA. ASA, CSSA, SSSA.

Peart, R. M., and J. R. Barrett. 1976. Simulation of crop ecosystem management. Winter Simulation Conference. Dec 6 – 8 1976. 1:389-401.

Radcliffe, D., R. Hayden, K. Watson, P. Crowley, and R.E. Phillips. 1980. Simulation of soil water within the root zone of a corn crop. Agron. J. 72:19-24.

Retta A, R.L. Vanaderlip. R.A., Higgins. L.J. Moshier, and A. M. Feyerherm. 1991. Suitability of corn growth models for incorporation of weed and insect stresses. Agron J 83:757-765.

Rickman, R.W., S.E. Waldman, and B. Klepper. 1996. MODWht3: A Development-Driven Wheat Growth Simulation. Agron. J . 88:176-185.

Ritchie, J.T. 1981. Water dynamics in the soil-plant-atmosphere system. Plant and Soil 58: 82-96.

Ritchie, J. T. 1998. Soil water balance and plant water stress. p. 42-54. *In* G. Y. Tsuji, G. Hoogenboom, and P. K. Thornton (Eds.). Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Saini, H.S. and S. Lalonde. 1998. Injuries to reproductive development under drought stress, and their consequences for crop productivity. p. 224-248. *In* A.S. Basra (ed.) Crop Sciences: Recent Advances. The Food Products Press, New York, London.

Saseendran, .S. A, K.K. Singh, L.S. Rathore, S.V. Singh, and S.K. Sinha. 2000. Effects of climate change on rice production in Kerala. International journal of climatic change 44: 495-514.

Saseendran, S. A., D.C. Nielsen, L. Ma, L.R. Ahuja, M.F. Vigil, and A.D. Halvorson. 2005a. Effectiveness of RZWQM for simulating alternative Great Plains cropping systems. Agron. J. 97:1183–1193.

Saseendran, S. A., K.G. Hubbard, K.K. Singh, N. Mendiratta, L.S. Rathore, and S.V. Singh. 1998. Optimum transplanting dates for rice in Kerala, India, determined using both CERES v3.0 and ClimProb. Agron. J. 90:185-190.

Saseendran, S. A., L. Ma, D. C. Nielsen, M. F. Vigil, and L. R. Ahuja. 2005b. Simulating planting date effects on corn production using RZWQM and CERES-Maize models. Agron. J. 97:58–71.

Saseendran, S. A., L. R. Ahuja, D. C. Nielsen, T. J. Trout, and L. Ma. 2008b. Use of crop simulation models to evaluate limited irrigation management options for corn in a semiarid environment, Water Resour. Res. 44, W00E02, doi:10.1029/2007WR006181.

Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, and M.F. Vigil. 2010. Simulating alternative dryland rotational cropping systems in the Central Great Plains with RZWQM2. J. Agron. 102:1521–1534.

Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-Wheat. Agron. J. 96:615–630.

Saseendran, S.A., D.C. Nielsen, D. Lyon, L. Ma, D.G. Felter, D.D. Baltensperger, G. Hoogenboom, and L.R. Ahuja,. 2009. Modeling responses of dryland spring triticale, proso millet, and foxtail millet to initial soil water in the High Plains. Field Crops Res. 113:48-63.

Saseendran, S.A., L.R. Ahuja, L. Ma, D.J. Timlin, C.O. Stockle, K.J. Boote, and G. Hoogenboom. 2008a. Current Water Deficit Stress Simulations in Selected Agricultural System Simulation Models. p.2-38. *In* L. R. Ahuja, V.R. Reddy, S.A. Sasendran, and Q. Yu (ed.) Response of crops to limited water: Understanding and modeling water stress effects on plant growth processes, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, USA.

Sau, F., K. J. Boote, W. M. Bostick, J. W. Jones, and M. I. Minguez. 2004. Testing and improving evapotranspiration and soil water balance of the DSSAT crop models. Agron. J. 96: 1244-1257.

Schneekloth, J.P., N.L. Klocke, G.W. Hergert, D.L. Martin, and R.T. Clark. 1991. Crop rotations with full and limited irrigation and dryland management. Transactions of the ASAE 34: 2373-2380.

Schneekloth, J.P., N.A. Norton, R.T. Clark and N.L. Klocke. 2001. Irrigating for maximum economic return with limited water. Univ. NE NebGuide G02-1422.

Schomberg, H.M., and J.L. Steiner. 1997. Comparison of residue decomposition models used in erosion prediction. Agron. J. 89:912-919.

Shaffer, M.J., K.W. Rojas, D.G. DeCoursey, and C.S. Hebson. 2000. Nutrient chemistry process-OMNI. p.119-144. *In* L.R. Ahuja, K.W. Rojas, J.D. Hanson, M.J. Shafer, and L. Ma (eds.). Root Zone Water Quality Model. Modelling management effects on water quality and crop production. Water Resources Publications, LLC, Highlands Ranch, CO.

Sinclair, T.R., and C.T. de Wit. 1976. Analysis of the carbon and nitrogen limitations to soybean yield. Agron. J. 68:319–324.

Sinclair, T.R., and E.R. Lemon. 1974. Penetration of photosynthetically active radiation in corn canopies. Agron. J. 66:202-205.

Sinclair, T.R., and N.G. Seligman. 1996. Crop modeling: from infancy to maturity. Agron. J. 88: 698-704.

Stewart, J.I., and M. Hagan. 1973. Functions to predict effects of crop water deficits. Journal of the irrigation and drainage division 99: 422-439.

Stockle, C.O., M.D., and R. Nelson. 2003. CropSyst, a cropping systems simulation model. Europ. J. Agronomy 18: 289-307.

Stockle, C.O., S.A. Martin., and G.S. Campbell. 1994. CropSyst, a cropping systems simulation model: Water/Nitrogen budgets and crop yield. Agricultural Systems 46: 335-359.

Tanner, C.B., and E.R. Lemon. 1962. Radiant energy used in evapotranspiration. Agron. J. 54:207-212.

Trout, T.J., W.C. Bausch, and G.W. Buchleiter. 2010. Water production functions for Central Plains Crops. An ASABE Conference Presentation. Paper Number: IRR10-9654. 5th National Decennial Irrigation CD-ROM Proceedings. ASABE Publication Number 711P0810cd. P8.

Tubiello, F.N., M.C. Donatelli, C. Rosenzweig, C.O. Stockle. 2000. Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations. European J. Agronomy 13:179-189.

Tuleen, D.M., and R.A. Frederiksen. 1981. A crop loss model for sorghum downy mildew. (Abstr.). Phytopathology 71:909.

Vanderlip, R.L., and G.F. Arkin. 1977. Simulating accumulation and distribution of dry matter in grain sorghum. Agron. J. 69:917-923.

Wilkerson, G.G., J.W. Jones, H.D. Coble, and J.L. Gunsolus. 1990. SOYWEED: A simulation model of soybean and common Cocklebur growth and competition. Agron. J. 82:1004-1010.

Yang, H.S., A. Dobermann, J.L. Lindquist, D.T. Walters,T.J. Arkebauer, and K.G. Cassman. 2004. Hybrid-maize—a maize simulation model that combines two crop modeling approaches. Field Crops Research 87:131–154.

Yocum, C.S., L.H. Allen, and E.R. Lemon. 1964. Photosynthesis under field conditions. VI. Solar radiation balance and photosynthetic efficiency. Agron. J. 56:249-253.

Zhang, L., and W. Dawes. 1998. WAVES—An integrated energy and water balance model. (CSIRO Land and Water Technical Report No. 31/98).

CHAPTER II

QUANTIFYING CROP WATER STRESS FACTORS FROM SOIL WATER MEASUREMENTS IN A LIMITED IRRIGATION EXPERIMENT*

INTRODUCTION

With competing demands for fresh water from various sectors of the burgeoning human enterprises, increasing productivity of the water allocated for irrigation is inevitable for sustained food security on the earth. The United Nations, Food and Agricultural Organization calls for all-around efforts from scientists for increasing water use efficiency (WUE) in irrigated agriculture (FAO, 2002) for a hunger free world. Owing to our inadequate understanding of the molecular mechanisms regulating WUE in plants, little advances have been made, so far, through the traditional genetic approaches to modify WUE in crop plants (Pascale, 2011). In the current state of affairs, there is a need and possibility for making agriculture water use less wasteful and more efficient through enhancing and applying the existing irrigation science and technologies (Hsiao et al., 2007). Being aware of the evolving pressure to conserve water in irrigated agriculture, especially in semiarid environments, considerable research is already being conducted to see if we can enhance WUE through the implementation of 'limited irrigation' water management practices for various crops in the Great Plains of the USA (Hergert et al, 1993; Schneekloth et al., 1991, 2001; Klocke et al. 2004; Hergert, 2010). Like any other agro-

*Author names for paper to be submitted: Saseendran, S.A., T.J. Trout, L.R. Ahuja, L. Ma, G. S. McMaster, D. C. Nielsen, A. A. Andales, J. L. Chávez, and J.M. Ham management practice, the transfer of the developed location-specific short-term limited irrigation technologies across locations has been confronted with practical difficulties owing to different precipitation regimes, soils and landscapes (Hergert, 2010).

Field experiments that encompass all the multi-year and multi-location variability in climate and soils are practically unfeasible. Simulation models can synthesize and integrate data collected from available limited-term field studies, and present a way to extrapolate results to long-term weather conditions and to other soils and climates (Mathews et al., 2002; Knisel and Turtola, 2000). Using CSM-CERES-maize model in DSSAT v4.0 (Jones et al., 2003), Saseendran et al. (2008a) demonstrated how a comprehensive agricultural system simulation model can be integrated with field experiments and long-term climate data to identify limited water irrigation management practices in the Great Plains of USA.

Innovative decision support systems developed with reliable cropping system models help in the efficient allocation of limited water resources, and its management by the farmers of the region. However, adequacy of agricultural system models for this application, especially in limited irrigation water management, depends upon accurately simulating the imposed soil water stress effects on crop growth and yield. Water stress decreases plant growth primarily by reducing cell division and expansion growth. Other known processes modulated by water stress are plant developmental rates, leaf initiation, photosynthesis, carbon allocation and partitioning, and root length and density in soil layers, resulting in reduced biomass and grain yield (Pereira and Chaves, 1993; Chartzoulakis et al., 1993; Passioura, 1994; Chen and Reynolds, 1997; Saini and Lalonde, 1998; Chaves et al., 2002; Saseendran et al., 2008b). In general, these effects are simulated in the current cropping system models, by describing a ‘water stress factor’ to modify the simulated plant growth and development processes.

Primarily, plants experience water stress when water supply in the soil fails to meet the evapotranspiration demand. Although it is easy to define the concept, accurate quantification and representation of a 'water stress factor' in crop models have been a challenge in system modeling (Ritchie, 1981; Saseendran et al., 2008b). Ritchie (1981) analyzed practical difficulties in using several plant parameters (e.g., stomatal conductance and leaf water potential) as 'water stress factors' in the system models, and felt that the empirical quantifications of crop growth and development processes as related to the soil water deficits such as fraction of plant available water in the root zone of the crop as a viable option. However, he also cautioned about the practical difficulties in the accurate quantification of the upper and lower limits of plant extractable water in the soil, and accurately simulating the soil water balance in cropping system models. Following Ritchie (1981), Brisson et al. (1992) implemented a stress factor based on plant water availability in the soil, relative to atmospheric demand, in a water balance model developed for its integration into crop models. Sinclair (1986) also used a similar stress factor in a soybean crop model. McCree and Fernandez (1989) used fraction volumetric soil water as stress factor for simulating physiological water responses of whole plants. Regardless of these efforts, in general, the cropping system models widely in use today [e.g., APSIM (McCown et al., 1996), CropSyst (Stockle et al., 2003), DSSAT-CSM (Jones et al., 2003; Woli et al., 2012), and RZWQM2 (Ahuja et al., 2000; Ma et al., 2009)] use the ratio of potential uptake to potential transpiration or actual to potential transpiration (supply-demand ratio) to represent water stress for modulating dry matter synthesis and expansion growth in crop simulations. A notable exception is in the usage of the 'fraction plant extractable water in the root zone soil' as water stress factor for modulating phenology and N fixation, in the APSIM cropping system model.

The RZWQM2 model has DSSAT-CSM crop modules for simulations of various crops and uses its water stress functions.

Inadequate crop growth simulations and the need for enhancing the water stress quantifications in many cropping system models including DSSAT and RZWQM2 have been reported in the literature (Cabelguenne et al., 1990; Castrignano et al., 1998; Nouna et al., 2000; Faria and Bowen, 2003; Sau et al., 2004; Saseendran et al., 2008a). Some of the recent crop models used 'soil water content' based 'water stress indices' for simulations. For instance, Sepaskhah et al. (2006) used a ratio of PAW (soil water above wilting point) to the fraction of PAW that is not readily available for plant extraction, as defined by Allen et al. (1998), for modulating simulated yields of wheat, corn and sugarbeet under water stress; Casadebaig et al. (2011) used the ratio of actual to maximum possible water content in the plant root zone as an index of water stress for simulating sunflower in the SUNFLO model.

In 2008, a field study was initiated at the Limited Irrigation Research Farm (LIRF) at Greeley in the Great Plains of Colorado, USA to collect information on response of commonly grown crops [winter wheat (*Triticum aestivum* L.), field corn (*Zea mays* L.), oil-type sunflower (*Helianthus annuus* L.), and dry (pinto) beans (*Phaseolus vulgaris* L.)] in this region to limited irrigation (Greeley experiments) (Trout et al., 2010; Bausch et al., 2011). A wide range of irrigation levels from fully irrigated (100% of ET demands) to about 40% of full irrigation is being tested. The data collected in the Greeley experiment is envisaged to evolve deficit irrigation practices for optimum yields, and also to develop effective stress factors for improved simulation of crop response to water in RZWQM2 and extension of results across soils and climates in the region (Trout et al., 2010). In this study, we explored the general relationships between plant available water in the soil, and measured grain yield, biomass, and fraction foliage cover (canopy cover) of corn in those experiments, and use those as the basis for quantifying crop responses to water stress in the RZWQM2 model. The specific objectives of the study were (1) to explore three plant water supply to demand ratios (i) PAW to alfalfa reference crop evapotranspiration (ETr) (WSF1), (ii) PAW to maximum PAW (MAW) (WSF2), and (iii) WSF2 to ETr (WSF3) as potential candidates for quantification of water stress; and (2) test the performance of these stress factors in RZWQM2 model for simulations of corn in the Greeley experiments. The model with modified WS factors (enhanced RZWQM2) was also tested for simulating dryland and limited irrigation studies at Akron, CO and at two more experiments in contrasting soils (sandy and sandy loam soils) available in DSSAT 4.5 database.

MATERIALS AND METHODS

The data for this study were collected from experiments conducted by the USDA-ARS at their Limited Irrigation Research Farm (LIRF) (40° 26’ N, 104° 38’ W, and 1428 m msl) near Greeley, Colorado during 2008-2011 (Greeley experiments). LIRF is a 16 ha field research facility developed to conduct research on crop responses related to irrigation. The site contains three types of soils, Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). Soil texture is fairly uniform throughout the 200 cm soil profile with average composition of 74% sand, 17% clay, and 9% silt. Plots are 12 rows wide (0.76 m row spacing for all the crops) by 40 m long and are replicated four times for each specific water treatment. Six water treatments are randomized within each replication. The six irrigation treatments were designed to meet certain percentages of potential crop ET (ETc) requirements during the growing seasons: 100% (T1), 85% (T2), 70%F (T3), 70% (T4), 55% (T5), and 40% (T6) of ETc. The amount of irrigation water for each treatment was estimated on a weekly basis based on reference ET demand (ETr), crop coefficient (Allen et al., 2005), rainfall, and soil water deficit. For all treatments except for T1 and T3, 20% of the estimated weekly amounts during vegetative growth period were saved and added to weekly amounts during the reproductive growth period.

Crop rows have a north/south orientation. Four crops are grown in rotation; these are: winter wheat, field corn, dry (pinto) beans and sunflower. Corn (cv. Dekalb 53-59) was planted on day of the year (DOY) 132, 131, 132 and 123 in 2008, 2009, 2010 and 2011, respectively, and harvested on DOY 310, 316, 292 and 310. Irrigation water is delivered to the corner of each plot and applied through polyethylene header pipes to drip irrigation tubing (16 mm diameter, thick walled tubing with 1.1 L/h conventional inline emitters spaced 30 cm apart) laid on the surface near each plant row. Flow rates and volumes to each water treatment are measured with turbine flow meters. Fertilizer as UAN was uniformly applied before planting and then with irrigation water during the growing seasons, to assure ample N.

Weather data were recorded on site (station GLY04) and available at http://ccc.atmos.colostate.edu/~coagmet/ are used in calculation of ETr. Soil water content was measured in each plot between 30 and 200 cm depth with neutron attenuation (503 DR Hydroprobe moisture gauge, Campbell Pacific Nuclear) in an access tube in the crop row near the center of each plot. A depth control stand (Evett et al., 2003) was used to control probe depth relative to the soil surface. Surface soil water content (0-15 cm) was measured with a MiniTrase portable TDR system (SoilMoisture Equipment Corp.). These measurements were made prior to each irrigation and following irrigation or precipitation event. When PAW near the soil surface was inadequate at planting time, the plots were sprinkler irrigated to assure good germination. Foliage cover (Fc, canopy cover) was estimated with a photosynthetically active radiation sensor (AccuPAR LP-80, Decagon Devices, Inc.) from above and below canopy measurements and from images acquired with a digital camera (mainly R6B) mounted on a “high boy” mobile platform and driven through the plots weekly. Grain yield and crop biomass at harvest of the crops were measured every year.

Data for testing the performance of the modified RZWQM2 in other soils and climates

In order to test the robustness of the new stress factors in RZWQM2 for simulations of corn across soils and locations, following three studies in which corn was grown either under irrigated or rainfed conditions combined with or without varying N rates were used.

As noted above, the CSM-CERES-Maize 4.0 was used with the soil water and N routines of RZWQM2 in the simulations. The DSSAT suite of cropping system models were used extensively for simulations of various crops across the world (Jones et al., 2003). In this study, for testing the enhanced RZWQM2, two irrigated corn experiments distributed with the DSSAT 4.5 package, one in a sandy loam soil conducted at, Zaragoza (41.43^{O}N, 0.49^{O}W, 0.23 km amsl), Spain in 1996 (SIAZ experiments) and another in a sandy soil at, Gainesville (29.63^{O}N, 82.37^{O}W, 0.01 km amsl), Florida, USA in 1982 (UFGA experiments) were used (Hoogenboom et al., 2010). The SIAZ experiment consisted of (1) full irrigation to meet the consumptive use demand of corn (cv. Prisma), (2) 50% of full irrigation, (3) a third of full irrigation (4) full in 1 and 2 phases (crop season is divided into three phases), (5)full irrigation in phases 1 and 3, (6) full irrigation in phases 2 and 3, (7) full irrigation in 1st phase, (8) full irrigation in 3rd phase, and (9) full irrigation in 2nd phase conducted in the year 1996 . The UFGA experiment consisted of corn (cv. McCurdy 84) under (1) rainfed with low N, (2) rainfed with high N,(3) irrigated with low N, (4) irrigated with high N, (5) water stress in vegetative stage with low N, and (6) water stress in vegetative stage with high N conducted in 1982.

The third experiment was conducted in a silt loam soil at Akron (40.15^{O}N, 103.14^{O}W, 1.38 km amsl), Colorado, USA under both irrigated and rainfed conditions (Akron experiments). These experiments were conducted over a period of eight yr at the Central Great Plains Research Station 6.4 km east of Akron, CO in a silt loam soil (fine montmorillonitic mesic Pachic Arguistoll). The irrigation experiments were during 1984, 1985, and 1986 in which corn hybrid 'Pioneer Brand 3732' (101-d relative maturity) was planted under a line-source gradient irrigation system with maximum water application next to the irrigation line and linearly declining water application with distance from the line. In 1985, additional irrigation treatments were imposed through drip irrigation using four irrigation levels determined by different threshold values of the Crop Water Stress Index (Nielsen and Gardner, 1987). The corn hybrid 'Pioneer Brand 3732' used in the irrigation studies was also used in the rainfed corn experiments from 1993 to 1997 at the location, therefore data during this period was used for simulations of the crop under rainfed conditions. Saseendran et al. (2008a) simulated the Akron experiments using the CERES-Maize v4.0 in within DSSAT (Jones et al., 2003). The cultivar parameters developed by Saseendran et al. (2008a) were used as starting point for calibration of the cultivar parameters in this study (Table 2-1).

Ma et al. (2011) protocol was adopted for calibration of the cultivar parameters in Greeley, SIAZ, UFGA and Akron experiments in this study. Grain yield data collected in the maximum irrigation treatment of the experiments was used in the calibration and the remaining treatments for validation. However, to be brief, the calibration and validation treatments are not discussed separately in the results and discussions below.

Water stress Factors

The following 'water stress factors' based on plant available water (PAW) status of the soil profile (plant water supply) and ETr (plant water demand) were computed:

$$WSF1 = \frac{PAW}{ETr} \qquad \text{(day)} \qquad \text{--------------------------} \quad (1)$$

$$WSF2 = \frac{PAW}{MAW} \qquad \text{(unitless)} \qquad \text{--------------------------} \quad (2)$$

$$WSF3 = \frac{WSF2}{ETr} \qquad \text{(day cm}^{-1}\text{)} \qquad \text{--------------------------} \quad (3)$$

where, *PAW* is assumed to be the plant available water in the soil root zone profile on a given day, and *MAW* is the maximum possible *PAW*, and *ETr* is the alfalfa reference crop evapotranspiration for the day, calculated using Allen et al. (2005) model. Ma et al. (2012) simulated the Greeley experiments for corn from 2008-2010 using the CSM-CERES-Maize v4.0 in RZWQM2. For calculation of PAW in the root zone of corn, we initially used the rooting depth simulated by Ma et al. (2012). However, we could not get enough PAW responses to the six irrigation treatments following the dynamic rooting depth with time; the different levels of irrigations did not result in separated PAW levels. Therefore, we tried various constant rooting depths of 0.5, 1.0, 1.5 and 2.0 m and selected 1m rooting depth to best represent PAW responses due to irrigations that can be quantitatively related to observed crop responses in the experiments.

Whereas, for a given duration of a day in the study, WSF1 and WSF2 are unitless, WSF3 has the unit of cm^{-1}. PAW and MAW are defined as:

$$PAW = \theta - PWP \qquad \text{--------------------------} \quad (4)$$

$$MAW = FC - PWP \quad \text{--------------------------} \quad (5)$$

where, θ is the measured water content for a soil layer, and FC and PWP are field capacity (drained upper limit) and permanent plant wilting point (lower limit) water contents of the same layer of the soil, respectively. We used the measured drained upper limit of soil water in each layer during the experiment (2008 to 2011) as an estimate of FC, and PWP was assumed to be half of the FC. This was found to be a reasonable approximation for the soil, as average pressure chamber measured 1.5 MPa water content for the soil was about 50% of its 0.03 MPa water content (Ma et al., 2012). The PAW in the soil of each replication of the six irrigation treatments was calculated separately using the FC and PWP information representing those plots. The PAWs calculated across the replications were averaged for each treatment and used for calculation of stress factors. As the crops in the experiments were uniformly irrigated at planting to assure adequate germination and establishment of crop stands, for delineation and analysis of treatments affects, we used the soil water data for the period approximately between 45 days after planting to crop physiological maturity for calculation of stress factors. However, the periods varied somewhat among the years and crops depending on the days the actual soil water measurements were made.

In the experiments, all the treatments had the same irrigation schedule through the season. The daily stress factors were first calculated separately for each crop season and replication of the six irrigation treatments on the day with soil water measurements. However, biomass and grain yield were measured only at harvest, therefore, the calculated daily stress factors were averaged to the end of the season (physiological maturity) separately for each replication and treatment. Additionally, treatment wise averages (across replications) of WSF1, WSF2 and WSF3 for a year as well as over the years were also calculated. Piecewise linear regression relationships were developed between the average stress factors and average relative grain yield (RGY), relative biomass (RBM) and relative foliage cover (RFc) responses:

$$RGY = f(WSF1 \text{ } or \text{ } WSF2 \text{ } or \text{ } WSF3) \quad \text{-------------------------- (6)}$$

$$RBM = f(WSF1 \text{ } or \text{ } WSF2 \text{ } or \text{ } WSF3) \quad \text{-------------------------- (7)}$$

$$RFc = f(WSF1 \text{ } or \text{ } WSF2 \text{ } or \text{ } WSF3) \quad \text{------------------------- (8)}$$

where, f is the piecewise linear function.

RGY, RBM and RFc were calculated as:

$$RGY = \frac{GY}{GYmax} \quad \text{-------------------------- (9)}$$

$$RBM = \frac{BM}{BMmax} \quad \text{-------------------------- (10)}$$

$$RFc = \frac{Fc}{CCmax} \quad \text{-------------------------- (11)}$$

where, G*Y, BM* and *Fc* are measured values of grain yield, biomass and fraction foliage cover (also used in literature as: ground cover or canopy cover) for each of the various irrigation levels in each crop season; and *GYmax, BMmax and Fcmax* represent their measured values in response to the maximum irrigation treatment (T1) for that season.

Comparisons of the stress factors for their effectiveness in explaining observed values of RGY, RBM and RFc over different water levels were judged based on the R^2 of the linear regression relationships between them.

In our measurements, Fc was defined as the percentage of the green crop foliage cover projected vertically onto the ground. Leaf area index (LAI) of a crop can be reasonably estimated from Fc by expressing it as an exponential function of LAI following the Beer–Lambert's law of light transmission through the plant foliage (canopy) and inverting the equation (Gonsamo, 2010) as:

$$1 - Fc = e^{-kLAI} \text{------------------- (12)}$$

$$LAI = -\frac{\ln(1-Fc)}{k} \text{ ------------------- (13)}$$

where, k is the extinction coefficient which is related to leaf spectral properties and leaf angles in the canopy.

As we did not have measurements of k in the study, Fc data was not converted into LAI for the analysis. The Fc data was used as a surrogate for LAI, an indicator for leaf expansion growth in the crop plants. All the crop response variables (grain yield, biomass and fraction foliage cover) were expressed relative to their maximum values as measured in the T1 were used in the analysis, hence non availability of absolute values of LAI should not affect the interpretations presented in terms of water stress affects on expansion growth in the study.

RZWQM2 Model

The RZWQM2 (Root Zone Water Quality Model), is a process-oriented agricultural system model that simulate the impacts of physical, biological and chemical processes for simulation of impacts of tillage, water, agricultural chemical and crop management practices on crop production and water quality (Ahuja et al., 2000). The CSM-CERES-maize 4.0 model of the DSSAT 4.0 (decision support system for agricultural technology transfer) package (Jones et al., 2003) linked to the soil water and nitrogen modules of RZWQM2 is used for simulation of corn in this study (Ma et al., 2009). Adequacies of RZWQM2 and its earlier versions for simulating corn growth under various agroclimatic conditions in the Great Plains of USA have been reported (Ma et al., 2003; Saseendran et al., 2004, 2005, 2008b, 2009, 2010). Ma et al. (2009) reported comparable simulation results of corn production using the CSM-CERES-Maize 4.0 model in RZWQM2 as the original CSM-CERES-Maize 4.0 model within DSSAT. Ma et al.

(2012) simulated the Greeley experiments for corn from 2008-2010 using the CSM-CERES-Maize v4.0 in RZWQM2.

For quantification of soil water deficit stress, RZWQM2 uses the water stress functions of DSSAT based on the ratio of potential root water uptake (TRWUP) to potential plant transpiration (EP_o) (Ritchie, 1998), referred hereafter as default WS factors (WSDef) (Fig. 2-1). When there is adequate water available in the soil for plant uptake, TRWUP is greater than EP_o and there is no water stress. However, TRWUP decreases as the soil dries out due to root water uptake, subsequently, a threshold is reached where the first WS factor or turgor factor (TURFAC) is activated to modulate expansive leaf growth. In both C3 and C4 plants, this point corresponds to the plant water level when the root water uptake combined with osmotic adjustments and cell wall extensibility fail to maintain turgor pressure to sustain cell division (mitosis) and expansion growth (Boyer, 1970; Cosgrove and Cleland, 1983; Neumann, 1995; Cosgrove, 1998). The TURFAC is defined as:

$$TURFAC = \frac{TRWUP}{RWUEP1 * EPo} \qquad \text{............ (14)}$$

where, *RWUEP*1 is a species-specific parameter, used for emulating the water stress level in the plants above which turgor pressure in the plant leaf cells fail to sustain expansion growth at the potential level, which is currently set to 1.5 for corn.

When *EPo* demand equals or exceeds the TRWUP, a second stress factor, called *SWFAC,* is activated:

$$SWFAC = \frac{TRWUP}{EPo} \qquad \text{............ (15)}$$

SWFAC mainly affects photosynthesis and other dry matter assimilation related processes. In plants, this stress sets in at a leaf water potential level, which is significantly below the TURFAC level, when the photosynthesis and other carbon assimilation processes are impaired due to water shortage. Reductions in photosynthesis occur mainly due to stomatal closure but also to a lesser extent from photoinhibition and reduction in metabolic potential in C3 plants (Boyer, 1970: Chaves et al., 2009). Reduction in photosynthesis due to stomatal closure is more complex in C4 plants due to the initial CO_2 concentration mechanism in operation in the mesophyll cells that are physically separated from the site of actual carbon fixation in the Calvin cycle (common to both C3 and C4 plants) located in the bundle-sheath cells. However, the water stress effects on carbon fixation other than the direct effects of stomatal conductance (i.e. effects on metabolic potential for reasons including photoinhibition) are common for both C3 and C4 crops (Chaves et al., 2009; Ghannoum, 2009). Notwithstanding, unlike C3 plants, the role of photorespiration as a protective electron sink against photoinhibition is negligible in C4 plants as photorespiration remains very low. In the model, for both C3 and C4 crops, both stress factors are used as a direct multiplier on growth or dry matter accumulation rate that ranges from 1 for no stress to 0 for complete stress.

In this study, the expressions in CSM-CERES-Maize module in RZWQM2 for TURFAC (Eq. 14) was replaced with the equation developed between RFc and the three soil water stress factors (i.e., Eq. 8) for simulation of corn. The expression for SWFAC (Eq. 15) was replaced with equations developed between RBM and RGY, and the three stress factors (i.e., Eq. 6).

Input data for the simulations and calibration of RZWQM2

RZWQM2 needs inputs of weather (daily solar irradiance, maximum and minimum temperature, wind speed, relative humidity, and precipitation as break point rainfall data), soil and crop management (planting dates, planting depth, row spacing and plant population;

amount, dates, and methods of irrigation and fertilizer applications; and dates and methods of tillage operations). Soil physical properties, soil profile depth and horizons (layers), soil texture, bulk density, and organic matter content are also needed. These data were collected at LIRF in the Greeley, SIAZ, UFGA and Akron experiments simulated in this study. For simulation, the RZWQM2 requires careful iterative calibration of its soil water component, followed by the nitrogen (N) and the plant growth components. 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 (Ma et al., 2012). The calibration procedure included matching simulation results with measured soil water, anthesis and maturity dates, maximum LAI, and final biomass and yield.

The RZWQM2 with the WSDef factors and crop/cultivar parameters calibrated by Ma et al. (2012) for simulating the Greeley experiment from 2008 to 2010 was used in the study. Yet, as various process interactions in the agricultural production system are highly complex, the model parameters obtained from calibration are not totally independent of the stress factor used. Therefore, for simulation of the crop using the three new water stress factors developed in this study, we slightly recalibrated the cultivar parameters to get reasonable match between the grain yield, biomass, LAI and soil water. However, one set of cultivar parameters could be used for all the three factors, WSF1, WSF2, WSF3 (Table 2-1); further improvements in simulations were not obtained through calibration for unique sets of parameters for WSF1, WSF2 and WSF3. Calibrations were performed only for the highest water level treatment in 2008, and these parameters were used for simulation of all other irrigation treatments in 2008, as well for all treatments in 2009, 2010 and 2011.

Saseendran et al. (2008a) simulated the Akron experiments using the CERES-Maize v4.0 within DSSAT (Jones et al., 2003). The cultivar parameters developed by Saseendran et al. (2008a) were used as starting point for calibration of the cultivar parameters in this study (Table 2-1). For calibration of the cultivar parameters in the SIAZ and UFGA experiments, the cultivar parameters available in the DSSAT 4.5 database was used as a starting point (Table 2-1). In all the calibrations, only the highest water level treatment in the experiments was used and rest of the treatments used in evaluations.

Statistics for Model Calibration and Evaluations

We evaluated the simulation results using: (i) Root Mean Squared Error (RMSE), Eq. (16), between simulated and observed values; (ii) relative RMSE (RRMSE) that varies between 0 and 100% Eq. (17), (iii) the index of agreement (d) between measured and simulated parameters (Willmott, 1981) which varies between 0 (poor model) and 1 (perfect model), Eq. (18); and (iv) coefficient of determination (R^2), Eq. (19).

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \qquad \text{---------------} \ (16)$$

$$\text{RRMSE} = \frac{RMSE}{O_{avg}} \qquad \text{----------------} \ (17)$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}\left(\left|Pi - O_{avg}\right| + \left|Oi - O_{avg}\right|\right)^2} \qquad \text{-------} \ (18)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})\right]^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2 \sum_{i=1}^{n}(P_i - P_{avg})^2} \qquad \text{------------} \ (19)$$

where, P_i is the ith simulated value, P_{avg} is the average of the simulated values, O_i is the ith observed value, O_{avg} is the average of the observed values, and n is the number of data pairs.

RESULTS AND DISCUSSION

Plant available water (PAW) in the soil profile

Large interannual variability in recorded precipitation during the vegetative and reproductive stages of growth of the crop were observed, consequently the applied irrigation amounts in different irrigation treatments also varied greatly (Table 2-2). In the four corn crop seasons during 2008 to 2011, precipitation received during the vegetative growth stages of the crop varied from 39 mm (2008) to 145 mm(2010), and the applied irrigations varied from 201 mm (2010) to 289 mm (2008) in the T1 treatment and from 42 (2010) to 111 mm (2008) in the T6 treatment (Table 2-2). Precipitation during the reproductive stages of the crop ranged between 38 mm in 2011 to 191 mm in 2008, and irrigations applied varied from 149 mm (2008) to 230 mm (2011) in the T1 treatment, and 26 mm in 2008 to 70 mm in 2010 in the T6 treatment. Highest daily amount of precipitation recorded during the four crop seasons (2008 to 2011) ranged from 64.5 mm on 14 August in 2008 [(DOY) 228] and 32.0 mm on 11 May 2011(DOY 131) (Fig. 2-2). Growing season number of rainy days was 38.5 days with highest, 50 days, in 2009 and lowest, 31 days in 2008.

Across the crop growth period of the crop, in general, the PAW status of the soil profile increased following the irrigation events and decreased following active crop uptake (data not shown). Due to larger irrigation amounts, highest PAWs were generally in the T1 treatment followed by T2, T3, T4, T5 and T6 treatments with lower irrigation levels. However, some large rain events like the 86.0 mm on DOY 229 in 2008 increased soil water content (SWC) under corn to FC in all the treatments in that year. Similarly, SWC of all the treatments come close to FC for all treatments in 2010 on DOY 200 for corn.

Water stress factors

Definite patterns in the relationships between RGY, RBM and RFc and the three soil water content-based stress factors (WSF1, WSF2 and WSF3) emerge when the average values across crop seasons were plotted together (Fig. 2-3). When overall pattern of these observed relationships deviated from the default pattern in RZWQM2, the pattern matched better with those used in APSIM model (Saseendran et al., 2008b) (Fig. 2-1). For quantification, we assumed piecewise linear as a reasonable approximation of the relationships between the computed water stress factors and crop responses in terms of RGY, RBM and RFc. As the number of data points (six) was not enough for a rigorous statistical analysis, we first sketched a horizontal line through the points with relative crop response equal to 1.0 (horizontal line parallel to the x-axis in Fig. 2-3). A linear regression was fitted to get the sloping line in the Figure with relative crop responses below 1.0. A third line was used to connect the lower end of the fitted sloping line representing the grain yield and biomass responses to the point where the relative response falls to 0.0 (origin of the axis). For this, we assumed that the relative biomass and grain growth ends when there is no PAW in the soil for plant uptake. However, expansion growth response (RFc) of plants cease at PAW levels well above zero (Boyer, 1970; Cosgrove and Cleland, 1983; Neumann, 1995; Cosgrove, 1998), therefore these lines were extended downward to meet the x-axis.

In general, the observed slopes of the lines representing the responses of corn to water stress factors in the Figure are steeper for RFc compared to RGY and RBM. The RGY and RBM responses to the three stress factors were similar enough to assume them as identical. The results clearly show an early (in stress onset) response in expansion growth (foliage cover as surrogate for LAI) of the plant due to water stress before dry matter assimilation processes are affected. These results are in line with the observation that the chemical signals from the roots of plants subjected to water deficit stress modulate cell expansion rate earlier and more than net carbon assimilation and translocation rates, and depending on the stress level, this can continue even after the plants had been re-watered (Boyer, 1970; Tardieu et al., 1999, 2000; Granier and Tardieu, 1999; McCoy et al., 1990). In corn, Boyer (1970) and Sobrado (1986) observed reductions in both leaf area and dry matter accumulation with soil water deficits, however the leaf expansion rate was observed to be more sensitive to low turgor, and the expansion ceased when turgor reached 0.2 MPa. These observed responses of plants to water stress has also been incorporated in crop simulation models by making the simulated expansion processes (leaf area) more sensitive to water stress than the biomass assimilation processes (photosynthesis) (McCree and Fernandez, 1989; Ritchie, 1998; Saseendran et al., 2008b). The results of differential effects of irrigation treatments on RGY and RBM in corn did not disagree from the reported relative enhanced sensitivity of leaf expansion growth to water deficit (Boyer, 1970).

Comparisons of water stress factors

The linear fit in RGY, RBM and RFc to the water stress factors (R^2 of the linear regressions in Fig. 2-3) was best for WSF3 with values between 0.96 and 0.99. In general, the R^2 of linear relationships between WSF2 and crop responses were less than WSF3 with values between 0.94 and 0.98. Relatively least accurate linear fit was between WSF1 and the three crop response variables (R^2 between 0.92 and 0.99). Quantitative, piecewise linear relationships between WSF1, WSF2 and WSF3 and RGY, RBM and RFc responses for the crop are useful for modeling the impacts of crop water stress on corn growth and development (Table 2-3). Overall ranking of the three stress factors based on the variances explained by them in the average RGY and RBM, and RFc data during 2008-2011 was in the order WSF3> WSF2 > WSF1.

Performance of WSF1, WSF2 and WSF3 in simulations of corn using RZWQM2

For simulation of corn, the default TURFAC (Eq. 14) and SWFAC (Eq. 15) stress factors computation procedures in CSM-CERES-Maize in RZWQM2 were replaced with relationships derived between RFc and RGY , respectively, with each of the three stress factors (WSF1, WSF2 and WSF3) (Eqs. 6, 7 and 8) as given in Figure 2-3 and Table 2-3. TURFAC or the new substitute modifies leaf, stem, ear and grain growth, and SWFAC or the substitute modifies photosynthesis and carbon portioning, rooting depth, leaf senescence and N mobilization to grains in the model. All the simulations across the four years (2008 to 2011) and six irrigation treatments (T1 to T6) using the three water stress factors were with the same initial soil water and nutrient conditions on the first day of the year as used in Ma et al. (2012) using the WSDef. The plant parameters used for simulating the experiments were calibrated manually following Ma et al. (2011) using the measured grain yield, biomass, and LAI in 2008, and used for simulating the experiments from 2008-2011 (Table 2-1). One set of coefficients were found suitable for simulations with the three new stress factors (Table 2-1). Simulated phenology dates were compared with approximate available field notes. In general, the anthesis and physiological maturity dates in the simulations were off by 3 to 6 days from the field measured dates in simulations from 2008-2011 with the three water stress factors.

Average value of the TURFAC or substitute simulated for WSDef, WSF1, WSF2 and WSF3 under T1 treatment in 2010 were 0.00, 0.41, 0.03, and 0.09, respectively, until the simulated crop LAI reached a value of 1.00 on DOY 173 (for discussion, the stress factors are shown to range from 0 for no stress to 1 for complete stress) (Fig. 2-4). However, appreciable differences in simulated WS between WSDef and the three WS factors were in the beginning of the crop season when the soil was not fully covered by the crop. The simulated TURFAC values after the crop LAI exceeded value of 3.50 (DOY 200) were 0.00, 0.01, 0.00 and 0.01, respectively. This difference was mainly due to the fact that with WSDef [Eq. (14) and (15)], water demand and supply is based on the potential plant water uptake and potential plant transpiration, both neglect the heating of the canopy (sensible heat) due to unmet soil evaporation demand. When the crop does not cover the soil completely and the soil evaporation demand is not met, the heat load developed in the soil is transmitted to the plants causing an enhancement in the water stress experienced by the plants. To account for this affect, in WSF1 and WSF3, the default potential transpiration demand is replaced with ETr demand [Eq. (1) and (3)]. However, WSF2 is only a ratio of the actual to potential PAW in the soil [Eq. (2)].

In general, soil water simulations across the four crop seasons (2008 to 2011) in response to WSF3 were comparable to Ma et al. (2012) simulations with the WSDef stress factor. Simulations with WSF1 and WSF2 were less accurate (Table 2-4).

Measured grain yields in 2008 in response to the six irrigation levels ranged from 11071 to 7546 kg ha^{-1}. Increase in biomass due to irrigation this year was 7781 kg ha^{-1}. Using the WSDef equations, Ma et al. (2012) simulated grain yields ranged from 10685 and 8774 kg ha^{-1}

with a gain of only 1911 kg ha^{-1} due to applied irrigation between the lowest and highest irrigation treatments. Simulated yield gains due to irrigations were overestimated by 1360, 406 and 948 kg ha^{-1} due to WSF1, WSF2 and WSF3, respectively. Overall, in 2008, WSF3 was found to simulate the crop better than WSF1 and WSF2, especially in grain yield and biomass simulations (Table 2-4; Fig. 2-5 and 2-6).

In 2009, the simulated total grain and biomass yield increase due to irrigation (difference between highest and lowest irrigation treatment) best matched measurements with the WSDef, differing only 198 and 256 kg ha^{-1} in yield and biomass from the measured (Figs. 2-5 and 2-6). However, overall, in simulations of grain yield, biomass and LAI across the six irrigation treatments, simulations with WSF3 showed lowest RRMSEs and highest d value (Table 2-4). Errors and d values in simulations of the 2009 experiments using WSDef were 6.3% and 0.96 for biomass, 8.1% and 0.97 for grain yield, and 46.8% and 0.83 for LAI. Noticeably, these LAI simulations were better by 8.1% in RRMSE compared to WSF3 simulations. However, as noted earlier, there were no measurements of LAI this year as well, as such, the data was derived from Fc estimates using a constant extinction coefficient (Farahani and DeCoursey, 2000) using Eq. 13. Possibly, the estimated LAI curve deviated from the field conditions in this season.

In 2010, simulations of grain yield and biomass using the WSF2 factor were best and reasonably accurate with RRMSE of 9.0 and 3.4%, respectively. Using the WSDef factor in RZWQM2 (Ma et al., 2012), the 2010 corn crop was simulated with RRMSE and d of 40.1% and 0.80 for LAI, 19.5% and 0.83 for biomass, and 10.6% and 0.92 for grain yield. These simulations, in general, were less accurate than those simulated using all the three stress factors tested in the study (WSF1, WSF2 and WSF3). As noted earlier, in the Greeley experiment, continuous direct measurements of LAI were available only for one crop season in 2010 in the

T1, T3, T4 and T5 treatments (Fig. 2-7). Overall, as reflected in the discussions above and as shown in Table 2-4, among the three stress factors WSF1, WSF2 and WSF3, estimate of LAI was best simulated with WSF3 with RRMSE of 34.4% and d of 0.96 (Table 2-4). Taking into account the measured deviations in LAI between replications [standard deviations (SD) plotted in Fig. 2-7], overall, the simulations using stress factors WSDef and WSF3 reasonably followed the measured crop growth in the field.

The crop season in 2011 was markedly different from the previous three years with highest measured maximum grain yield of 11809 kg ha^{-1} (highest in four years of experiments) due to highest irrigation level (T1, at 100% ET) and lowest grain yield of 3434 kg ha^{-1} (lowest in four years of experiments) in response to the lowest irrigation level (T6, at 40% ET). The measured grain yield in response to T1 this year was 7, 15 and 25% higher than those measured in 2008, 2009 and 2010, respectively, while the lowest measured grain yield was lower by 54, 32 and 26%. Similar large differences were also reflected in the measured biomass and LAI values. The simulations using WSDef stress factors under predicted the yield in response to the highest irrigation (T1) by 34% and over predicted the yield in response to the lowest irrigation (T6) by 23%. Nonetheless, simulations of these grain yield values were much better (best among the three new stress factors) with the WSF3 with deviations in the highest grain yield (T1) by -3.5 % and lowest grain yield (T6) by -26.2 % . Simulated grain yield differences between the highest and lowest irrigations this year using the WSDef and WSF3 stress factors were 4402 and 7061 kg ha^{-1} , respectively, against the measured difference of 8375 kg ha^{-1}. The RRMSE of LAI simulations this year was best for simulations with WSF1 (26.4%) (Table 2-4). Simulations using WSDef factor had RRMSEs and d values of 26.8% and 0.98 for LAI, 9.3% and 0.93 for biomass, and 20.7% and 0.86 for grain yield.

In simulations of the crop using RZWQM2, averaged across the four years, WSF3 was found to simulate the crop better than the other two WS factors (WSF1 and WSF2), especially in grain yield and biomass simulations (Table 2-5; Figs. 2-5 and 2-6).

Simulations of irrigation experiments from the DSSAT database

The SIAZ experiments consisted of nine treatments with different combinations of water and N levels distributed across various stages of growth of corn, stands out for its complexity in the water and N treatments and their interactions. Measured grain yields reported in this experiment ranged from 5620 to 12340 kg ha^{-1} (Fig.2-8; Table 2-6), using the enhanced RZWQM2, we simulated this experiment exactly with the same initial water and N conditions as it was done using the CSM-CERES-Maize and –IXIM-maize models available within the DSSAT 4.5 for simulations of corn (Jones et al., 2003; Hoogenboom et al., 2010; Lizaso et al. 2011). The full irrigation treatment to meet the consumptive use demand of corn was used for calibration of the cultivar parameters. To be brief, the results of both calibration and validation simulations are discussed together below. Simulated phenology dates of anthesis and physiological maturity were compared with available field measurements. In general, the anthesis and physiological maturity dates in the simulations were off by 0 to 3 days from the field measured dates.

Grain yield, biomass and LAI simulations of RZWQM2 using the WSF3 had lower RMSE than simulations using the WSDef, WSF1 and WSF2 (Fig. 2-8, Table 2-6). The RRMSE of grain yield simulations ranged between 14.6 % with WSF3 and 21.5% with WSF1 stress factors.

The UFGA experiment was also conspicuous for its complexity in treatments with six different combinations of water and N applied differentially in the vegetative and reproductive stages of growth of corn. Using the enhanced RZWQM2, we simulated this experiment also exactly with the same initial water and N conditions as it was done using the CSM-CERES-Maize and –IXIM-maize models available within the DSSAT 4.5 for simulations of corn. Simulated dates of anthesis and physiological maturity were compared with field measurements. In summary, the anthesis and physiological maturity dates in the simulations were off by 1 to 4 days from the field measured dates. Grain yield and biomass simulations of this experiment using the four WS factors (WSDef, WSF1, WSF2 and WSF3) were comparable to each other with RMSE of grain yield varying between 313 and 547 kg ha^{-1} (Table 2-6, Fig. 2-9). The RMSE of biomass varied between 1329 and 1982 kg ha^{-1}. However, the lowest RMSE for grain yield (313 kg ha^{-1}) was obtained using WSF1, and lowest RMSE for biomass (1329 kg ha^{-1}) was obtained using WSF3. When RMSE of LAI simulations with the four WS factors were also comparable to each other varying between 0.26 and 0.83, the lowest value was obtained using WSF2 and highest with WSF1. Collectively, simulations of the SIAZ experiment with RZWQM2 enhanced with the WSF3 stress factor (RMSE of 449 kg ha^{-1}, 1329 kg ha^{-1} and 0.36, respectively, for grain yield, biomass and LAI) were more accurate than simulations with the other three WS factors.

Simulations of Akron experiments

Grain yields in the irrigation studies of the Akron experiments (total of 26 grain harvests across three years) were simulated with RMSE of 669, 846, 1300, and 326 kg ha^{-1} using the RZWQM2 enhanced with WSDef, WSF1, WSF2 and WSF3, respectively (Table 2-7, Fig. 2-10). Biomass harvested at the end of the season were simulated with RMSE of 1699, 2064, 4983 and

1685 kg ha^{-1}, respectively (Table 2-7). In summary, both grain yield and biomass in the irrigation studies were simulated best by WSF3 than the other three WS factors.

In general, accuracies of grain yield simulations in the rainfed experiments also were best using WSF3 compared to the other WS factors (Table 2-7, Fig. 2-10). RMSE of grain yields were 837, 521, 409 and 231 kg ha^{-1}, respectively, using the WSDef, WSF1, WSF2 and WSF3 factors in RZWQM2. While simulating the Akron experiments, Saseendran et al. (2008a) identified an outlier in the rainfed measured grain yield in 1997 (Fig. 2-10). This year, the lowest grain yield of 357 kg ha^{-1} was obtained when the rainfall and other weather conditions during the crop growing season were comparable to other years in which measured grain yield ranged from 1611 to 3689 kg ha^{-1}. Neglecting this value, the RMSE of grain yield simulated in the rainfed trials varied between 125 kg ha^{-1} using WSF3 and 504 kg ha^{-1} using WSF1. Using the WSDef factor in the model, grain yields (excluding the 1997 data) in the rainfed studies were simulated with an RMSE of 331 kg ha^{-1}. RMSE of biomass simulations in the rainfed trials (including 1997) using the four water stress factors were comparable varying between 1015 kg ha^{-1} using WSDef and 1049 kg ha^{-1} using WSF1. In summary, in the Akron experiments, simulations using WSF3 in RZWQM2 was more accurate than simulations using WSDef, WSF1 and WSF2. However, accurate quantifications of the soil water based WS factors in RZWQM2 for simulation of specific crops will demand accurate measurements and specification of water in the root zone soil profile at planting, sometimes limiting its applications in experiments where these are not measured.

SUMMARY AND CONCLUSIONS

In simulation modeling, there is need to define water stress factors based on commonly measured as well as simulated soil or plant parameters. In the early 1980s, scientists proposed use of water stress factors based on water available in the soil for plant extraction for crop simulations. In this study, the soil water measurements that span the whole growing season under corn grown under six irrigation treatments designed to meet 100 to 40% of ETc requirements during the growing season were analyzed for developing water stress factors that explain crop growth responses to the applied water. Potential water stress factors were calculated for the crop as ratios of PAW to ETr (WSF1), PAW to MAW (WSF2), and WSF2 to ETr (WSF3). Variance explained by the relationship between the three stress factors and relative responses of grain yield, biomass and fraction of foliage cover was highest for WSF3 followed by WSF2 and WSF1. Out of the three water stress factors tested, WSF3 was found to be better than others in simulations of corn grain yield, biomass and LAI in the Greeley experiments. Better simulations using WSF3 in RZWQM2 were obtained in simulations of corn under both rainfed and irrigated conditions at Akron, Colorado, USA, and in two irrigation experiments in two contrasting soils (a sandy loam soil at, Zaragoza, Spain and a sandy soil at Gainesville, Florida, USA), verified the capability of the modified model for simulations across soils and climates. Notwithstanding, similar testing across more locations in the world will help in building further confidence on the robustness of this stress factor in RZWQM2 for simulation of corn and other crops across climates and soils.

Table 2-1. Plant parameters calibrated for CSM-CERES-Maize simulations of corn hybrids in the Greeley, SIAZ, UFGA and Akron experiments using the WSDef (Ma et al., 2012), WSF1, WSF2 and WSF3 water stress factors within RZWQM2.

Acronyms used and definitions of traits.	Parameter values				
	Greeley experiments (cv. Dekalb 53-59)		UFGA experiments (cv. McCurdy 84)	SIAZ experiments (cv. Prisma)	Akron experiments (cv. Pioneer Brand 3732)
	WSDef	WSF1, WSF2 and WSF3	WSDef, WSF1, WSF2 and WSF3	WSDef, WSF1, WSF2 and WSF3	WSDef, WSF1, WSF2 and WSF3
P1 - Degree days (base temperature of 8 ºC) from seedling emergence to end of juvenile phase (thermal degree days).	260	260	260	280	300
P2 - Day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate].	0.40	0.60	0.30	0.22	0.60
P5 - Degree days (base temperature of 8 ºC) from silking to physiological maturity (thermal degree days)	540	600	910	779	595
G2 - Potential kernel number	800	990	980	709	720
G3 - Potential kernel growth rate (mg/(kernel d)	10	7.80	7.1	7.27	9.9
PHINT - Degree days required for a leaf tip to emerge (phyllochron interval) (thermal degree days)	50.0	46.00	43.0	49.0	51

Table 2-2. Total seasonal irrigation and precipitation during the vegetative (V) and reproductive (R) stages of corn under six irrigation treatments during 2008 to 2011 in the limited irrigation experiments at Greeley, Colorado (LIRF).

Irrigation treatment	Irrigation/precipitation, mm							
	V	R	V	R	V	R	V	R
Corn (cv. Dekalb 53-59)	2008		2009		2010		2011	
Precipitation	39	191	135	94	145	55	138	38
T1	289	149	202	216	201	164	255	230
T2	227	111	169	179	130	160	203	185
T3	202	80	146	154	114	133	182	147
T4	186	86	102	148	88	132	177	129
T5	136	45	68	100	61	98	129	92
T6	111	26	50	59	42	70	97	60

T1 = Treatment #1, T2=Treatment # 2, T3= Treatment #3, T4= Treatment # 4, T5= Treatment # 5, T6 = Treatment # 6. Dates of first tassel appearance in the field was used for differentiating between vegetative and reproductive stages.

Table 2-3. Quantitative relationships for the relative responses of corn relative grain yield (RGY) and foliage cover (RFc) to the three soil water stress factors (WSF1, WSF2, and WSF3).

RGY and RBM	RFc
WSF1	WSF1
RGY=0.09 WSF1 + 0.64 for 5.1<WSF1<10.4. RGY=0.12 WSF1 for WSF1<5.1. RGY =1 for 10.4<WSF1.	RFc= 0.22 WSF1-0.39 for 3.1<WSF1<11.6. RFc= 0.0 for WSF1 < 3.1. RFc= 1 for 11.6 < WSF1.
WSF2	WSF2
RGY=1.69 WSF2 + 0.01 for 0.3<WSF2<0.60. RGY =1.39 WSF2 for WSF2<0.3. RGY =1 for 0.60<WSF2.	RFc= 2.28 WSF2-0.41 for 0.19<WSF2< 0.62. RFc = 0.0 for WSF2 < 0.19. RFc=1 for 0.62 < WSF2.
WSF3	WSF3
RGY=0.81 WSF3 + 0.14 for 0.48<WSF3<1.10. RGY = 1.20 WSF3 for WSF3<0.48. RGY = 1 for 1.10>WSF3.	RFc= 1.10 WSF3-0.25 for 0.26<WSF3<1.22. RFc= 0.0 WSF3 for WSF3 < 0.26. RFc=1 for 1.22 < WSF3.

Table 2- 4. Evaluation statistics for simulations of total profile soil water, leaf area index (LAI), biomass and grain yield against measured values in the 2008, 2009, 2010, and 2011 in the Greeley experiments. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

Year	Total profile(0-180 cm) water				LAI				Biomass				Grain yield			
	RMSE (cm)	RRMSE %	R^2	d	RMSE	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d
									WSDef							
2008	3.85	13.0	0.75	0.87	1.07	54.7	0.84	0.79	1756	9.6	0.85	0.87	1016	10.6	0.84	0.79
2009	2.40	7.3	0.77	0.97	0.94	46.8	0.62	0.83	1152	6.3	0.88	0.96	672	8.1	0.95	0.97
2010	3.02	8.4	0.55	0.83	0.68	40.1	0.85	0.80	2932	19.5	0.83	0.78	823	10.6	0.92	0.92
2011	4.83	15.6	0.10	0.74	0.68	26.8	0.69	0.98	1603	9.3	0.92	0.93	1691	20.7	0.69	0.86
									WSF1							
2008	3.72	12.7	0.76	0.87	1.07	55.1	0.72	0.81	1666	9.1	0.98	0.94	644	6.7	0.99	0.96
2009	2.27	6.9	0.73	0.92	1.12	56.5	0.37	0.77	1961	10.8	098	0.93	696	8.4	0.96	0.97
2010	2.87	7.9	0.47	0.80	0.79	46.7	0.80	0.88	586	3.9	0.98	0.99	698	9.0	0.94	0.97
2011	8.16	26.4	0.13	0.68	0.67	26.4	0.75	0.99	2425	14.07	0.97	0.94	951	11.7	0.95	0.96
									WSF2							
2008	5.68	19.2	0.75	0.77	0.87	44.4	0.70	0.87	1286	7.0	0.86	0.95	496	5.4	0.88	0.97
2009	4.09	12.4	0.77	0.90	1.09	54.6	0.62	0.77	1249	6.9	097	0.97	864	10.4	0.96	0.96
2010	2.74	7.6	0.48	0.82	0.61	36.2	0.87	0.96	1877	12.5	0.99	0.94	813	10.5	0.93	0.96
2011	7.50	24.2	0.12	0.69	0.79	31.0	0.63	0.98	756	4.4	0.98	0.99	862	10.5	0.96	0.99
									WSF3							
2008	4.68	15.8	0.77	0.83	1.07	54.0	0.64	0.79	1704	9.3	0.92	0.93	412	5.3	0.97	0.98
2009	3.58	10.9	0.75	0.91	1.09	54.9	0.48	0.75	954	5.3	0.97	0.98	551	6.7	0.97	0.98
2010	2.79	7.7	0.47	0.82	0.58	34.4	0.88	0.96	1807	12.1	0.99	0.94	777	10.0	0.96	0.97
2011	4.38	14.2	0.07	0.85	0.79	31.6	0.60	0.98	882	5.1	0.99	0.99	761	9.3	0.94	0.98

Table 2-5. Evaluation statistics (pooled data from six irrigation treatments each in the four crops seasons of 2008, 2009, 2010 and 2011) for simulations of grain yield and biomass against measured values in the Greeley experiments. RMSE: Root Mean Square Error, RRMSE: relative RMSE, and R^2: coefficient of determination.

Grain yield			Biomass		
RMSE ($kg\ ha^{-1}$)	RRMSE %	R^2	RMSE ($kg\ ha^{-1}$)	RRMSE %	R^2
		WSDef			
1102	12.9	0.73	2106	13.2	0.81
		WSF1			
815	9.5	0.88	1793	10.4	0.92
		WSF2			
828	9.8	0.88	1352	8.2	0.89
		WSF3			
685	7.9	0.95	1403	8.9	0.89

Table 2-6. Evaluation statistics (pooled data from SIAZ96 experiment in a sandy loam soil at Zaragoza, Spain and UFGA82 experiment in a sandy soil at Gainesville, Florida distributed with DSSAT 4.5) for simulations of grain yield and biomass using the three stress factors (WSF1, WSF2 and WSF3) and the default stress factor (WSDef) against measured values. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

Grain yield (kg ha^{-1})				Biomass				LAI			
RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE	RRMSE %	R^2	d
Experiment in a sandy loam at Zaragoza, Spain in 1996											
WSDef											
1833	20.5	0.63	0.86	4061	22.9	0.47	0.74	0.88	20.9	0.19	0.61
WSF1											
1971	21.5	0.24	0.60	4620	26.1	0.13	0.53	0.75	17.8	0.32	0.66
WSF2											
1771	19.3	0.67	0.87	3196	18.1	0.54	0.81	0.74	17.7	0.22	0.67
WSF3											
1341	14.6	0.65	0.89	3591	20.3	0.46	0.75	0.63	15.0	0.64	0.68
Experiment in a sandy soil at Gainesville, Florida in 1982											
WSDef											
547	8.4	0.98	0.99	1386	10.6	0.96	0.98	0.29	8.9	0.72	0.98
WSF1											
313	4.6	0.99	0.99	1982	15.2	0.99	0.98	0.83	25.8	0.74	0.91
WSF2											
456	6.8	0.98	0.99	1584	12.1	0.96	0.99	0.26	8.0	0.80	0.99
WSF3											
449	6.6	0.98	0.99	1329	10.4	0.96	0.99	0.36	11.1	0.59	0.97

Table 2-7. Evaluation statistics (pooled data from rainfed experiments from 1993 to 1997, and irrigation trials with line source and drip systems from 1984 to 1986 at Akron, Colorado, USA) for simulations of grain yield and biomass using the three stress factors (WSF1, WSF2 and WSF3) and the default stress factor (WSDef) against measured values in the Akron experiments. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

	Grain yield				Biomass			
	RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d
				WSDef				
Irrigated	669	8.5	0.97	0.97	1699	13.5	0.21	0.61
Rainfed	837	8.5	0.86	0.97	1015	22.5	0.49	0.99
				WSF1				
Irrigated	846	10.8	0.87	0.95	2064	16.5	0.22	0.68
Rainfed	521	27.4	0.68	0.92	1049	23.3	0.68	0.91
				WSF2				
Irrigated	1300	16.6	0.99	0.91	4983	39.7	0.05	0.26
Rainfed	409	21.5	0.94	0.99	1027	22.7	0.84	0.99
				WSF3				
Irrigated	326	4.2	0.99	0.99	1685	13.3	0.38	0.63
Rainfed	231	12.3	0.94	0.99	1017	22.6	0.62	0.99

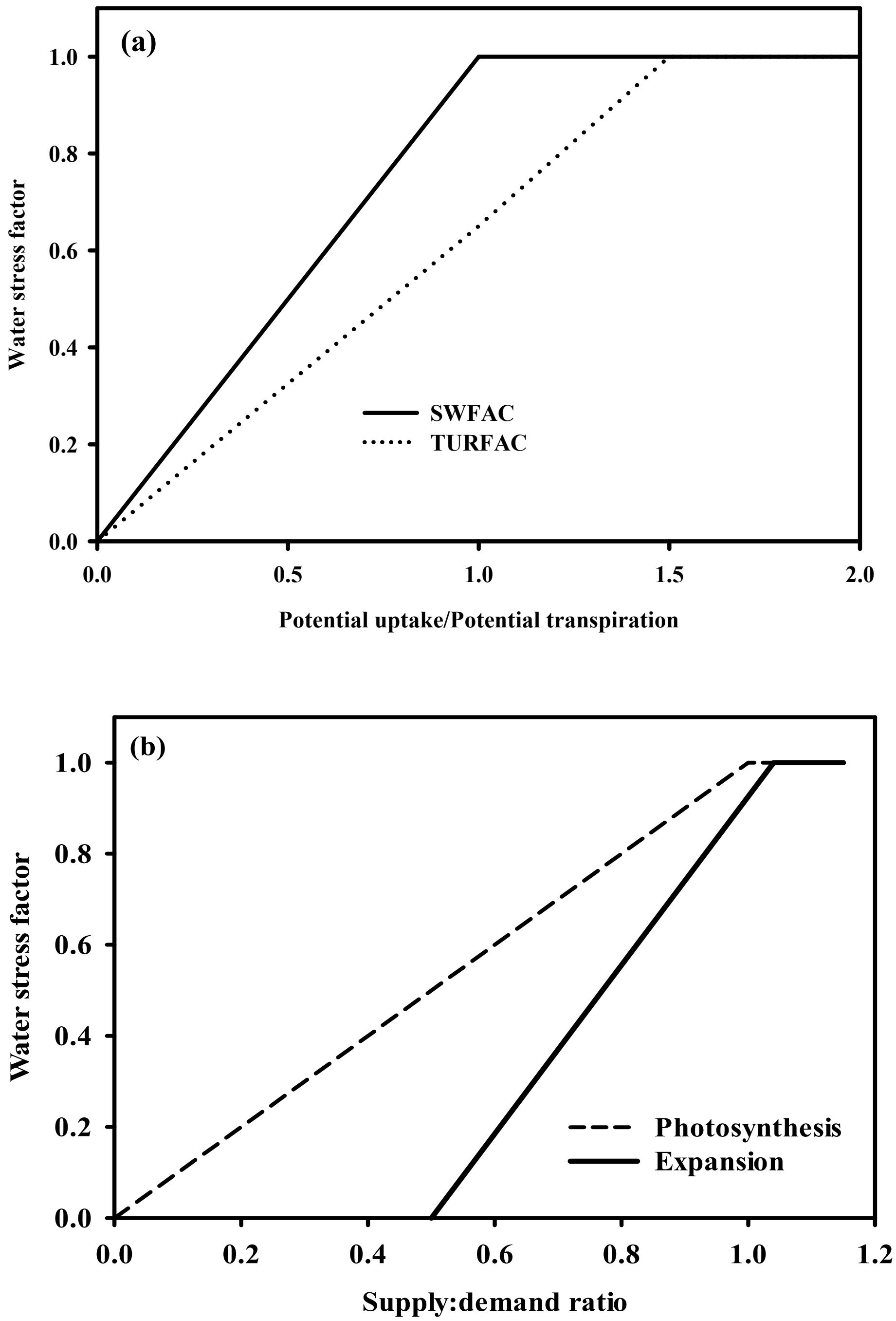

Fig. 2-1. Relationships used to calculate soil water stress factors, SWFAC and TURFAC in (a) RZWQM2, and (b) APSIM (Saseendran et al., 2008b).

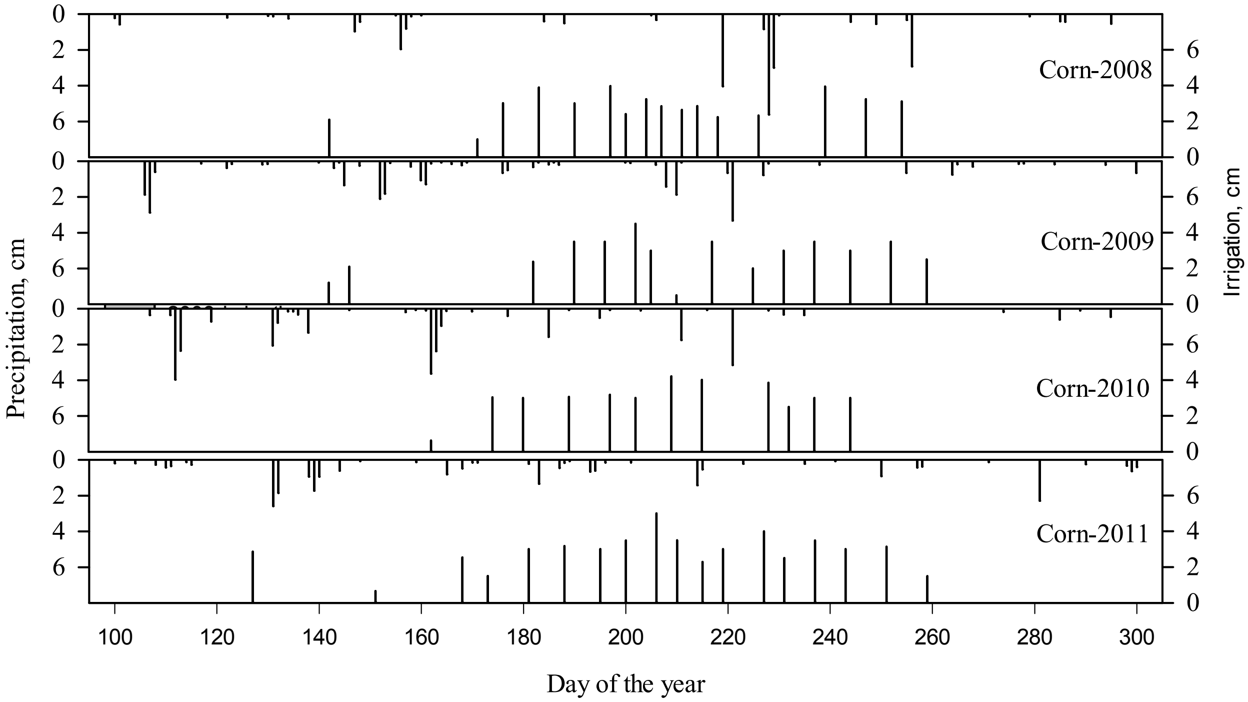

Fig. 2-2. Irrigation applied (right vertical axes) in the maximum irrigation treatment (T1) and daily precipitation (left vertical axes) received during the corn growth seasons (100^{th} to 300^{th} day of the year) of 2008, 2009, 2010 and 2011.

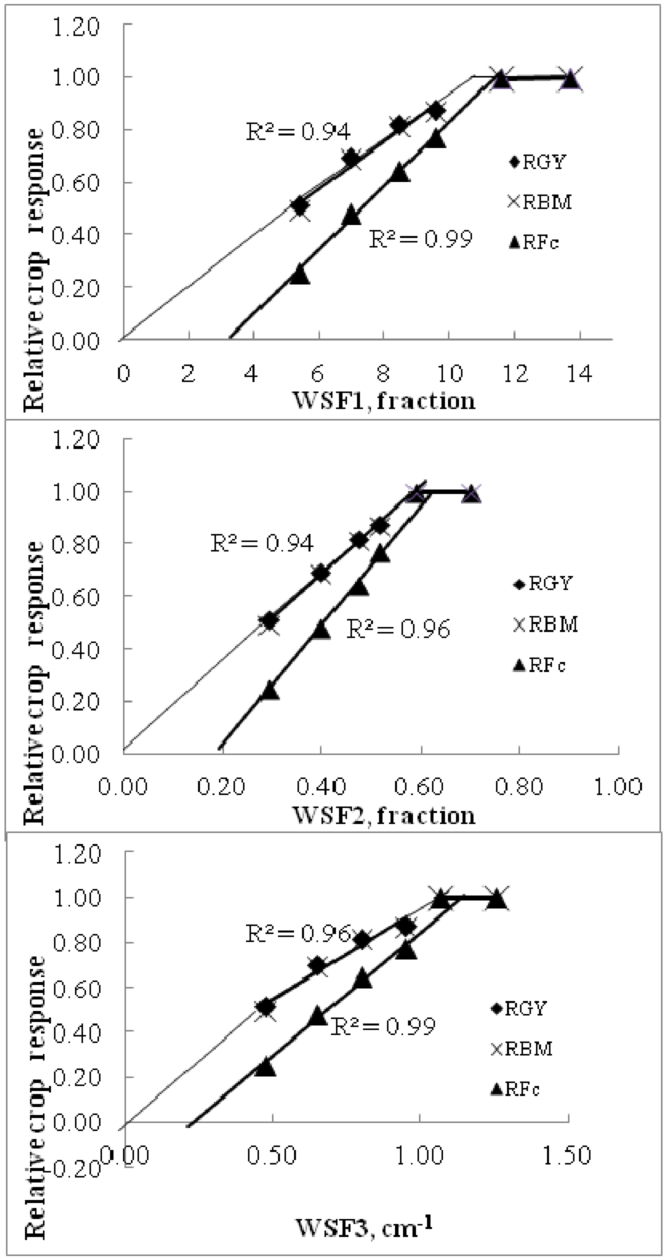

Fig. 2-3. Piecewise linear regression relationships between the three water stress factors (average daily WSF1, WSF2 and WSF3) and the three relative crop response variables (RGY, RBM and RFc) of corn, averaged across the four crop seasons of 2008-2011. R^2 shown is for the dark fitted sloping line which has values less than 1 on the Y-axis. Complete set of the piecewise linear relationships are presented in Table 2-3.

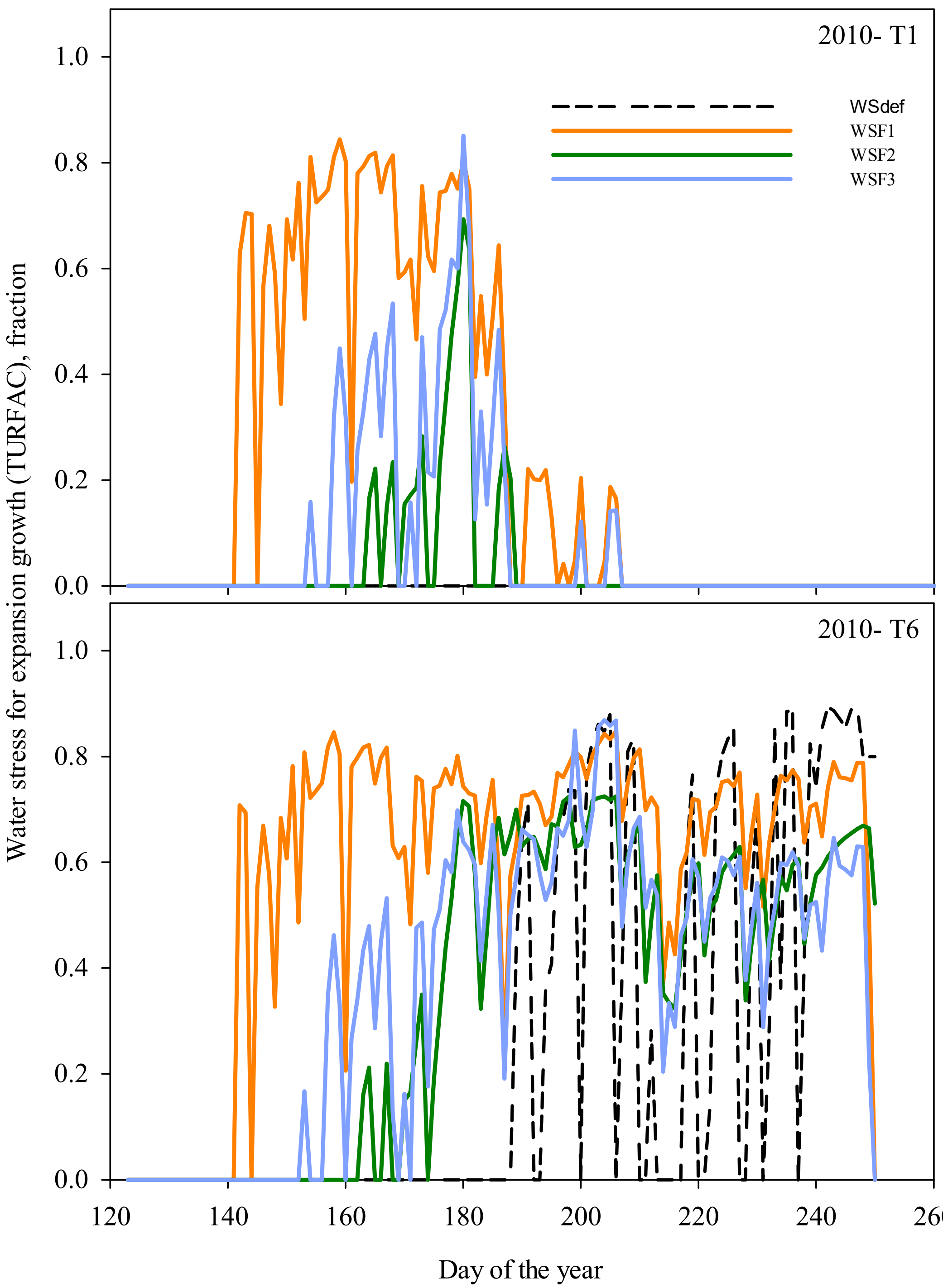

Fig. 2-4. Comparison between the water deficit stress for corn growth (TURFAC or substitute) simulated in response to the default water stress (WS) factor (WSDef) and the three new WS factors (WSF1, WSF2 and WSF3) in 2010 under T1 (high water) and T6 (lowest water) treatments. The stress factors are shown to range from 0 for no stress to 1 for complete stress.

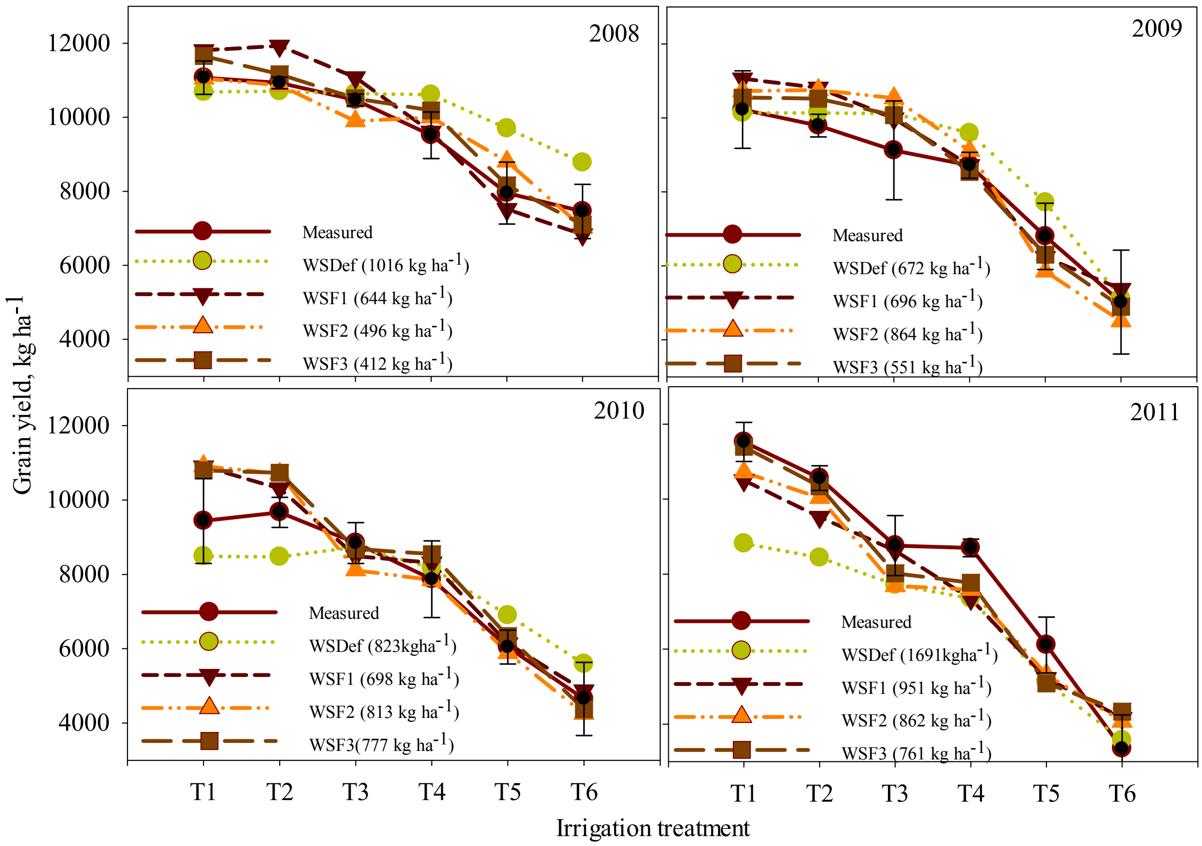

Fig. 2-5. Comparison between measured, and simulated corn grain yields in six irrigation treatments from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSF1, WSF2 and WSF3. Error bars indicate one standard deviation in the measured data. Ma et al. (2012) simulated grain yield using the WSDef stress factor also is shown. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSEs across years were: 1102, 815, 828 and 685 kg ha^{-1} for Ma et al. (2012), and WSF1, WSF2, and WSF3 stress factors, respectively.

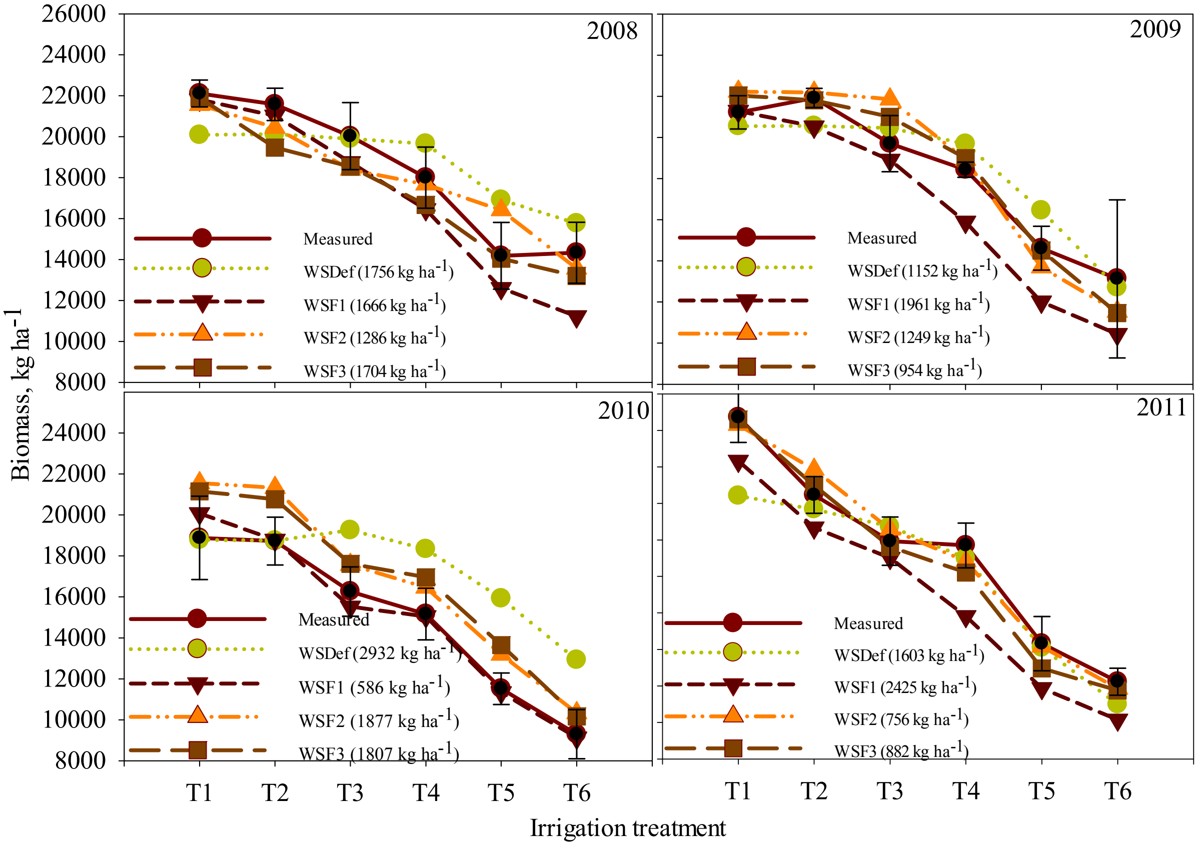

Fig. 2-6. Comparison between measured, and simulated corn biomass in six irrigation treatments from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSF1, WSF2 and WSF3. Error bars indicate one standard deviation in the measured data. Ma et al. (2012) simulated biomass using the WSDef stress factor also is shown. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSEs across years were: 2106, 1793, 1352 and 1402 kg ha^{-1} for Ma et al. (2012), and WSF1, WSF2, and WSF3 stress factors, respectively.

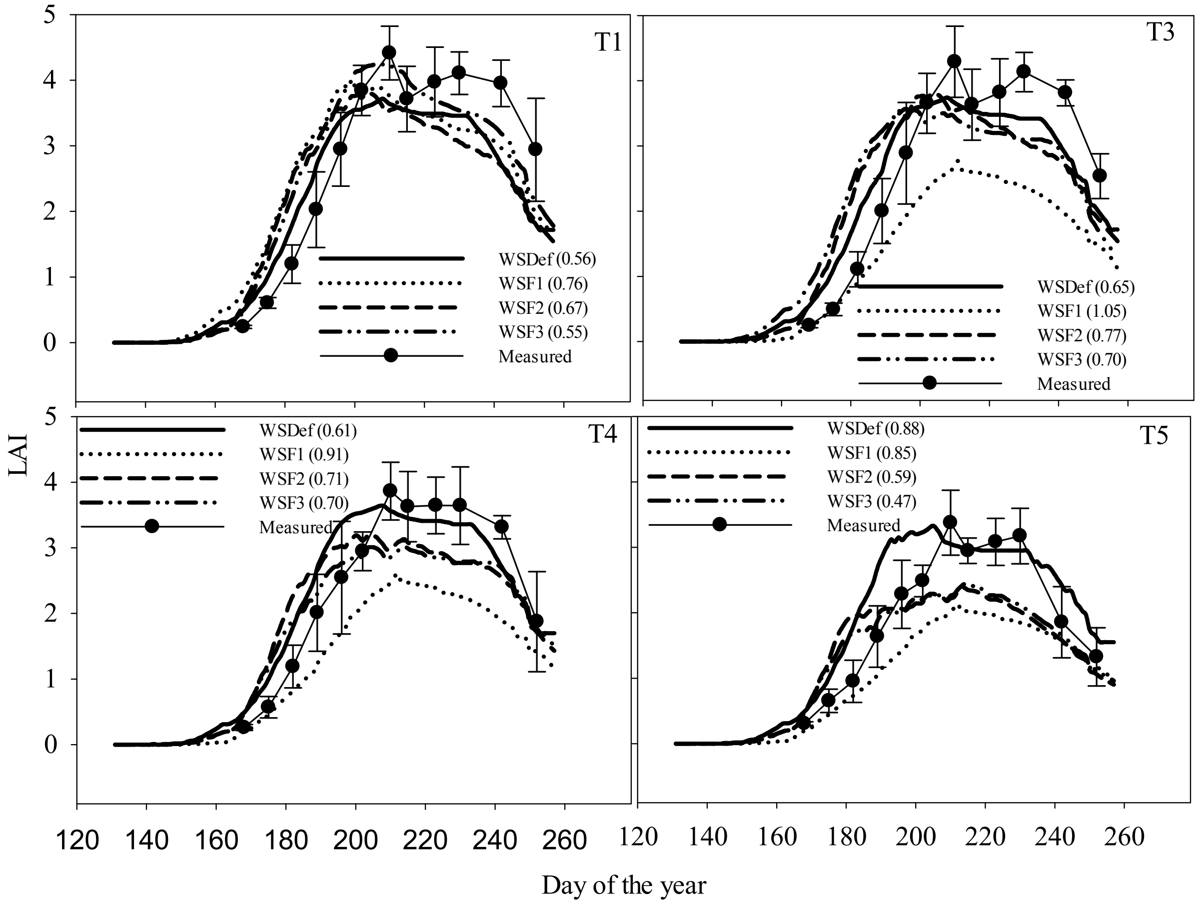

Fig. 2-7. Comparisons of measured and simulated corn LAI using stress factors WSF1, WSF2 and WSF3 in 2010 in the T1, T3, T4 and T5 treatments. Ma et al. (2012) simulated LAI using WSDef stress factor also is shown. Error bars show one standard deviation in the measurements. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSEs of LAI simulations across the four treatments were 0.68, 0.89, 0.69 and 0.61 for the Ma et al. (2012), and WSF1, WSF2 and WSF3 stress factors, respectively.

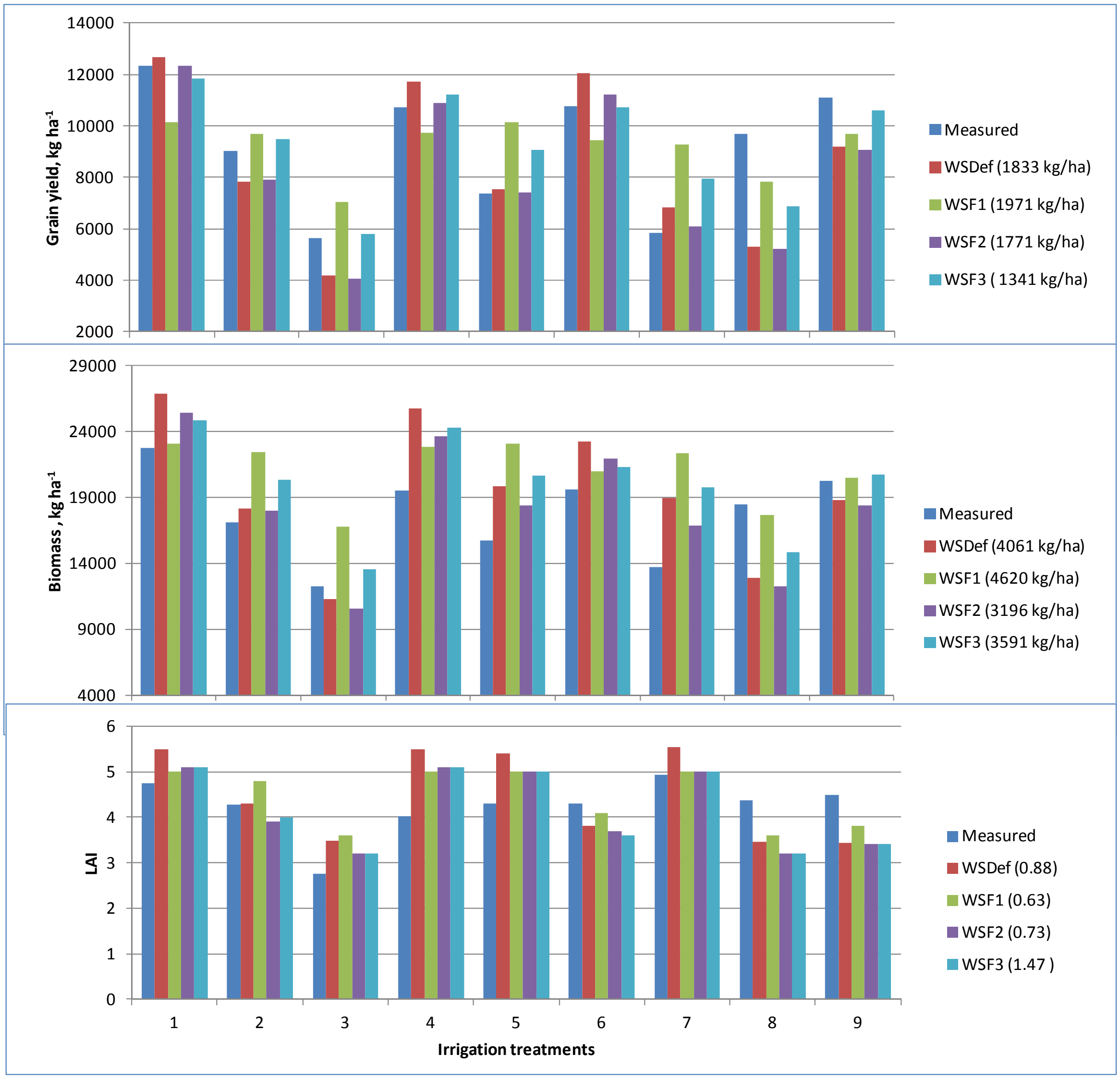

Fig. 2-8. Simulations of grain yield, biomass, and LAI in the SIAZ96 experiment distributed with DSSAT 4.5 using RZWQM2 enhanced with WSF1, WSF2 and WSF3 stress factors. Enclosed in parenthesis of the legends are root mean square errors (RMSE).

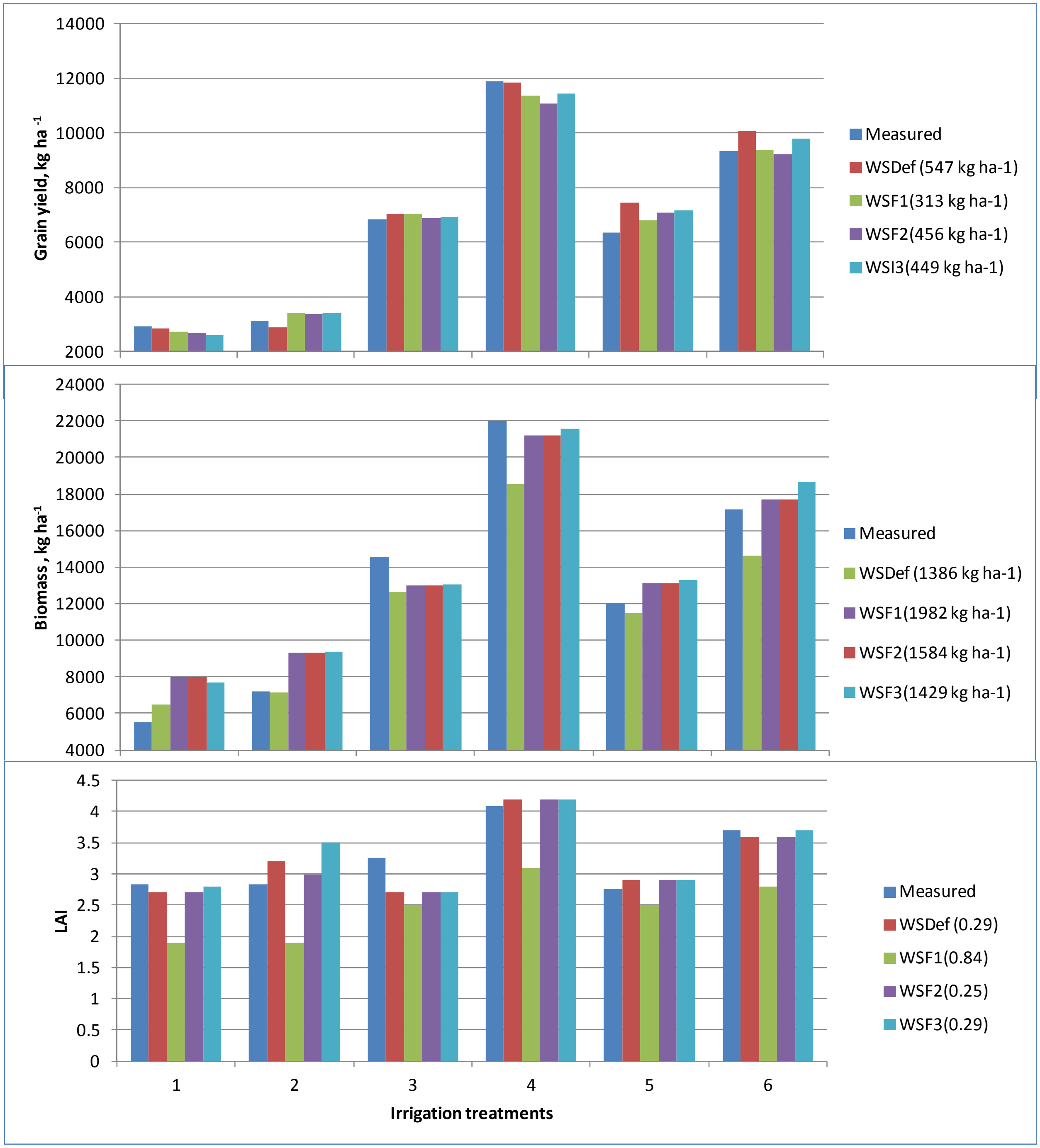

Fig. 2-9. Simulations of grain yield, biomass, and LAI in the UFGA82 experiment distributed with DSSAT 4.5 using RZWQM2 enhanced with WSF1, WSF2 and WSF3 stress factors. Enclosed in parenthesis of the legends are root mean square errors (RMSE).

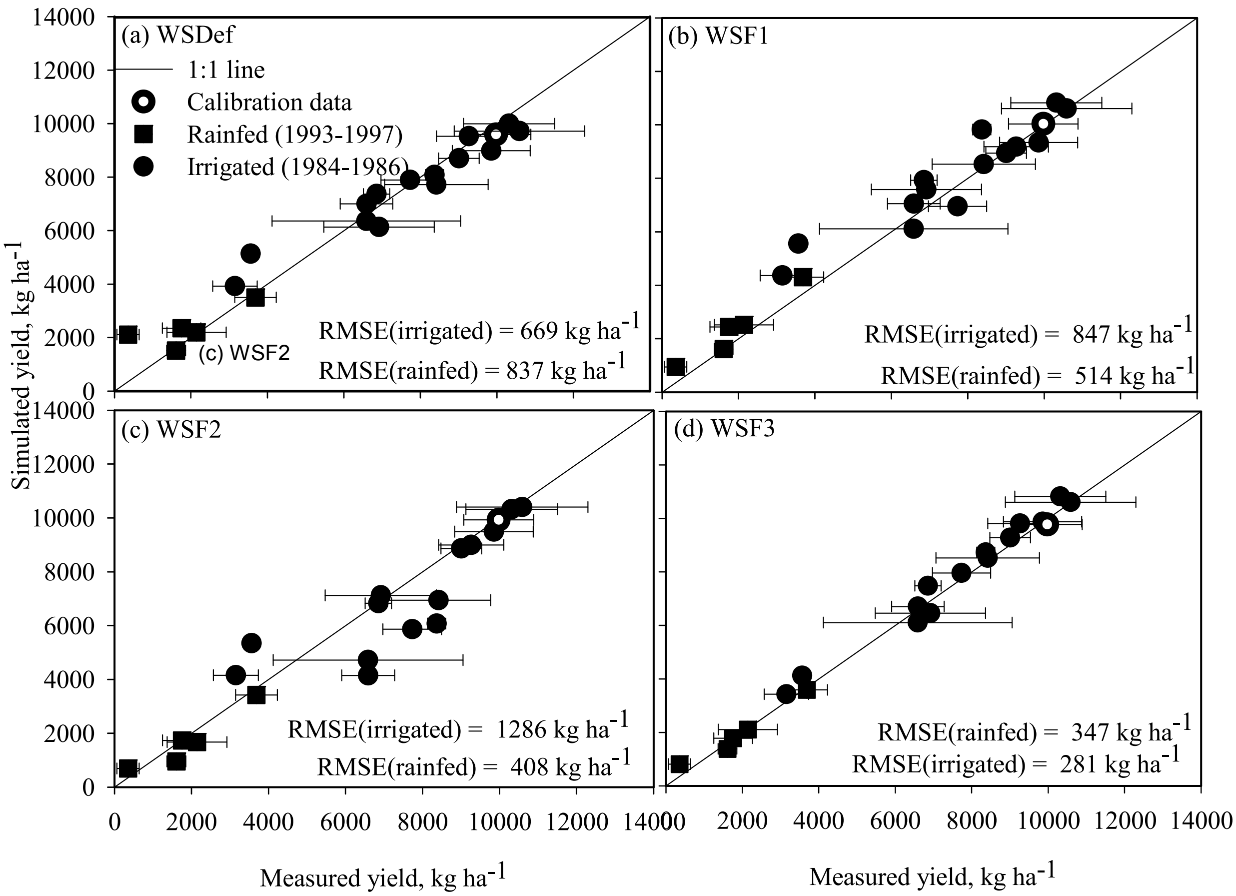

Fig. 2-10. Measured and simulated corn grain yield in the irrigated (1984 to 1986) and rainfed experiments (1993 to 1997) at Akron, Colorado. Error bars indicate 1 standard deviation about the mean of the treatment replications. RMSE = Root Mean Square Error.

REFERENCES

Ahuja, L.R., K.W. Rojas, J.D. Hanson, M.J. Shafer, and L. Ma. (eds.). 2000. Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resources Publications, LLC, Highlands Ranch, CO.

Allen R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Irrigation and Drainage Papers, No. 56. Food and Agriculture Organization (FAO), Rome, Italy. 300pp.

Allen, R. G., I.A, Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder. 2005. The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers. Reston, VA.

Bausch, W., T. Trout, and G. Buchleiter. 2011. Evapotranspiration adjustments for deficit-irrigated corn using canopy temperature: a concept. Irrig. and Drain. 60: 682–693.

Boyer, J.S. 1970. Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiol. 46:234-235.

Brisson, N., B. Seguin, and P. Bertuzzi. 1992. Agrometeorological soil water balance for crop simulation models. Agricultural and Forest Meteorology 59: 267-287.

Cabelguenne, M., C.A. Jones, J.R. Marty, P.T. Dyke, and J.R. Williams. 1990. Calibration and validation of EPIC for crop rotations in Southern France. Agricultural Systems 33:154-171.

Casadebaig, P., L.Guilioni, J. Lecoeur, A. Christophe, L. Champolivier, and P. Debaeke. 2011. SUNFLO, a model to simulate genotype-specific performance of the sunflower crop in contrasting environments. Agricultural and Forest Meteorology 151: 163–178.

Castrignano, A., N. Katerji, F. Karam, M. Mastrorilli, and A. Hamdy. 1998. A modified version of CERES-Maize model for predicting crop response to salinity stress. Ecological Modeling 111:107–120.

Chartzoulakis, K., B. Noitsakis, and I. Therios. 1993. Photosynthesis, plant growth and dry matter distribution in kiwifruit as influenced by water deficits. Irrig. Sc. 14:2-5.

Chaves, M.M, J. Flexas, and C. Pinheiro. 2009. Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. Annals of Botany 103: 551–560.

Chaves, M.M., J.S. Pereira, J. Maroco, M.L. Rodrigues, C.P.P. Ricardo, M.L. Osorio, I. Carvalho, T. Raria, and C. Pinheiro. 2002. How plants cope with water stress in the field. Photosynthesis and growth. Annals of Botany 89:907-916.

Chen J. L., and J.F. Reynolds. 1997. A coordination model of whole plant carbon allocation in relation to water stress. Annals of Botany 80:45-55.

Cosgrove D.J. 1998. Cell wall loosening by expansins. Plant Physiology 118**:** 333–339.

Cosgrove, D.J., and R.E. Cleland. 1983. Solutes in the free space of growing stem tissues. Plant Physiology 72**:** 326–331.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. Vadose Zone J. 2:643-649.

FAO (Food and Agriculture Organization of the United Nations). 2002. Crops and drops: Making the best use of water for agriculture Natural Resources Environ. Dept., FAO, Rome.

Farahani, H. J., and DeCoursey, D. G. 2000. Potential evapotranspiration processes in the soil-crop-residue system. p52-80. *In* L.R. Ahuja, K.W. Rojas, J. D. Hanson, M.J. Shafer, L. Ma (eds.). Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resources Publications, LLC, Highlands Ranch, CO.

Faria, R. T., and Bowen, W. T. 2003. Evaluation of DSSAT soil-water balance module under cropped and bare soil conditions. Brazilian Archives of Biology and Technology 46(4):489-498.

Ghannoum, O. 2009. C_4 photosynthesis and water stress. Annals of Botany 103:635-644.

Gonsamo, A. 2010. Leaf area index retrieval using gap fractions obtained from high resolution satellite data: Comparisons of approaches, scales and atmospheric effects. International Journal of Applied Earth Observation and Geoinformation 12: 233–248.

Granier, C., and F. Tardieu. 1999. Water deficit and spatial pattern of leaf development. Variability in response can be simulated using a simple model of leaf development. Plant Physiol. 119:609-619.

Hall, A.E. 2004. Breeding for adaptation to drought and heat in cowpea. Eur. J. Agron 21: 447–454.

Hergert, G. W. 2010. Limited irrigation of conventional and biofuel crops. Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney, NE., February 24-25, 2010. Available from CPIA, 760 N. Thompson, Colby, Kansas.

Hergert, G.W., N.L. Klocke, J.L. Petersen, P.T. Nordquist, R.T. Clark, and G.A. Wicks. 1993. Cropping systems for stretching limited irrigation supplies. J. Prod. Ag. 6: 520-529.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, K.J. Boote, L.A. Hunt, U. Singh, J.L. Lizaso, J.W. White, O. Uryasev, F.S. Royce, R. Ogoshi, A.J. Gijsman, and G.Y.

Tsuji. 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM].University of Hawaii, Honolulu, Hawaii.

Hsiao, T.C., P. Steduto, and E. Fereres. 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irr. Sci. 25:209–231.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping system model. Europ. J. Agron. 18:235-265.

Klocke, N.L., J.P. Schneekloth, S.R. Melvin, R.T. Clark, and J.O. Payero. 2004. Field scale limited irrigation scenarios for water policy strategies. Applied Engineering in Agriculture 20: 624-631.

Knisel, W.G., and E. Turtola. 2000. GLEAMS model application on a heavy clay soil in Finland. Agric. Water Manage. 43:285-309.

Lizaso, J.L., K. J. Boote, J. W. Jones, C. H. Porter, L. Echarte, M. E. Westgate, and G. Sonohat. 2011. CSM-IXIM: A New Maize Simulation Model for DSSAT Version 4.5. Agron. J. 103: *766-779.*

Ma, L., D.C. Nielsen, L.R. Ahuja, R.W. Malone, S.A. Saseendran, K.W. Rojas, J.D. Hanson, J.G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. Trans. ASAE 46:39-49.

Ma, L., G. Hoogenboom, S. A. Saseendran, P. N. S. Bartling, L. R. Ahuja, and T. R. Green. 2009. Estimates of soil hydraulic properties and root growth factor on soil water balance and crop production. Agron. J. 101:572–583.

Ma, L., L.R. Ahuja, S.A. Saseendran, R.W. Malone, T.R. Green, B.T. Nolan, P.N.S. Bartling, G.N. Flerchinger, K.J. Boote, and G. Hoogenboom. 2011. A Protocol for Parameterization and Calibration of RZWQM2 in Field Research. p 2-64. *In*: L.R. Ahuja and L. Ma (eds.), Methods of introducing system models into agricultural research. Advances in Agricultural Systems Modeling Series 2.

Ma, L., T.J. Trout, L.R. Ahuja, W.C. Bausch, S.A. Saseendran, R.W. Malone, D.C. Nielsen. 2012. Calibrating RZWQM2 model for maize responses to deficit irrigation. Agricultural Water Management 103:140– 149.

Mathews, R., W. Stephens, T. Hess, T. Middleton, and A. Graves. 2002. Applications of crop/soil simulation models in tropical agricultural systems. Adv. Agron. 76:32-124.

McCown, R.L., G.L. Hammer, J.N.G. Hargreaves, D.L. Holzworth, and D.M. Freebairn. 1996. APSIM: A Novel Software System for Model Development, Model Testing, and Simulation in Agricultural Systems Research, Agric. Syst. 50: 255-271.

McCoy, E.L., L. Boersma, and M. Ekasingh. 1990. Net carbon allocation in soybean seedlings as influenced by soil water stress at two soil temperatures. Bot. Gaz. 151:497-505.

McCree, K.J. and Ferndandez, C.J., 1989. Simulation model for studying physiological water stress responses of whole plants. Crop Sci. 29: 354-360.

Neumann, P.M. 1995. The role of cell wall adjustment in plant resistance to water deficits. Crop Sci. 35:1258-1266.

Nielsen, D.C., and B.R. Gardner. 1987. Scheduling irrigations for corn with the crop water stress index (CWSI). Appl. Agric. Res. 2:295-300.

Nouna, B.B., N. Katerji, and M. Mastrorilli. 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance. Europ. J. Agron. 13:309–322.

Pascale, De S., L.D. Costa, S. Vallone. G. Barbieri, and A. Maggio. 2011. Increasing Water Use Efficiency in Vegetable Crop Production: From Plant to Irrigation Systems Efficiency. HortTechnology 21(3):302-308.

Passioura, J.B. 1994. The yield of crops in relation to drought. p. 344-359. *In* K.J. Boote (ed.) Physiology and determination of crop yield. Madison, Wisconsin, USA. ASA, CSSA, SSSA.

Pereira, J.S., and M. M. Chaves. 1993. Plant water deficits in Mediterranean ecosystems. p. 237-251. *In* J. A. Smith and H. Griffiths (ed.) Plant responses to water deficits from cell to community. Oxford: BIOS Scientific Publishers Limited.

Ritchie, J. T. 1998. Soil water balance and plant water stress. p. 42-54. *In* G. Y. Tsuji, G. Hoogenboom, and P. K. Thornton (Eds). Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Ritchie, J.T. 1981. Water dynamics in the soil-plant-atmosphere system. Plant and Soil 58: 82-96.

Saini, H.S. and S. Lalonde. 1998. Injuries to reproductive development under drought stress, and their consequences for crop productivity. p. 224-248. In A.S. Basra (ed.) Crop Sciences: Recent Advances. The Food Products Press, New York, London.

Saseendran, S. A., L. R. Ahuja, D. C. Nielsen, T. J. Trout, and L. Ma. 2008a. Use of crop simulation models to evaluate limited irrigation management options for corn in a semiarid environment, Water Resour. Res. 44, W00E02.

Saseendran S.A., L.R. Ahuja, L. Ma, D.J. Timlin, C.O. Stockle, K.J. Boote, and G. Hoogenboom. 2008b. Current Water Deficit Stress Simulations in Selected Agricultural System Simulation Models, *in* L. R. Ahuja, et al. (Eds.), Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, USA. pp. 2-38.

Saseendran, S. A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on a winter wheat cropping system using RZWQM and CERES-wheat. Agron. J. 96:615-630.

Saseendran, S. A., L. Ma, D.C. Nielsen, M.F. Vigil, and L.R. Ahuja. 2005. Simulating planting date effects on crop production using RZWQM and CERES-maize models. Agron. J. 97:58-71.

Saseendran, S.A., D.C. Nielsen, D. Lyon, L. Ma, D.G. Felter, D.D. Baltensperger, G. Hoogenboom, and L.R. Ahuja,. 2009. Modeling responses of dryland spring triticale, proso millet, and foxtail millet to initial soil water in the High Plains. Field Crops Res. 113:48-63.

Saseendran, S.A., D.C. Nielsen, L. Ma., L.R. Ahuja, and M.F. Vigil. 2010. Simulating alternative dryland rotational cropping systems in the Central Great Plains with RZWQM2. Agron. J. 102:1522-1534.

Sau, F., K. J. Boote, W. M. Bostick, J. W. Jones, and M. I. Minguez. 2004. Testing and improving evapotranspiration and soil water balance of the DSSAT crop models. Agron. J. 96: 1244-1257.

Schneekloth, J.P., N.A. Norton, R.T. Clark and N.L. Klocke. 2001. Irrigating for maximum economic return with limited water. University of Nebraska, Lincoln, NE. NebGuide G1422.

Schneekloth, J.P., N.L. Klocke, G.W. Hergert, D.L. Martin, and R.T. Clark. 1991. Crop rotations with full and limited irrigation and dryland management. Trans. ASAE 34: 2373-2380.

Sepaskhah, A.R., A.R. Bazrafshan-Jahromi, and Z. Shirmohammadi-Aliakbarkhani. 2006. Development and Evaluation of a Model for Yield Production of Wheat, Maize and Sugar beet under Water and Salt Stresses. Biosystems Engineering 93 (2):139–152.

Sinclair, T.R., 1986. Water and nitrogen limitations in soybean grain production. I-Model development. Field Crops Res., 15:125-141.

Sobrado, M.A. 1986. Tissue water relations and leaf growth of tropical corn cultivars under water deficits. Plant, Cell and Environment 9:451- 457.

Stockle, C.O., M. Donatelli, and R. Nelson. 2003. CropSyst, a cropping systems simulation model. Europ. J. Agronomy 18:289-307.

Tardieu, F., C. Granier, and B. Muller. 1999. Research review: Modeling leaf expansion in a fluctuating environment: are changes in specific leaf area a consequence of changes in expansion rate? New Phytol. 143:34-43.

Tardieu, F., M. Reymond, P. Hamard, C. Granier, and B. Muller. 2000. Spatial distributions of expansion rate, cell division rate and cell size in maize leaves: a synthesis of the effects of soil water status, evaporative demand and temperature. Journal of experimental botany 51:1505-1514.

Trout, T.J., W.C. Bausch, and G.W. Buchleiter. 2010. Water Production Functions for Central Plains Crops. An ASABE Conference Presentation. Paper Number: IRR10-9654. 5th National Decennial Irrigation CD-ROM Proceedings. ASABE Publication Number 711P0810cd. P8.

Willmont, C.J. 1981. On the validation of models. Physical geography 2:184-194.

Woli, P. J.W. Jones, K.T. Ingram, and C.W. Fraisse. 2012. Agricultural Reference Index for Drought (ARID). Agron. J. 104:287–300.

CHAPTER III

ENHANCING RZWQM2 FOR WATER STRESS RESPONSES OF CORN (*Zea mays* L.)*

INTRODUCTION

Soil water deficit is one of the major abiotic stresses, which adversely affects crop growth and yield (Hsiao et al., 2007). This adverse effect is brought about in two major ways. Lack of adequate soil water supply and reduced plant water uptake reduce cell division for leaf elongation and root enlargement, which lead to a decline in leaf area for photosynthesis and nutrient ion transport to the root surface in the soil. The water stress also directly affects many biochemical reactions and physiological growth processes, such as photosynthesis, carbon allocation and partitioning, phasic developmental rates and phenology (Chen and Reynolds, 1997; Tardieu et al., 2000; Chaves et al., 2002; Cakir, 2004; Shao et al., 2008). Corn (*Zea Mays* L.) has long been reported to be very sensitive to water deficits, especially during its reproductive stages (Denmead and Shaw, 1960; Hall et al., 1981; Grant et al., 1989; Bai et al., 2006).

Corn production in the Great Plains of Colorado, USA has increased noticeably in the past decades with the availability of irrigation systems and cultivars with improved radiation and water use efficiency (Norwood, 2001; Castleberry et al., 1984; Hergert et al., 1993). However, the crop water stress due to low precipitation, limited irrigation water available, and high

*Author names for paper to be submitted: Saseendran, S.A, L.R. Ahuja, L. Ma, T.J. Trout, D. C. Nielsen, A.A. Andales, J. L. Chávez, and J.M. Ham temperatures are still the main limiting factors for corn and other agricultural production in the region (Halvorson et al., 1999; Norwood, 1999). Greater demands for fresh water resources from various sectors of the human enterprises in the region, today, necessitate even more judicial and efficient use of limited available water for sustained crop production in the region (Saseendran et al., 2008b; DeJonge et al., 2011).

In the above context, agricultural system models are the potential state of the science tools for developing whole-system-based crop and water management practices for optimized use of limited precipitation and supplementary irrigation for crop production (Jackson et al., 1990; Saseendran et al. 2008b; DeJonge et al., 2011; Salazar, 2012). Accurate quantification of crop responses to water stress (WS) in agricultural system models is critical for their applications for this purpose. In most system models, the WS effect is accounted through specification of a 'water stress factor', which is generally expressed as a supply/ demand ratio to modulate the crop growth and development processes (Ritchie, 1981; Saseendran et al., 2008a), with slight variation in the form of this factor. All major crop system models, APSIM (McCown et al., 1996), CropSyst (Stockle et al., 2003), and DSSAT (Jones et al., 2003; Ritchie, 1998; Woli et al., 2012) use the ratio of potential uptake to potential transpiration, or actual to potential transpiration to represent water stress for modulating photosynthesis and leaf expansion growth in crop simulations. A notable exception is in the usage of the 'fraction plant extractable water in the root zone soil' as water stress factor for modulating phenology and N fixation, in the APSIM model. The RZWQM2 model, uses the DSSAT v4.0 (CSM-CERES and CROPGRO) crop models for simulations of various crops and uses its water stress functions (Ahuja et al., 2000; Ma et al., 2009). Modifications of the CSM-CERES-Maize model have been reported recently for improved photosynthesis and leaf area simulation in the CSM-CERES-Maize 4.5

and CSM-IXIM-Maize 4.5 versions of the corn model within DSSAT 4.5 (Jones et al., 2003; Hoogenboom et al., 2010; Lizaso et al., 2011). However, these models still use the same water stress factors as version 4.0. The need for better quantification of water stress factors has been reported in several past studies (Cabelguenne et al., 1990; Castrignano et al., 1998; Nouna et al., 2000; Faria and Bowen, 2003; Sau et al., 2004; Saseendran et al., 2008a; DeJonge et al., 2011).

In this study, we modified the current DSSAT stress factors in the RZWQM2 in three different ways (WSI1, WSI2 and WSI3) as explained below. Main objective was to test these three WS factors for simulating the detailed multi-level irrigation experiments in corn from 2008 to 2011 at Greeley, CO, using the RZWQM2 model with the embedded CSM-CERES-Maize 4.0 crop growth module. The model with modified WS factors was also tested for simulating dryland and limited irrigation studies at Akron, CO and at two more experiments in sandy and sandy loam soils available in DSSAT 4.5 database.

FORMULATION OF WATER STRESS FACTORS

As noted above, the RZWQM2 uses the water stress functions of DSSAT based on the ratio of potential root water uptake (TRWUP) to potential plant transpiration (EP_o) (Ritchie, 1998), referred hereafter as default WS factors (WSDef). In simulations under well-watered conditions, TRWUP is higher than EP_o and there is no water stress (Fig. 3-1). As the soil dries out due to root water uptake, TRWUP decreases. At a certain stage, a threshold is reached where the first WS factor or turgor factor to modulate expansive leaf growth, called TURFAC, is activated. In both C3 and C4 plants, this point corresponds to the situation when the root water uptake combined with osmotic adjustments and cell wall extensibility (in meristematic cells) fail to maintain turgor pressure to sustain cell division (mitosis) and leaf expansion growth (Boyer, 1970; Cosgrove and Cleland, 1983; Neumann, 1995; Cosgrove, 1998). The TURFAC is defined as:

$$TURFAC = \frac{TRWUP}{RWUEP1 * EPo} \quad \text{............ (1)}$$

where, *RWUEP*1 is a species-specific parameter, used for emulating the water stress level in the plants below which turgor pressure in the plant leaf cells fail to sustain expansion growth at the potential level, which is currently set to 1.5 for corn. This suggests that the plant start experiencing WS for expansion growth when TRWUP is 1.5 times of EPo.

When *EPo* demand equals or exceeds the TRWUP, a second stress factor, called *SWFAC,* is activated:

$$SWFAC = \frac{TRWUP}{EPo} \quad \text{............ (2)}$$

SWFAC mainly affects photosynthesis and other dry matter accumulation related processes. In plants, this stress sets in at a leaf water potential level, which is significantly below the TURFAC level, when the photosynthesis and other carbon assimilation processes are impaired due to water shortage. Both TURFAC and SWFAC stress factors are used as direct multipliers on leaf growth and dry matter accumulation rate that ranges from 1 for no stress to 0 for complete stress.

The TRWUP in CSM-CERES-maize module in RZWQM2 is computed using a simplified analytic solution of radial flow of water to plant roots in the soil profiles (Eq. 3 given below) (Ritchie, 1998). The EP_o is computed from potential evapotranspiration in the soil-residue-canopy system modeled using the ‘extended Shuttleworth-Wallace ET model’ (Farahani and Ahuja, 1996: Farahani and DeCoursey, 2000).

The simplified close-form equation of (Ritchie et al., 1998) used to calculate the TRWUP in Eq. (1) and (2) above is:

$$TRWUP = \sum_{i=1}^{N} \frac{k1 * e^{k2*(SW(i)-LL(i))}}{k3 - \ln(RLV(i))} * RLV(i) * \Delta Z(i) \qquad \text{----------------} \ (3)$$

where, RLV(i) is root length density in soil layer i; k1, k2 and k3 are constants; SW(i) and LL(i) are, respectively, soil water content and lower limit of plant available water in layer i; Z(i) is soil depth of layer i.

WSI1

Equation (3) was derived from the theory of radial flow to a single root with several simplifying assumptions (Gardner, 1960). It assumes that the hydraulic conductivity of all soils is similar when normalized with respect to the lower limit soil water content (approximately corresponding to 1.5 MPa soil water tension). This assumption may be nearly correct when the soil water content is near lower limit but has larger errors for higher soil water contents. The equation also assumes that the water potential gradient between the root and the soil remains constant even when the soil dries out; in fact the water potential of the roots changes considerably throughout the day and so will the gradient. The equation of Nimah and Hanks (1973) solves the same radial flow of water to the roots numerically without the above assumptions. Therefore, we explored the use of Nimah-Hanks equation option in the RZWQM2 for more rigorous computation of the TRWUP as described below.

In the RZWQM2 soil water routine, between rainfall or irrigation events, the soil water is redistributed by using the Richards' equation (Eq. 4) (Ahuja et al., 2000) in which the sink term S(z, t) includes the rates of root water uptake and contribution to tile flow from a given soil depth. The root water uptake part of the sink term, S_r (z, t) (cm hr^{-1}), is computed using the Nimah and Hanks (1973) equation (Eq. 5):

$$\frac{\partial\theta}{\partial z} = \frac{\partial}{\partial z}\left[K(h,z)\frac{\partial h}{\partial z} - K(h,z)\right] - S(z,t) \qquad \text{---------------------(4)}$$

$$S_r(z,t) = \frac{[H_r + (R_r\, z) - h(z,t) - s(z,t)]R(z)\, K(\theta)}{\Delta x\, \Delta z} \qquad \text{---------------------- (5)}$$

where, S(z,t) = sink term for root water uptake and tile drainage rates (cm hr^{-1}); θ= volumetric soil water content (cm^3 cm^{-3}); t = time (hr); z = soil depth (cm, assumed positive downward); h = soil-water pressure head (cm); K = unsaturated hydraulic conductivity (cm hr^{-1}), a function of h and z; H_r = an effective root water pressure head (cm); R_r = a root resistance term and the product (R_r z) accounts for gravity term and friction loss in H_r (assumed = 1.05); s(z,t) = the osmotic pressure head (assumed = 0 cm); Δx = the distance from plant roots to where h(z,t) is measured (assumed =1 cm); Δz = soil depth increment (cm); R(z) = proportion of the total root activity in the depth increment Δz, obtained from the plant growth model.

The sum total of S_r (z, t) over the transient root zone gives the total root water uptake TRWUP for any given time. The actual uptake cannot exceed the potential transpiration demand (EP_o) of the atmosphere; this is obtained by varying the value of H_r in Eq. (5) until the total uptake is equal to or less than the EP_o. The total potential uptake ($TRWUP_{NH}$) is calculated from summation of Eq. (5) with H_r set equal to -1.5 MPa as the permanent wilting point (PWP, can vary with crop species).

The WSI1 stress factors are then calculated as:

$$\text{SWFAC} = \frac{(\text{TRWUP}_{\text{NH}})}{\text{EP}_{\text{o}}} \qquad \text{---------------------- (6)}$$

and

The formulation of TURFAC with the new SWFAC for corn is then:

$$\mathrm{TURFAC} = \frac{\mathrm{SWFAC}}{1.5} \qquad \text{--------------------- (7)}$$

WSI2

In addition to the above computation of $TRWUP_{NH}$, we also realized that Eq. (1) and (2) neglect the water stress that the plants may experience due to heating of the canopy by the latent heat energy partitioned to potential soil evaporation but not used in soil evaporation when the surface soil water content is limiting. Therefore, we explored to include stress due to additional canopy heating in calculation of the WS factors by changing their formulation as described below.

We changed formulation of SWFAC in Eq. (6) by replacing EPo by ET, the potential crop ET, in the denominator and adding actual soil evaporation (E_S) for the day in the numerator:

$$\mathrm{SWFAC} = \frac{\mathrm{TRWUP_{NH}} + \mathrm{E_S}}{\mathrm{ET}} \qquad \text{---------------------- (8)}$$

The formulation of TURFAC, using the new SWFAC, remains the same as in Eq. (7).

WSI3

The stress factor WSI3 is essentially the same as WSI2 except that the calculation of TURFAC (Eq. 9). Instead of using SWFAC and an arbitrary factor of 1.5 in the denominator of Eq. (7) to calculate TURFAC, we explored several values of the root water pressure H_r in Eq. (5) at which the TRWUP (denoted as TRWUPtg) will begin to be insufficient to maintain the turgor pressure (includes water uptake due to osmotic gradient adjustments) in the leaves for expansion growth. We found that the H_r value of -0.1 MPa gave the best results, close to those obtained with using Eq. (7). The new TURFAC was then defined as:

$$\text{TURFAC} = \frac{\text{TRWUP}_{\text{tg}} + \text{E}_{\text{S}}}{\text{ET}} \qquad \text{------------------------------} \ (9)$$

SWFAC remains the same as in Eq. (8). The motivation for using TRWUP_{tg} to calculate TURFAC, instead of using an arbitrary factor of 1.5, was to relate TURFAC to a biophysical factor of root water potential at which the leaf expansion growth starts to be affected. The value of -0.1 MPa (1 bar) seems like a reasonable value of that critical potential. However, this value needs to be further evaluated with more data, along with improvement of the leaf growth module.

MATERIALS AND METHODS

Greeley, Colorado experiments

The field experiments for development of the WS factors in this study were conducted at the Limited Irrigation Research Farm (LIRF) (40° 26’ N, 104° 38’ W, and 1428 m amsl) of the Water Management Research Unit, USDA-ARS near Greeley, Colorado during 2008-2011. Detailed description of the experiments is available in Trout et al. (2010). In brief, the LIRF is a 16 ha field irrigation research facility for various crops (corn, winter wheat, sun flower and dry bean) of the region. Soils in the farm are Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents). All the three soils have fairly uniform texture in the 200 cm profile with average of 74% sand, 17% clay, and 9% silt. Irrigation treatments are replicated four times in 9 X 40 m plots (0.76 m row spacing). Six water treatments are randomized within each replication (Table 3-1).

The six irrigation treatments were designed to meet certain percentages of potential crop ET (ETc) requirements during the growing seasons, starting 3 to 4 weeks after planting: 100% (T1), 85% (T2), 70%F (T3), 70% (T4), 55% (T5), and 40% (T6) of ETc (Table 3-1). The amount of irrigation water for each treatment was estimated on a weekly basis based on alfalfa reference ET demand (ETr; Allen et al., 2005), crop coefficient, rainfall, and soil water deficit (Trout et al., 2010; Bausch et al., 2011). For all the treatments except for T1 and T3, 20% of the estimated weekly amounts during vegetative growth period were saved and added to weekly amounts during the reproductive growth period.   Crop rows have a north/south orientation.

Field corn (*Zea mays* L.) (cv: Dekalb 53-59) was planted on 132, 131, 131 and 123 day of the year (DOY) and harvested on DOY 310, 316, 292, and 310 in 2008, 2009, 2010 and 2011, respectively. A 2.0 cm irrigation was applied after planting in all plots to assure good germination. Fertilizer as UAN was applied before planting and then with irrigation water during the growing seasons, to assure ample N for stress free growth.

Soil water content was measured in each plot between 30 and 200 cm depth with a neutron probe (503 DR Hydroprobe moisture gauge, Campbell Pacific Nuclear) in an access tube in the crop row near the center of each plot. Surface soil water content (0-15 cm) was measured with a MiniTrase portable TDR system (Soil Moisture Equipment Corp.). These measurements were made prior to each irrigation and following an irrigation or precipitation event. Weather data were recorded on site (GLY04) and available at http://ccc.atmos.colostate.edu/~coagmet/ were used in calculation of ETr.

Grain yield and crop biomass at harvest of the three crops were measured every year. However, biomass was measured only in a few plant samples, which may make these measurements less reliable than grain yields. Leaf area index (LAI) measurements were not made systematically, and continuous full season measurements were made (LI-3000C Portable Leaf Area Meter) only in 2010 in the T1, T3, T4 and T5 treatments. However, canopy cover (C_c) was estimated with a nadir view digital camera (ADC, TetraCam, Inc.) mounted on a “high boy” mobile platform and driven through the plots weekly. The C_c data were used to roughly calculate LAI using the Farahani and DeCoursey (2000) equation for corn and utilized for comparative evaluation of LAI simulations by the model across different water levels. Phenology notes in terms of days to tasseling were available in 2008 and 2009.

Akron, Colorado experiments

One set of experiments was conducted in a silt loam soil (fine montmorillonitic mesic Pachic Arguistoll) at Akron (40.15^{O}N, 103.14^{O}W, 1.38 km amsl), Colorado, USA under both irrigated and rainfed conditions over a period of eight years. In the irrigation experiments, conducted during 1984, 1985, and 1986, corn hybrid ‘Pioneer Brand 3732’ (101-d relative maturity) was planted under a line-source gradient irrigation system with maximum water application next to the irrigation line and linearly declining water application with distance from the line. In 1985, additional irrigation treatments were imposed through drip irrigation using four irrigation levels determined by different threshold values of the Crop Water Stress Index (Saseendran et al., 2008b). The corn hybrid ‘Pioneer Brand 3732’ used in the irrigation studies was also used in the rainfed corn experiments from 1993 to 1997 at the location, therefore data during this period was used for simulations of the crop under rainfed conditions. Saseendran et al. (2008b) simulated the Akron experiments using the CERES-Maize v4.0 in within DSSAT (Jones et al., 2003). The cultivar parameters developed by Saseendran et al. (2008b) were used as starting point for calibration of the cultivar parameters in this study (Table 3-3). Ma et al. (2011)

protocol was adopted for calibration of the cultivar parameters. Grain yield data collected in the drip irrigation treatment (wettest, 213 mm applied) in 1985 was used in the calibration. The calibrated cultivar specific coefficients were then used for simulating the crop in the 10 remaining irrigation treatments from 1984 to 1986, and 5 rainfed experiments from 1993 to 1997.

DSSAT datasets

The DSSAT suite of cropping system models have been used extensively for simulations of various crops across the world (Jones et al., 2003). In this study, the enhanced RZWQM2 was further tested for simulations of corn in two irrigation experiments distributed with the DSSAT 4.5 package, one in a sandy loam soil conducted at Zaragoza (41.43^{O}N, 0.49^{O}W, 0.23 km amsl), Spain in 1996 (SIAZ experiments) and another in a sandy soil conducted at Gainesville (29.63^{O}N, 82.37^{O}W, 0.01 km amsl), Florida, USA in 1982 (UFGA experiments) (Hoogenboom et al., 2010). The SIAZ experiment consisted of: (1) full irrigation to meet the consumptive use demand of the crop, (2) 50% of full irrigation, (3) a third of full irrigation, (4) full during the first 2 phases (crop season was divided into three phases), (5)full irrigation in phases 1 and 3, (6) full irrigation in phases 2 and 3, (7) full irrigation in 1st phase, (8) full irrigation in 3rd phase, and (9) full irrigation in 2nd phase conducted in the year 1996 . The UFGA experiment consisted of corn under (1) rainfed low N, (2) rainfed high N, (3) irrigated low N, (4) irrigated high N, (5) water stress in vegetative stage with low N, and (6) water stress in vegetative stage with high N conducted in 1982.

RZWQM2 Model

The agricultural system model, RZWQM2 (Root Zone Water Quality Model), is process-oriented, and combines the biological, physical and chemical processes for simulation of impacts of agro-management practices (tillage, water, agricultural chemical, and crop) on soil water, crop production and water quality (Ahuja et al., 2000). The CSM-CERES-maize 4.0 module is embedded within the RZWQM2 for simulation of corn growth (Ma et al., 2009). The RZWQM2 and its previous versions have has been used extensively for simulating corn growth under various conditions in the Great Plains of USA (Ma et al., 2003; Saseendran et al., 2004, 2005, 2008b, 2009, 2010). Advantages of using the RZWQM2 model come from combining the detailed simulations of soil surface residue dynamics, tillage and other soil management practices, and detailed soil water and soil carbon/nitrogen processes of RZWQM with the detailed crop specific plant growth modules of the DSSAT 4.0 suite of crop models. Ma et al. (2005, 2006, 2009) reported comparable simulation results of soybean and maize production using the RZWQM-DSSAT (RZWQM2) hybrid models as the original CROPGRO and CERES models within DSSAT. Ma et al. (2012) simulated the LIRF experiments for corn from 2008-2010 using the CSM-CERES-Maize v4.0 in RZWQM2.

Input data for the simulations and calibration of RZWQM2

RZWQM2 model needs inputs of daily weather (daily solar irradiance, maximum and minimum temperature, wind speed, relative humidity, and precipitation as break point rainfall data), soil and crop management (planting dates, planting depth, row spacing and plant population; amount, dates, and methods of irrigation and fertilizer applications; and dates and methods of tillage operations). It also requires soil physical properties (soil profile depth and horizons or layers, and soil texture, bulk density), soil water retention curve, soil hydraulic conductivity, and organic matter content in the profile by horizon. These input data were collected in the LIRF experiments or were derived from collected data. Soil water retention curves and saturated hydraulic conductivity of each soil horizon are represented in the form of the Brooks and Corey equations (Ahuja et al., 2000). The soil water retention curves (SWRC) for the model soil water balance were obtained from soil-core measured soil bulk density and field estimated field capacity (assumed to be equal to 0.033 MPa suction water content) and by assuming that 50% of field capacity is wilting point (1.5 MPa suction water content), which is close to the average ratio between 1.5 MPa water content and 0.033 MPa water content measured in the laboratory cores and as reported by Rawls et al. (1982). The Brooks-Corey equation was fitted to these data for each of the soil layers to obtain the SWRC (Brooks and Corey, 1964) (Table 3-2). Hydraulic conductivity values were obtained from soil texture and SWRC using the default tables or empirical equations in the model.

As various process interactions in the agricultural production system are highly complex, the model parameters required for reliable simulation of the system need careful calibration based on measured results (Ma et al., 2011). The RZWQM2 requires careful iterative calibration of its parameters for soil water component, followed by the nitrogen (N) and the plant growth components. 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 (Ma et al., 2011). The calibration procedure included matching simulation results with measured soil water, transpiration, ET, anthesis and maturity dates, maximum LAI, and final biomass and yield. Unfortunately, due to complex interactions the calibrated parameters, especially the crop cultivar parameters, are not completely independent of the type of stress factors used in the model.

Therefore, the RZWQM2 cultivar parameters calibrated by Ma et al. (2012) with the default WS factors (WSDef) for simulating the LIRF experiments from 2008 to 2010 were used in this study as a starting point, and adjusted slightly for the new WS factors for comparisons of the best possible results from using the default factors with those from the modified WS factors.

Statistics for Model Calibration and Evaluations

We evaluated the simulation results using: (i) Root Mean Squared Error (RMSE), Eq. (9), between simulated and observed values; (ii) relative RMSE (RRMSE) that varies between 0 and 100% Eq. (10), (iii) the index of agreement (d) between measured and simulated parameters (Willmott, 1981) which varies between 0 (poor model) and 1 (perfect model), Eq. (11); and (iv) coefficient of determination (R^2), Eq. (12).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad \text{--------------- (9)}$$

$$\mathrm{RRMSE} = \frac{RMSE}{O_{avg}} \quad \text{---------------- (10)}$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(|Pi - O_{avg}| + |Oi - O_{avg}|)^2} \quad \text{------- (11)}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})\right]^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2 \sum_{i=1}^{n}(P_i - P_{avg})^2} \quad \text{------------ (12)}$$

where P_i is the ith simulated value, P_{avg} is the average of the simulated values, O_i is the ith observed value, O_{avg} is the average of the observed values, and n is the number of data pairs.

RESULTS AND DISCUSSIONS

Greeley, Colorado experiment

Measured rainfall and irrigation varied markedly between the crop seasons from 2008 to 2011 in the LIRF experiments (Table 3-1). However, in the absence of measured initial conditions, all the RZWQM2 simulations in this study, across the four years (2008 to 2011), six treatments (T1 to T6) and the three water stress factors (WSI1, WSI2 and WSI3), were with the same initial soil water and nutrient conditions on the first day of the year (initial water content on January 1 of each year was assumed to be at field capacity in the upper 450 mm and half of the plant available water (PAW) below this depth as followed in Ma et al. (2012). Ma et al. (2012) initially calibrated the model for plant and soil parameters using data collected in 2008 and then refined them for simulating the experiments in 2009 and 2010. Unfortunately, as stated above the calibrated plant parameters are affected by the choice of the WS factors due to complex interactions between them; in other words the parameters were selected that gave the best results for yield and biomass with the default WS factor, WSDef. Recognizing this fact in the calibrated plant parameters for responses to water stress with the default WSDef, against which comparisons were made, the final cultivar parameters found by Ma et al. (2012) for LIRF experiments were slightly fine tuned for the best simulations of the measured grain yield, biomass, and LAI when the three different water stress factors were used in simulations. These parameters were calibrated manually following Ma et al. (2011) using the measured grain yield, biomass, and LAI in 2008, and used for simulating the experiments from 2008-2011 (Table 3-3). However, the changes in the parameters were not large and one set of coefficients were found suitable for simulations with WSI1, WSI2 and WSI3 stress factors (Table 3-3). Simulated phenology dates were compared with available field notes. In general, the anthesis and physiological maturity dates in the simulations were off by 2 to 7 days from the field estimated dates in simulations from 2008-2011 with the three water stress factors.

Comparison of the changes in different SWFAC and TURFAC stress factors.

In general, appreciable differences in simulated WS between WSdef and the three new WS factors were in the beginning of the crop season when the soil was not fully covered by the crop (for discussion, the stress factors are shown to range from 0 for no stress to 1 for complete stress) . Average TURFAC values simulated using WSdef, WSI1, WSI2 and WSI3 under T1 treatment were 0.00, 0.00, 0.31 and 0.14, respectively, until the simulated crop LAI reached a value of 1.00 on DOY 166 (Fig. 3-2 and 3-3). Corresponding SWFAC values simulated were 0.0, 0.0, 0.01 and 0.01, respectively. The simulated TURFAC and SWFAC values after the crop LAI exceeded value of 3.50 on DOY 192 was 0.00 for all the four WS factors (Fig. 3-3). The difference in the stress factors simulated in the early phases of the crop development was mainly due to the fact that in the WSdef [Eq. (1) and (2)], water demand and supply is based on the potential plant water uptake and potential plant transpiration, both neglect the heating of canopy (sensible heat) due to unmet soil evaporation demand. When the crop does not cover the soil completely and the soil evaporation demand is not met, the heat load developed in the soil is transmitted to the plants causing an enhancement in the water stress experienced by the plants. To account for this effect, in all the stress factors except WSI1 [Eq. (6) and (7)], we have the default potential transpiration demand replaced with ET demand [Eq. (8) and (9)]. However, WSI1 is simply a ratio of the actual $TRWUP_{NH}$ to EP_O [Eq. (6)]. Additionally, WSI2 and WSI3 have actual soil evaporation (E_s) added to the $TRWUP_{NH}$ in the numerator of the equations

[Eq.(8) and (9)] to account for the portion of the soil evaporation demand actually met by rain and irrigation in the experiments.

Soil water simulations

In addition to management (soil-water-crop), water stress experienced by crop plants is directly related to the water storage capacity of the soil, its depletion and replacement (Ritchie, 1981). Therefore, adequate calibrations of the model for soil water simulations are important for the correct estimation of WS factors that affect crop growth and development. Soil water simulations under all the treatments in response to the three stress factors (WSI1, WSI2 and WSI3) were reasonably accurate in 2008, 2009 and 2010. In these years, RRMSE of total profile (180 cm) soil water simulations was between 7.3 and 15.6 %, and d index between 0.68 and 0.97 (RMSE between 2.4 and 5.5 cm, and R^2 between 0.40 and 0.77) (Table 3-4). Error statistics for soil water simulations in 2011 were higher, with RRMSE between 10.2 and 23.0% (RMSE between 3.15 and 7.09 cm; R^2 between 0.06 and 0.32; and d index between 0.52 and 0.92) (Table 3-4). Differences in error statistics across the years occurred due to the fact that there were differences in the soil properties across plots in the LIRF experiment, as corn was planted in different plots in different years (2008 to 2011). However, a single set of average soil properties were used in the simulation (Table 3-2). Nonetheless, excepting 2011, differences in error statistics in soil water simulations between the three WS factors were not appreciable (Table 3-4). These error statistics are also comparable to those obtained by Ma et al. (2012) in simulations of the experiment with the default WS factor, WSDef (Table 3-4).

LAI simulations

As noted earlier, in the LIRF experiment, continuous direct measurements of LAI were available only for one crop season in 2010 in the T1, T3, T4 and T5 treatments (Fig. 3-3, Table 3-4). Overall, in 2010, the LAI was best simulated with WSI2 with an RRMSE of 36.4% and d of 0.95. Detailed treatment-wise comparisons also showed that the simulations using WSI2 with RMSE from 0.44 to 0.53 outperformed other stress factors in treatments T3, T4 and T5 (Fig. 3-3). In T1, WSI3 simulated LAI with an RMSE of 0.34 and WSI2 with an RMSE of 0.52. Taking into account the measured deviations in LAI between replications [standard deviations (SD) plotted in Fig. 3-3], overall, the simulations using stress factors WSDef and WSI2 reasonably followed the measured crop LAI in the field. Overall superiority of WSI2 may be related to its accounting for some WS due to heating of canopy in early stages.

Grain yield and biomass simulation

Measured grain yields in 2008 in response to the six irrigation levels ranged from 11071 to 7546 kg ha^{-1} with a maximum gain of 3615 kg ha^{-1} due to the applied irrigation between highest and lowest treatments (Fig. 3-4a). Similar gain in biomass due to irrigation this year was 7781 kg ha^{-1} (Fig. 3-5a). Using the WSDef equations, Ma et al. (2012) simulated grain yields ranging from 10685 and 8774 kg ha^{-1} with a gain of 1911 kg ha^{-1} due to applied irrigation between the lowest highest irrigation treatments, underestimating the measured gain by 1704 kg ha^{-1}. For simulations with the three new stress factors, the simulated maximum yield gains due to irrigations were underestimated by 151, 585 and 897 kg ha^{-1} for WSI1, WSI2 and WSI3, respectively. Similarly, simulations of maximum biomass gain due to irrigation with the three new stress factors were 7246, 7991, 10770 kg ha^{-1}, respectively, compared with measured gain of

7781 kg ha^{-1} and gain of 4322 kg ha^{-1} simulated using WSDef factor (Ma et al., 2012). In 2008, RMSE of grain yield simulations using the three stress factors did not differ appreciably, ranging between 345 kg ha^{-1} for WSI1 and 502 kg ha^{-1} for WSI3, compared with RMSE of 1016 kg ha^{-1} with the WSDef factor (Ma et al., 2012) (Table 3-4, Fig. 3-4a). Nonetheless, biomass simulations differed considerably with a highest RMSE of 2986 kg ha^{-1} for WSI3 and lowest RMSE of 896 kg ha^{-1} for WSI2, compared with RMSE of 1756 kg ha^{-1} with WSDef (Table 3-4, Fig. 3-5a). Higher errors in simulated LAI (RMSE = 0.90) resulted in higher errors in the biomass simulated with WSI3. Simulations using WSDef, Ma et al.(2012) reported RMSE of 1016 kg ha^{-1} for grain yield, 1756 kg ha^{-1} for biomass and 1.07 for LAI. In general, simulations of the crop using WSI1 and WSI2 were substantially better than using the WSDef (Table 3-4, Fig 3-4a). In summary, this year, simulations with WSI2 were more accurate than simulations with the remaining stress factors tested.

In 2009, in simulations of grain yield across the six irrigation treatments, those with WSI2 showed lowest RMSE, RRMSE and highest d compared to WSDef, WSI1 and WSI3 (Table 3-4, Fig. 3-4b). Excepting the biomass simulations using WSI3, biomass and LAI simulations using the three stress factors were also appreciably better than simulations with the WSDef (Table 3-4, Fig. 3-5b). In summary, in 2009 also simulations with WSI2 were more accurate than simulations with the remaining stress factors tested.

In 2010, measured highest grain yield and biomass due to the maximum irrigation treatment (T1 at 100% ET) was 9436, which was 15, 8 and 20% lower than the measured highest grain yields due to T1 in 2008, 2009 and 2011, respectively (Table 3-4, Fig. 3-4c). However, the measured grain yield due to T6 this year was lower than that in 2008 and 2009 by 38% and 7%, but more than that in 2011 by 35%. Simulations with WSDef stress factor in RZWQM2 gave

10% under-estimation of the highest yield and 20% over-estimation of the lowest yield in 2010. Obviously, the measured variations in grain yields in response to irrigations this year were not correctly simulated with WSDef. Simulations using the WSI2 were best and accurate with 1% under estimation of highest and 2% over estimation of the lowest yield. Using WSDef, simulations of the crop across the six irrigation treatments were with RRMSE and d of 40.1% and 0.80 for LAI, 19.5% and 0.83 for biomass, and 10.6% and 0.92 for grain yield, respectively. These simulations also, in general, were less accurate than those simulated using WSI1, WSI2 and WSI3 (Table 3-4, Figs. 3-4c and 3-5c). Among the three new stress factors introduced, RMSE of biomass simulations using WSI2 (1668 kg ha^{-1}) and WSI3 (1611 kg ha^{-1}) were comparable to each other and better than WSI1 (2322 kg ha^{-1}) (Table 3-4, Fig. 3-5c). Therefore, in summary, in this season unlike 2008 and 2009 above, crop simulations using both WSI2 and WSI3 were comparable to each other and better than WSDef and WSI1 (Table 3-4, Fig. 3-4c and 3-5c).

The crop season in 2011 was markedly different from the previous three years with highest measured maximum grain yield of 11809 kg ha^{-1} (highest in four years of experiments) due to highest irrigation level (T1, at 100% ET) and lowest grain yield of 3434 kg ha^{-1} (lowest in four years of experiments) in response to the lowest irrigation level (T6, at 40% ET). The measured grain yield in response to T1 this year was 7, 15 and 25% higher than those measured in 2008, 2009 and 2010, respectively (Fig. 3-4d). Also, equally conspicuous was the lowest measured grain yield due to the lowest irrigation level which was lower by 54, 32 and 26%, respectively. Similar differences were also reflected in the measured biomass (Fig. 3-5d). Simulations with WSDef were with 34% under- prediction of the yield in response to the highest irrigation (T1) and 23% over-prediction of the yield in response to the lowest irrigation (T6). On the contrary, simulations of these grain yield values had less error (best among the three new stress factors) with the WSI2 with deviations in the highest grain yield (T1) by -14% and lowest grain yield (T6) by 2%. Simulated grain yield differences between the highest and lowest irrigation treatments this year using the WSDef and WSI2 stress factors were 4402 and 5688 kg ha^{-1} , respectively, against the measured value of 8375 kg ha^{-1}. Also, in general, in response to the six irrigation treatments, simulations of grain yield, and biomass with WSI2 were considerably more accurate than those with WSDef, WSI1 and WSI3 as reflected in the error statistics (RMSE, RRMSE, R^2 and d) (Table 3-4; Fig. 3-4d and 3-5d). Between WSDef, WSI1, WSI2, and WSI3 this year, biomass simulated using WSI3 with an RMSE of 4261 kg ha^{-1}, deviated considerably from the measured values (Table 3-4; Fig. 3-5d). RMSE of biomass predictions using WSI2 was 740 kg ha^{-1}, and using WSDef and WSI1 were 1603, 977, respectively.

In summary, averaged across the years (2008 to 2011) of data, simulations of LAI, grain yield and biomass with WSI2 were also better than WSDef and the other two (WSI1 and WSI3) WS factors (Table 3-5).

Akron experiments

There were 5, 11, and 10 irrigation events in 1984, 1985 and 1986, respectively, in the irrigation trials in the Akron experiments (Saseendran et al., 2008b). Grain yields of these experiments (total of 26) were simulated with RMSE of 669, 851, 442, and 656 kg ha^{-1} using the RZWQM2 enhanced with WSDef, WSI1, WSI2 and WSI3, respectively (Table 3-6, Fig. 3-6a). Biomass harvested at the end of the season (total of 25 data points) was simulated with RMSE of 1699, 2152, 1655 and 3702 kg ha^{-1}, respectively (Table 3-6, Fig. 3-6b). Simulations of biomass using the WSI3 was noticeably with larger errors as the water stress (TURFAC) simulated using it was considerably higher than with other WS factors. In summary, both grain yield and biomass in the irrigation trials were simulated best by WSI2 than other WS factors in RZWQM2.

In general, accuracies of grain yield simulations in the rainfed experiments also were best with WSI2 compared to the other WS factors (Table 3-6, Fig. 3-6a). RMSE of grain yields were 837, 701, 472 and 675 kg ha^{-1}, respectively, using the WSDef, WSI1, WSI2 and WSI3 factors in RZWQM2. While simulating the Akron experiments, Saseendran et al. (2008b) identified an outlier in the rainfed measured grain yield in 1997 (Fig. 3-6a). This year, the lowest grain yield of 357 kg ha^{-1} was obtained when the rainfall and other weather conditions during the crop growing season were comparable to other years in which measured grain yield ranged from 1611 to 3689 kg ha^{-1}. Neglecting this value, the RMSE of grain yield simulated in the rainfed trials varied from 57 kg ha^{-1} with WSI2 to 377 kg ha^{-1} with WSI1. Using the WSDef factor in the model, grain yields were simulated with an RMSE of 297 kg ha^{-1}. RMSE of biomass simulations in the rainfed trials varied between 711 kg ha^{-1} for WSI2 and 1018 kg ha^{-1} for WSI3. Like in the case of irrigation trials in the Akron experiments, biomass simulations were less accurate with WSI3 than WSI1 and WSI2 in the rainfed experiments as well. However, WSDef simulations also were with similar errors (RMSE = 1015 kg ha^{-1}).

DSSAT datasets

The SIAZ experiments conducted in 1996 in a sandy loam soil at Zaragoza, Spain distributed with the DSSAT 4.5 package consisted of nine treatments with nine different combinations of water and N levels distributed across various stages of growth of corn. It stands out in the database for its complexity in the water treatments. Measured grain yields reported in this experiment ranged from 5620 to 12340 kg ha^{-1}.

Using WSDef, WSI1, WSI2 and WSI3 in RZWQM2, we simulated this experiment exactly with the same initial water and N conditions as it was done using the CSM-CERES-Maize and –IXIM-maize models available within the DSSAT 4.5 for simulations of corn (Jones et al., 2003; Hoogenboom et al., 2010; Lizaso et al. 2011). Grain yield, biomass and LAI simulations of RZWQM2 using the WSI2 stress factor had lower RMSE (1536 kg ha^{-1} for grain yield, 3198 kg ha^{-1} for biomass and 0.77 for LAI) than simulations using the WSDef (RMSE of 1833 kg ha^{-1} for grain yield, 4061 kg ha^{-1} for biomass and 0.88 for LAI), as well as WSI1 (RMSE of 1667 kg ha^{-1} for grain yield, 4011 kg ha^{-1} for biomass and 1.15 for LAI) and WSI3 (RMSE of 1774 kg ha^{-1} for grain yield, 5062 kg ha^{-1} for biomass and 1.47 for LAI) factors (Fig. 3-7, Table 3-7). The RRMSE of grain yield simulations ranged between 16.7 % with WSI2 and 20.0% with WSDef stress factors.

The UFGA experiment conducted in a sandy soil at Gainesville, Florida, USA in 1982 was also conspicuous for its complexity in treatments with six different combinations of water and N applied differentially in the vegetative and reproductive stages of growth of corn. Using the enhanced RZWQM2, we simulated this experiment also exactly with the same initial water and N conditions as it was done using the CSM-CERES-Maize and –IXIM-maize models available within the DSSAT 4.5 for simulations of corn. Grain yield and biomass simulations of this experiment using the four WS factors (WSDef, WSI1, WSI2 and WSI3) were comparable to each other with RMSE of grain yield varying between 523 and 698 kg ha^{-1} , and RMSE of biomass varying between 1150 and 1386 kg ha^{-1}. However the lowest RMSE for grain yield (523 kg ha^{-1}) and biomass (1150 kg ha^{-1}) were obtained for WSI2. When RMSE of LAI simulations with the four WS factors were comparable to each other varying between 0.29 and 0.69, the lowest value was obtained for WSDef. However, this superior result was not reflected in the simulations of biomass and grain yields (Fig. 3-8 and Table 3-7). In summary, simulations of the SIAZ and UFGA experiments with RZWQM2 enhanced with the WSI2 stress factor were more accurate than simulations with the other three WS factors.

SUMMARY AND CONCLUSIONS

For applications in limited irrigation management, agricultural system models require enhancements for more accurate crop responses to soil water deficit stress. Limited irrigation experiments in corn conducted at the Limited Irrigation Research Farm (LIRF) of the USDA-ARS near Greeley, Colorado during 2008-2011 gave us a unique opportunity to quantify and test three (WSI1, WSI2 and WSI3) stress factors for simulation of corn using the CSM-CERES-Maize v4.0 model with the soil water and N routines in RZWQM2. The default water deficit stress factor in RZWQM2 was based on the ratio of water available for plant uptake (water supply) and the potential transpiration demand (demand for water). Our simulations with the new stress factors showed that the crop responses to water can be substantially improved by incorporation of soil evaporation in both the supply and demand terms in the water stress quantifications in the model. Out of the three water stress factors tested, WSI2 was found to be better than others in simulations of corn grain yield, biomass and LAI. It was noteworthy, in the simulations of RZWQM2 with the WSI2 stress factor, that grain yield and biomass were improved simultaneously and the magnitudes of the errors were reasonable for model applications in water management. Superior simulations of RZWQM2 enhanced with WSI2 over other WS factors of corn under both rained and irrigated conditions at Akron, Colorado, USA;

and two irrigation experiments in two contrasting soils, a sandy loam soil at, Zaragoza, Spain and a sandy soil at Gainesville, Florida, USA, verified the capability of the enhanced model for simulations across soils and climates. Notwithstanding, similar testing across locations in the world will facilitate in building further confidence on the robustness of this stress factor in RZWQM2 for simulation of corn and other crops across climates and soils. Further development and testing of the WSI3 factor concept is needed.

Table 3-1. Total seasonal irrigation and precipitation during the vegetative (V) and reproductive (R) stages of corn under six irrigation treatments from 2008 to 2011 in the limited irrigation experiments at Greeley, Colorado (LIRF).

Irrigation treatment	Irrigation/precipitation, mm							
	V	R	V	R	V	R	V	R
	2008		2009		2010		2011	
Precipitation	39	191	135	94	145	55	138	38
T1 (100 % of ETc, F)	289	149	202	216	201	164	255	230
T2 (85% of T1, V)	227	111	169	179	130	160	203	185
T3 (70% of T1, F)	202	80	146	154	114	133	182	147
T4 (70% of T1, V)	186	86	102	148	88	132	177	129
T5 (55% of T1, V)	136	45	68	100	61	98	129	92
T6 (40% of T1, V)	111	26	50	59	42	70	97	60

T1 =Treatment #1, Treatment # 2, T3= Treatment #3, T4= Treatment # 4, T5= Treatment # 5, T6 = Treatment # 6. V= variable, F= fixed. In the V treatments, 20% of the estimated weekly amounts of irrigation requirement during vegetative growth period were withheld and added to weekly amounts during the reproductive growth period, and this was not done in the F treatments.

Table 3-2. Soil parameters estimated from field measured soil water contents in the Greeley, Co experiments.

Soil Depth (cm)	Bulk Density ρ_b (g cm^{-3})	θ_s (cm^3 cm^{-3})	$\Theta_{1/3}$ (cm^3 cm^{-3})	Θ_{15} (cm^3 cm^{-3})	h_b (cm)	λ (dimensionless)
0-15	1.492	0.437	0.262	0.131	20.04	0.182
15-30	1.492	0.437	0.249	0.124	15.15	0.182
30-60	1.492	0.437	0.220	0.110	7.75	0.182
60-90	1.568	0.408	0.187	0.093	4.64	0.182
90-120	1.568	0.408	0.173	0.086	2.95	0.182
120-150	1.617	0.390	0.162	0.081	2.71	0.182
150-200	1.617	0.390	0.198	0.099	8.04	0.182

θ_s, θ_{fc} and θ_{wp} are soil water contents at field saturation, field capacity (drained upper limit) and plant wilting point (drained lower limit). h_b is the air entry water suction, and λ the pore size distribution index obtained by fitting the Brooks-Corey equation for obtaining the soil water retention curve (Brooks and Corey, 1964).

Table 3-3. Plant parameters calibrated for RZWQM2-CERES simulations of corn hybrids in the LIRF, SIAZ, UFGA and Akron experiments using the WSDef, WSI1, WSI2 and WSI3 water stress factors.

Acronyms used and definitions of traits.	Parameter values								
	LIRF experiments		UFGA experiments		SIAZ experiments			Akron experiments	
	WSDef	WSI1, WSI2 and WSI3	WSI1	WSDef, WSI2 and WSI3	WSDef	WSI1	WSI2 and WSI3	WSI1	WSDef, WSI2 and WSI3
P1 - Degree days (base temperature of 8 ºC) from seedling emergence to end of juvenile phase (thermal degree days).	260	260	260	260	280	280	280	290	290
P2 - Day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate].	0.40	0.60	0.40	0.30	0.32	0.22	0.22	0.60	0.80
P5 - Degree days (base temperature of 8 ºC) from silking to physiological maturity (thermal degree days)	540	620	920	910	800	800	800	595	615
G2 - Potential kernel number	800	1000	890	980	729	729	749	720	690
G3 - Potential kernel growth rate (mg/(kernel d)	10	6.90	7.0	7.1	7.5	7.37	7.77	9.9	9.3
PHINT - Degree days required for a leaf tip to emerge (thermal degree days)	50.0	43.0	43.0	43.0	46.0	41.0	46.0	41.0	38.9

Table 3-4. Evaluation statistics for simulations of total profile soil water, leaf area index (LAI), biomass and grain yield using the three stress factors (WSI1, WSI2 and WSI3) against measured values in the 2008, 2009, 2010, and 2011 LIRF irrigation experiments. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

Year	Total profile(0-180 cm) water				LAI				Biomass				Grain yield			
	RMSE (cm)	RRMSE %	R^2	d	RMSE	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d
						WSDef										
2008	3.85	13.0	0.75	0.87	1.07	54.7	0.84	0.79	1756	9.6	0.85	0.87	1016	10.6	0.84	0.79
2009	2.40	7.3	0.77	0.97	0.94	46.8	0.62	0.83	1152	6.3	0.88	0.96	672	8.1	0.95	0.97
2010	3.02	8.4	0.55	0.83	0.68	40.1	0.85	0.80	2932	19.5	0.83	0.78	823	10.6	0.92	0.92
2011	4.83	15.6	0.10	0.74	0.68	26.8	0.69	0.98	1603	9.3	0.92	0.93	1691	20.7	0.69	0.86
						WSI1										
2008	3.84	13.0	0.75	0.89	0.81	55.1	0.72	0.89	992	9.1	0.93	0.97	345	6.7	0.96	0.99
2009	3.21	9.7	0.60	0.93	1.16	57.8	0.64	0.75	812	4.4	0.96	0.99	399	3.9	0.99	0.99
2010	4.43	12.2	0.41	0.70	0.76	45.1	0.76	0.90	2322	15.5	0.97	0.87	552	7.2	0.96	0.97
2011	4.17	13.5	0.31	0.57	0.80	31.4	0.80	0.99	977	5.8	0.99	0.99	1188	14.2	0.99	0.94
						WSI2										
2008	4.50	15.4	0.68	0.82	0.81	38.4	0.72	0.89	896	5.7	0.93	0.98	355	5.9	0.97	0.99
2009	3.19	9.7	0.58	0.94	1.07	57.8	0.63	0.75	725	5.0	0.96	0.98	380	4.5	0.99	0.99
2010	2.43	7.4	0.72	0.95	0.72	36.4	0.72	0.95	1668	11.1	0.97	0.94	572	7.3	0.94	0.97
2011	2.12	7.2	0.32	0.74	0.73	29.0	0.72	0.98	740	4.4	0.99	0.99	1150	13.7	0.99	0.99
						WSI3										
2008	3.80	13.0	071	0.78	0.90	43.0	0.75	0.86	2986	12.7	0.88	0.83	502	8.8	0.92	0.97
2009	3.76	11.3	0.66	0.96	0.95	47.2	0.52	0.79	2772	15.2	0.98	0.88	524	6.3	0.98	0.98
2010	5.53	15.3	0.40	0.68	0.65	38.5	0.82	0.96	1611	8.1	0.97	0.98	337	3.1	0.99	0.99
2011	2.25	8.2	0.19	0.80	0.91	35.9	0.72	0.97	4261	25.1	0.95	082	1445	9.3	0.99	0.92

Table 3-5. Evaluation statistics for pooled data from six irrigation treatments for each of the four crops seasons of 2008, 2009, 2010 and 2011 in the LIRF experiments, for simulations of grain yield and biomass using the three stress factors (WSI1, WSI2 and WSI3) against measured values. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

Grain yield				Biomass			
RMSE ($kg\ ha^{-1}$)	RRMSE %	R^2	d	RMSE ($kg\ ha^{-1}$)	RRMSE %	R^2	d
			WSDef				
1102	12.9	0.73	0.89	2081	12.1	0.81	0.88
			WSI1				
676	7.9	0.92	0.96	1468	8.5	0.92	0.93
			WSI2				
671	7.9	0.96	0.99	1184	9.8	0.93	0.97
			WSI3				
818	9.6	0.94	0.98	3094	18.0	0.84	0.90

Table 3-6. Evaluation statistics for pooled data from rainfed experiments from 1993 to 1997, and irrigation trials with line source and drip systems from 1984 to 1986 at Akron, Colorado, for simulations of grain yield and biomass using the three stress factors (WSI1, WSI2 and WSI3) and the default stress factor (WSDef) against measured values. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

	Grain yield				Biomass			
	RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	d
				WSDef				
Irrigated	669	8.5	0.97	0.97	1699	13.5	0.21	0.61
Rainfed	837	8.5	0.86	0.97	1015	22.5	0.49	0.99
				WSI1				
Irrigated	851	10.9	0.91	0.96	2152	17.2	0.64	0.54
Rainfed	701	16.8	0.97	0.99	865	19.2	0.96	0.99
				WSI2				
Irrigated	442	5.6	0.96	0.99	1655	13.2	0.65	0.67
Rainfed	472	2.5	0.99	0.99	711	15.7	0.97	0.99
				WSI3				
Irrigated	656	8.3	0.79	0.97	3702	29.5	0.18	0.43
Rainfed	675	16.2	0.94	0.99	1018	22.6	0.81	0.99

Table 3-7. Evaluation statistics for pooled data from SIAZ96 experiment in a sandy loam soil at Zaragoza, Spain and UFGA82 experiment in a sandy soil at Gainesville, Florida distributed with DSSAT 4.5, for simulations of grain yield and biomass using the three stress factors (WSI1, WSI2 and WSI3) and the default stress factor (WSDef) against measured values. RMSE: Root Mean Square Error, RRMSE: relative RMSE, d: index of agreement, and R^2: coefficient of determination.

Grain yield (kg ha^{-1})				Biomass				LAI			
RMSE (kg ha^{-1})	RRMSE %	R^2	d	RMSE (kg ha^{-1})	RRMSE %	R^2	D	RMSE	RRMSE %	R^2	d
Experiment in a sandy loam at Zaragoza, Spain in 1996											
WSDef											
1833	20.5	0.63	0.86	4061	22.9	0.47	0.74	0.88	20.9	0.19	0.61
WSI1											
1667	18.9	0.70	0.88	4011	22.7	0.44	0.73	1.15	27.2	0.11	0.36
WSI2											
1536	16.7	0.68	0.89	3198	16.7	0.48	0.73	0.77	18.3	0.23	0.55
WSI3											
1774	19.4	0.60	0.86	5062	28.6	0.52	0.69	1.47	34.8	0.19	0.44
Experiment in a sandy soil at Gainesville, Florida in 1982											
WSDef											
547	8.4	0.98	0.99	1386	10.6	0.96	0.98	0.29	8.9	0.72	0.98
WSI1											
625	7.8	0.98	0.99	1368	10.4	0.94	0.98	0.55	16.9	0.53	0.95
WSI2											
523	9.2	0.99	0.99	1150	8.8	0.96	0.99	0.55	16.8	0.55	0.95
WSI3											
698	10.3	0.95	0.99	1247	17.2	0.95	0.97	0.69	21.2	0.60	0.92

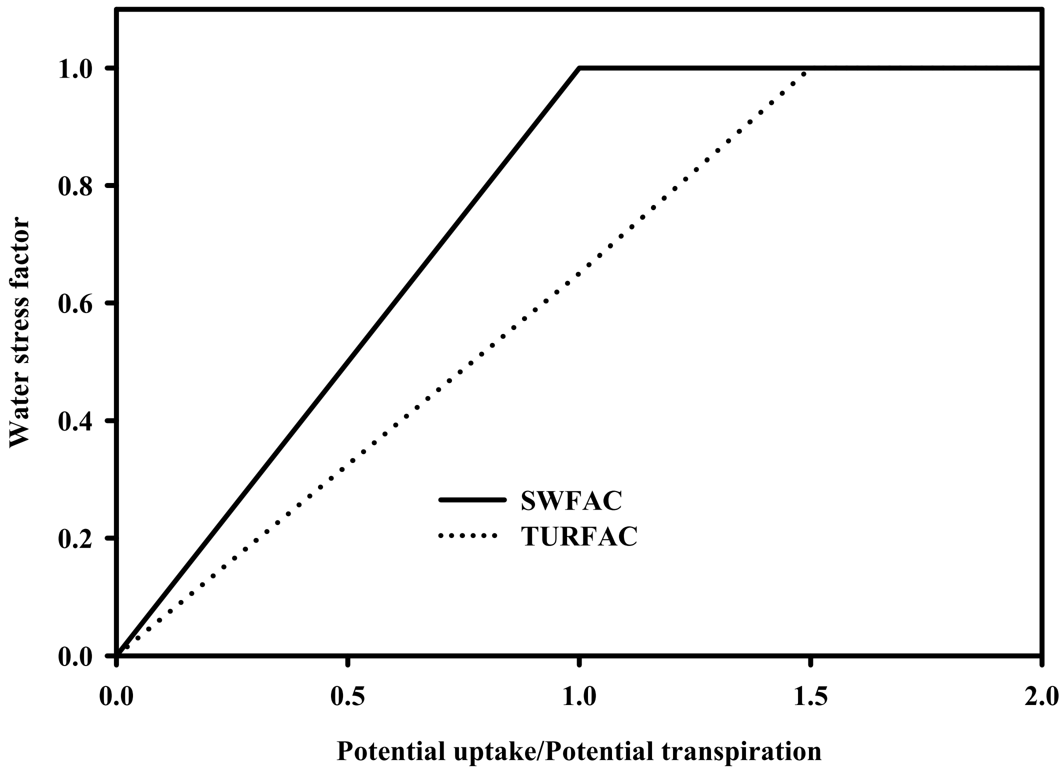

Fig. 3-1. Relationships used to calculate soil water stress factors, SWFAC and TURFAC in DSSAT-CSM models (Ritchie 1998).

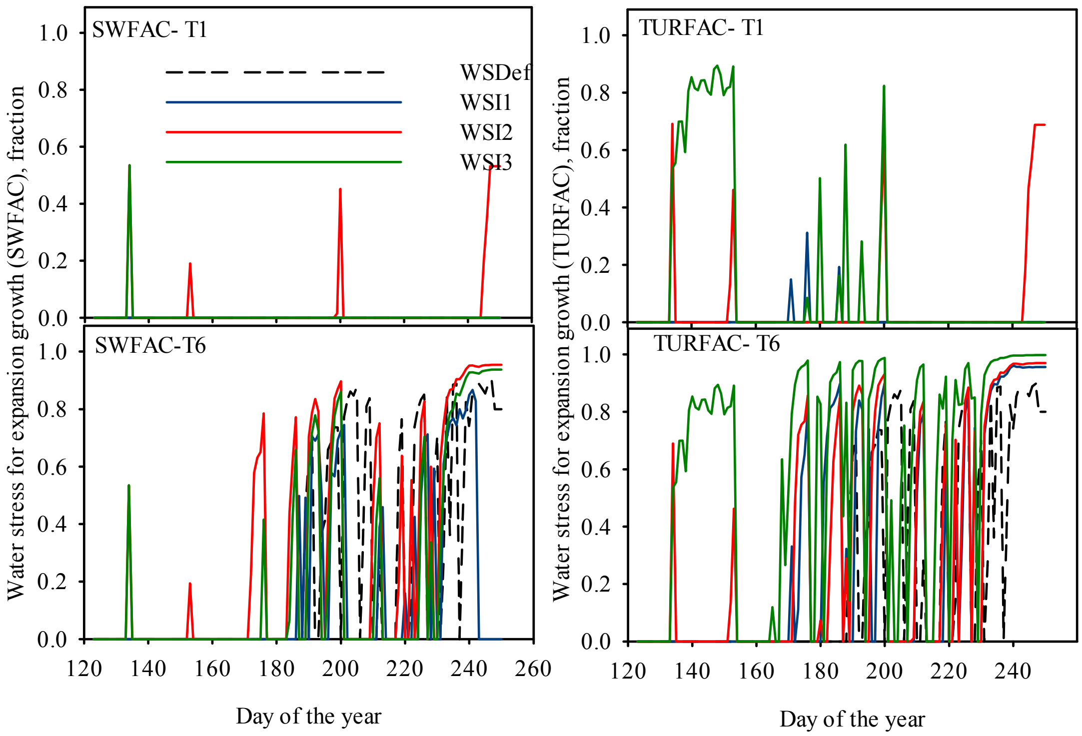

Fig. 3-2. Comparison between the water deficit stress for corn growth (SWFAC and TURFAC) simulated in response to the default water stress (WS) factor (WSdef) and the three new WS factors (WSI1, WSI2 and WSI3) in 2010 under T1 (highest water) and T6 (lowest water) treatments. The stress factors are shown to range from 0 for no stress to 1 for complete stress.

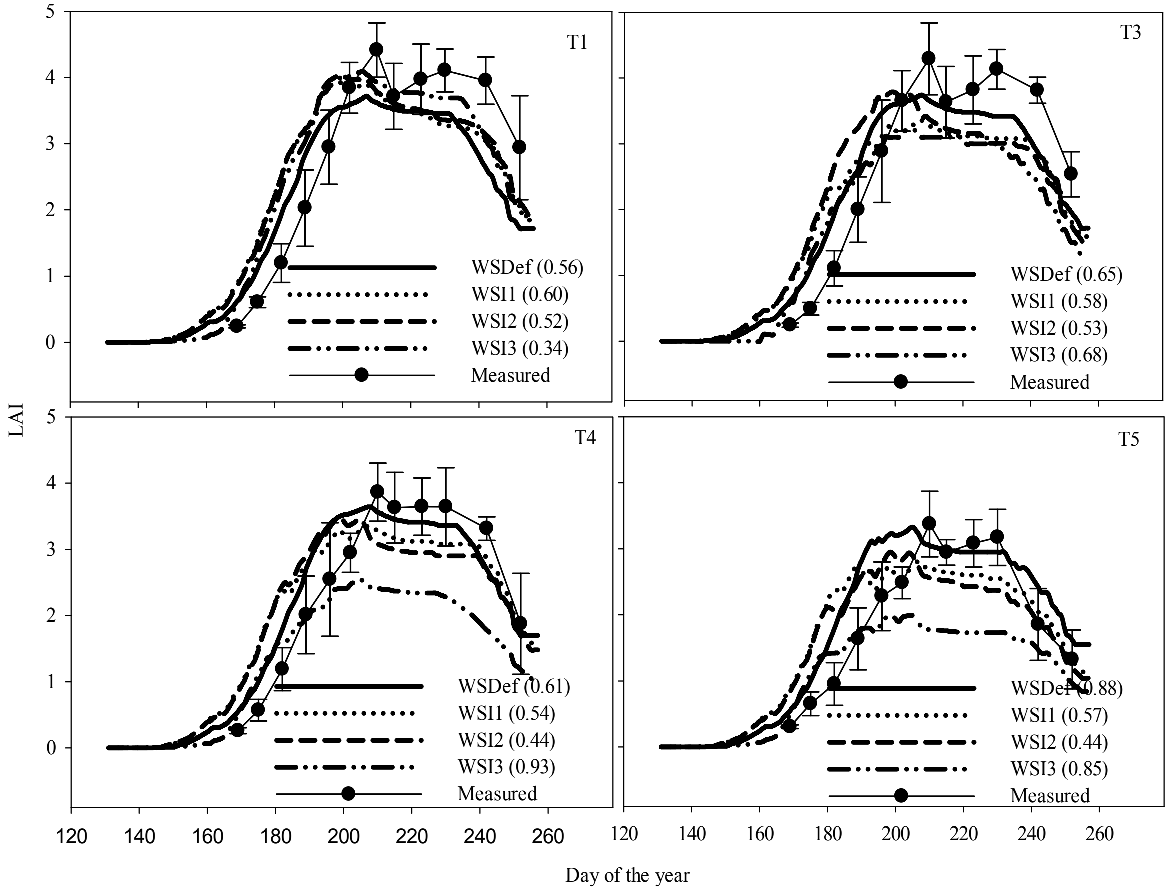

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Fig. 3-3. Comparisons of measured and simulated corn LAI using stress factors WSI1, WSI2 and WSI3 in 2010 in the T1, T3, T4 and T5 treatments. Ma et al. (2012) simulated LAI using WSDef stress factor also is shown. Error bars show one standard deviation in the measurements. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSE of LAI simulations across treatments were 0.68, 0.55, 0.48 and 0.74 for the Ma et al. (2012), WSI1, WSI2 and WSI3 stress factors, respectively.

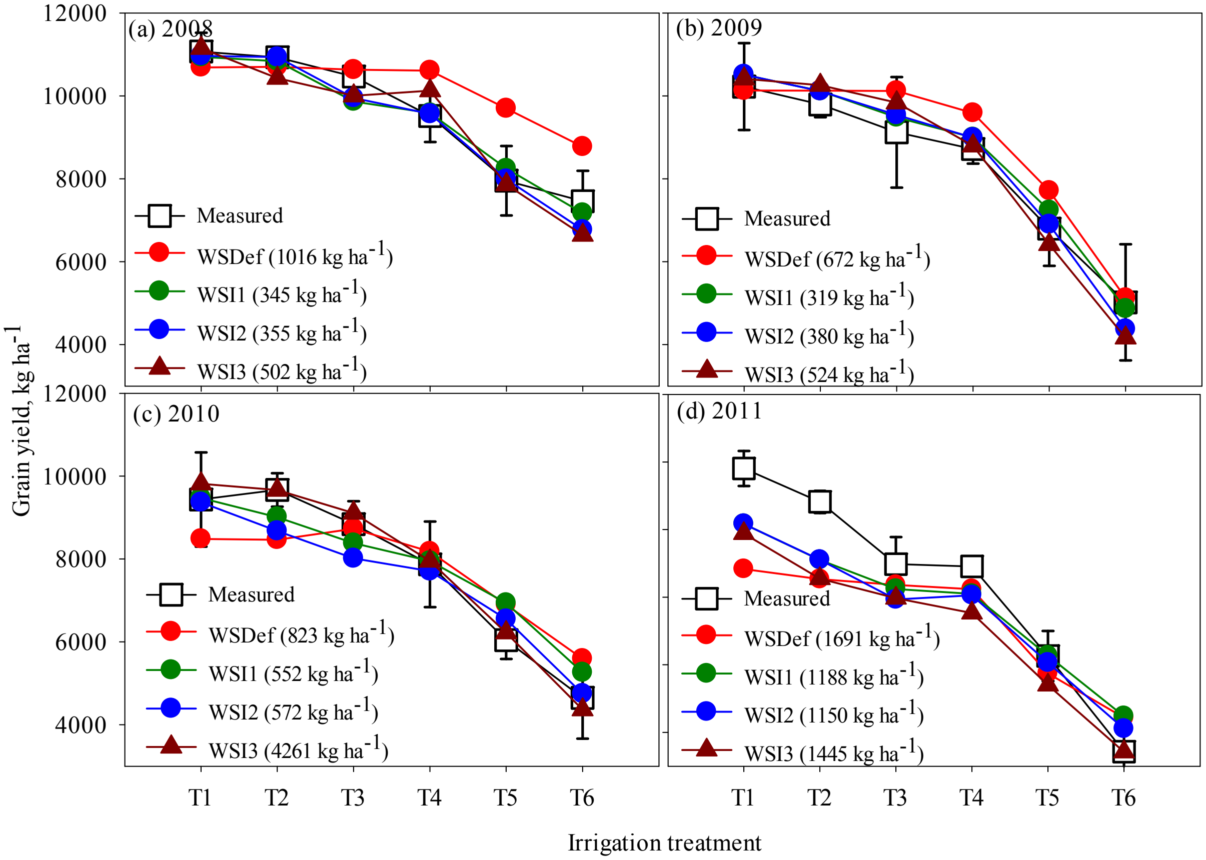

Fig. 3-4. Comparison between measured, and simulated corn grain yields in six irrigation treatments from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSI1, WSI2 and WSI3. Error bars indicate one standard deviation in the measured data. Ma et al. (2012) simulated grain yield using the model default water stress factor (WSDef) also is shown. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSE across years were: 1102, 676, 671 and 818 kg ha^{-1} for WSDef, WSI1, WSI2 and WSI3 stress factors, respectively.

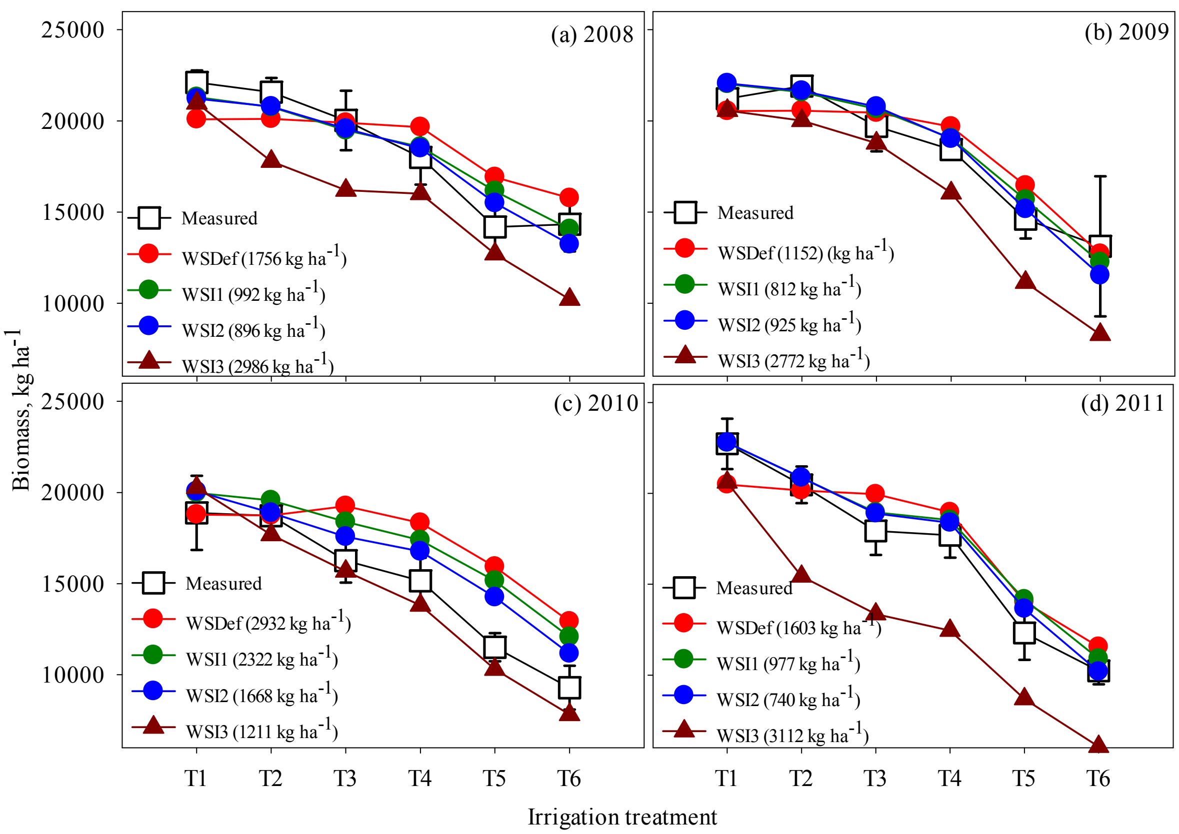

Fig. 3-5. Comparison between measured, and simulated corn biomass in six irrigation treatments from 2008 to 2011. Simulations were made with the CSM-CERES-Maize model within RZWQM2 using the stress factors WSI1, WSI2 and WSI3. Error bars indicate one standard deviation in the measured data. Ma et al. (2012) simulated biomass using the model default water stress factor (WSDef) also is shown. Enclosed in parenthesis of the legends are root mean square errors (RMSE). Average RMSE across years were: 2081, 1468, 1184 and 3094 kg ha^{-1} for WSDef, WSI1, WSI2 and WSI3 stress factors, respectively.

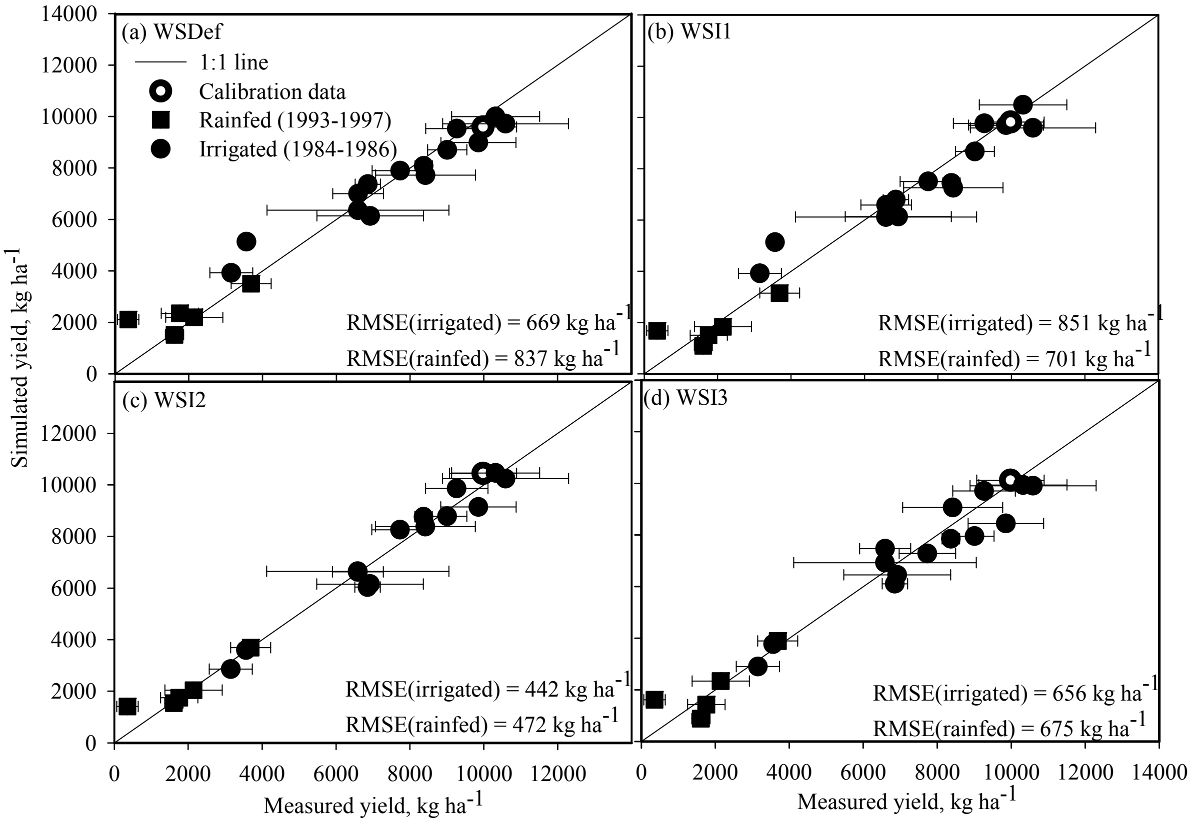

Fig. 3-6a. Measured and simulated corn grain yield in the irrigated (1984 to 1986) and rainfed experiments (1993 to 1997) at Akron, Colorado. Error bars indicate 1 standard deviation about the mean of the treatment replications. RMSE = Root Mean Square Error.

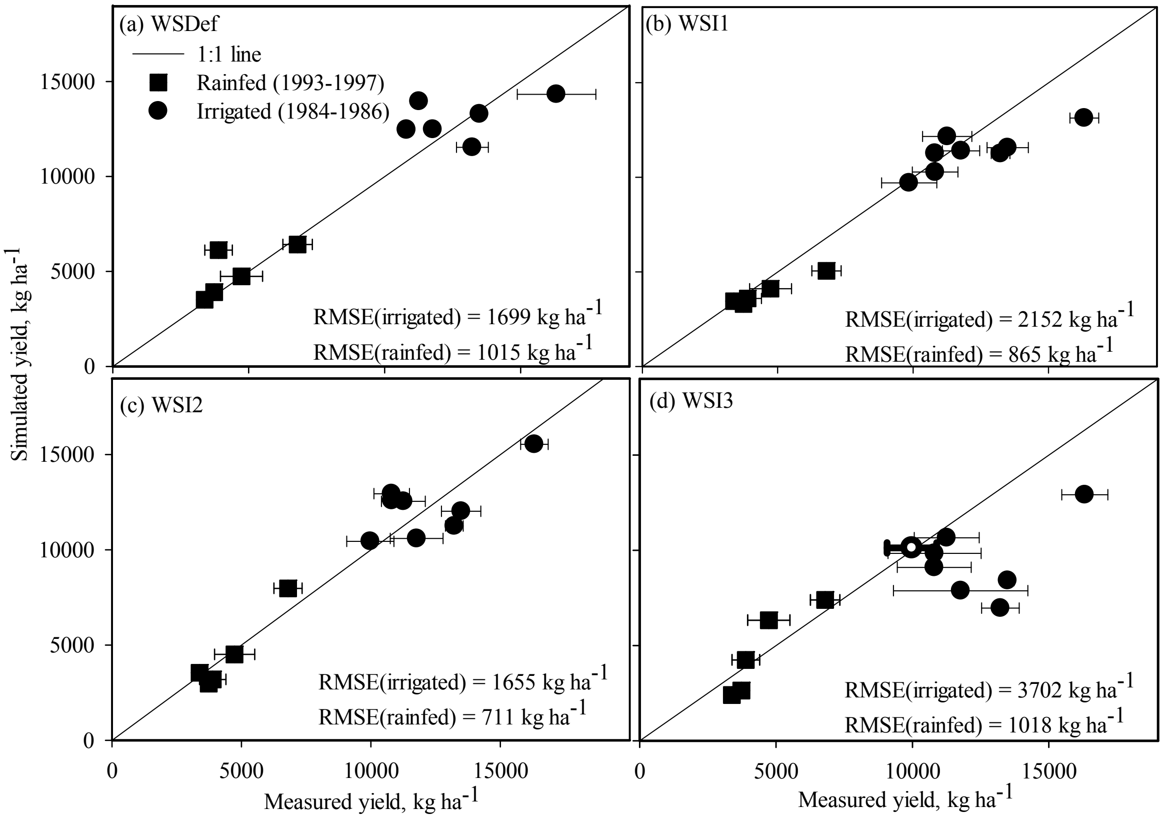

Fig. 3-6b. Measured and simulated corn biomass in the irrigated (collected only in 1984 and 1985 line source irrigation treatments) and rainfed experiments (1993 to 1997) at Akron, Colorado. Error bars indicate 1 standard deviation about the mean of the treatment replications. RMSE = Root Mean Square Error.

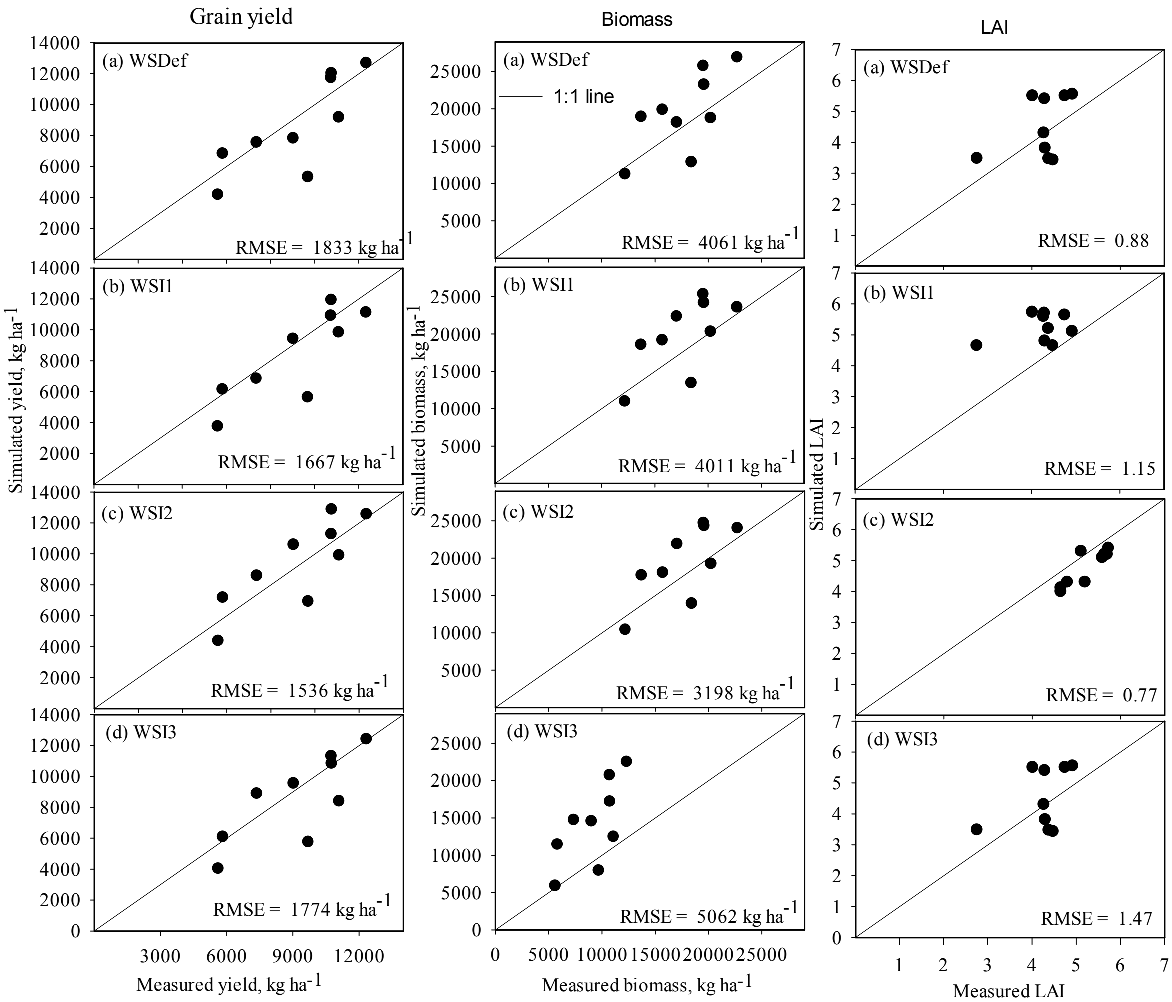

Fig. 3-7. Simulations of grain yield, biomass, and LAI in the SIAZ96 experiment distributed with DSSAT 4.5 using RZWQM2 with (a) WSDef, (b) WSI1, (c) WSI2 and (d) WSI3 stress factors. RMSE= root mean square error.

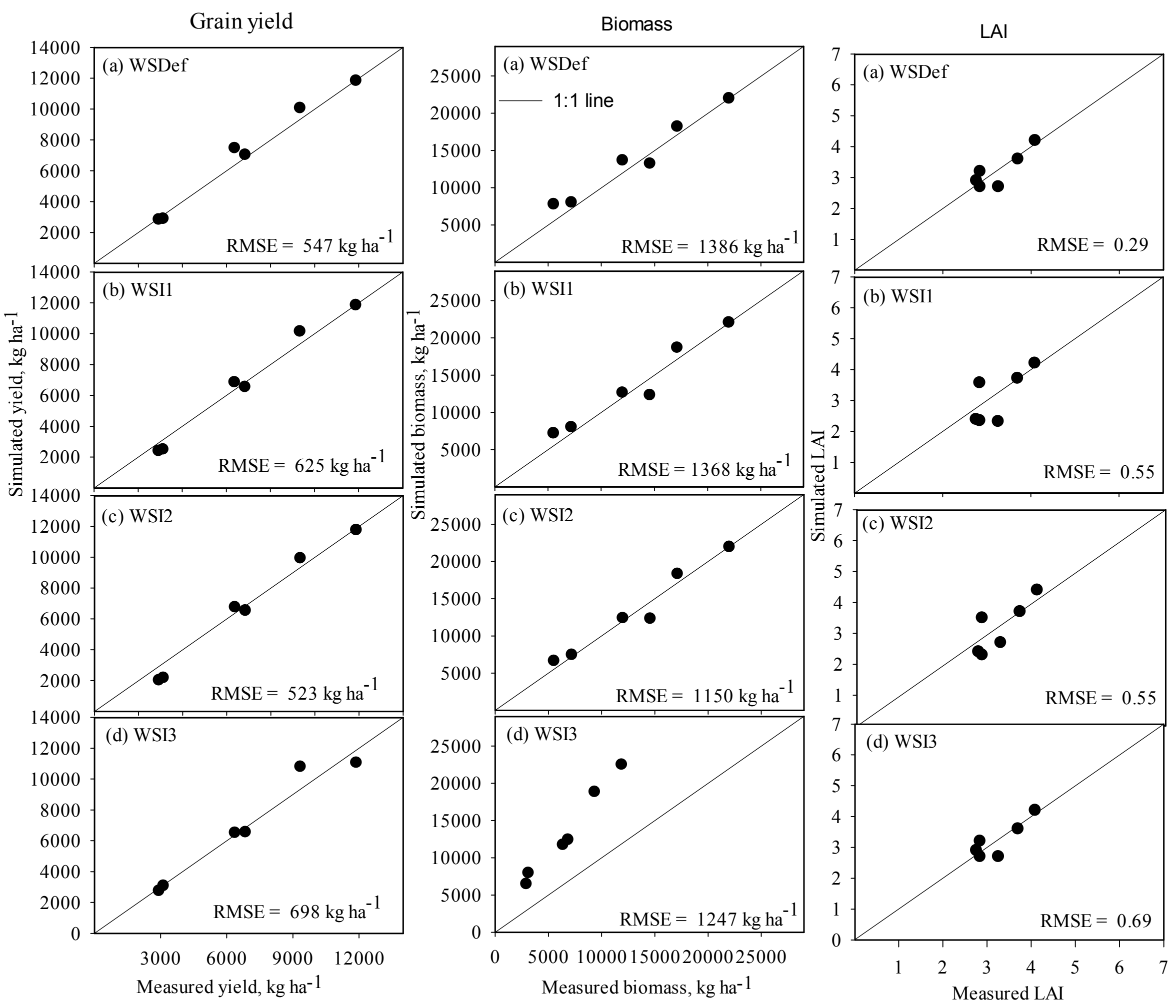

Fig. 3-8. Simulations of grain yield, biomass, and LAI in the UFGA82 experiment distributed with DSSAT 4.5 using RZWQM2 with (a) WSDef, (b) WSI1, (c) WSI2 and (d) WSI3 stress factors. RMSE= root mean square error.

REFERENCES

Ahuja, L. R., Rojas, K. W., Hanson, J. D., Shafer, M. J., Ma, L. (Eds.), 2000. Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water resources publications, LLC, Colorado, USA. 372p.

Allen, R. G., I.A, Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder. 2005. The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers. Reston, VA.

Bai, L.P., F.G. Sui, T.D. Ge, Z.H. Sun, Y.Y. Lu, and G.S. Zhou. 2006. Effect of soil drought stress on leaf water status, membrane permeability and enzymatic antioxidant system of maize. Pedosphere 16: 326-332.

Bausch, W., T. Trout, and G. Buchleiter. 2011. Evapotranspiration adjustments for deficit-irrigated corn using canopy temperature: a concept. Irrig. and Drain. 60: 682–693.

Boyer, J.S. 1970. Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiol. 46:234-235.

Brooks., R. H., and A. T. Corey. 1964. Hydraulic properties of porous media. Hydrology Paper 3, Colorado State University, Fort Collins, CO, USA. 2-15.

Cabelguenne, M., C.A. Jones, J.R. Marty, P.T. Dyke, and J.R. Williams. 1990. Calibration and validation of EPIC for crop rotations in Southern France. Agricultural Systems 33:154-171.

Cakir R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res. 89: 1–6.

Castleberry, R.M., C.W. Crum, and C.R. Krull. 1984. Genetic yield improvement of U. S. maize cultivars under varying fertility and climatic environments. Crop Sci. 42:34-36.

Castrignano, A., N. Katerji, F. Karam, M. Mastrorilli, and A. Hamdy. 1998. A modified version of CERES-Maize model for predicting crop response to salinity stress. Ecological Modeling 111:107–120.

Chaves, M.M., J.S. Pereira, J. Maroco, M.L. Rodrigues, C.P.P. Ricardo, M.L. Osorio, I. Carvalho, T. Raria, and C. Pinheiro. 2002. How plants cope with water stress in the field. Photosynthesis and growth. Annals of Botany 89:907-916.

Chen J. L., and J.F. Reynolds. 1997. A coordination model of whole plant carbon allocation in relation to water stress. Annals of Botany 80:45-55.

Cosgrove D.J. 1998. Cell wall loosening by expansins. Plant Physiology 118**:** 333–339.

Cosgrove, D.J., and R.E. Cleland. 1983. Solutes in the free space of growing stem tissues. Plant Physiology 72**:** 326–331.

DeJonge, K.C., Andales, A.A., Ascough, J.C., and Hansen, N. 2011. Modeling of full and limited irrigation scenarios for corn in a semiarid environment. Transactions of the ASABE 54: 481–492.

Denmead, O.T., and R.H. Shaw. 1960. The Effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52:273-275.

Farahani, H. J., and DeCoursey, D. G. 2000. Potential evapotranspiration processes in the soil-crop-residue system. p52-80. *In* L.R. Ahuja, K.W. Rojas, J. D. Hanson, M.J. Shafer, L. Ma (eds.). Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resources Publications, LLC, Highlands Ranch, CO.

Farahani, H.J., and L.R. Ahuja. 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Trans. ASAE 39:2052-2064.

Faria, R. T., and Bowen, W. T. 2003. Evaluation of DSSAT soil-water balance module under cropped and bare soil conditions. Brazilian archives of biology and technology 46:489-498.

Gardner, W.R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89:64-73.

Grant, R.F., B.S. Jackson, J.R. Kiniry, and G.F. Arkin. 1989. Water deficit timing effects on yield components in maize. Agron. J. 81:62-65.

Hall, A.J., J.H. Lemcoff, and N. Trapani. 1981. Water stress before and during flowering in maize and its effects on yield, its components, and their determinants. Maydica 26:19-38.

Halvorson, A.D., A.L. Black, J.M. Krupinsky, and S.D. Merrill. 1999. Dryland winter wheat response to tillage and nitrogen within an annual cropping system. Agron. J. 91:703-707.

Hergert, G.W., N.L. Klocke, J.L. Peterson, P.T. Nordquist, R.T. Clark, and G.A. Wicks. 1993. Corn and sorghum cropping systems for stretching limited irrigation supplies. J. Prod. Agric. 6:520-529.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, K.J. Boote, L.A. Hunt, U. Singh, J.L. Lizaso, J.W. White, O. Uryasev, F.S. Royce, R. Ogoshi, A.J. Gijsman, and G.Y. Tsuji. 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM].University of Hawaii, Honolulu, Hawaii.

Hsiao, T.C., P. Steduto, and E. Fereres. 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irr. Sci. 25:209–231.

Jackson, B.S., T.J. Gerik, and D.F. Wanjura. 1990. Use of COTTAM for scheduling limited irrigation. J. Prod. Agric. 3: 420-425.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. European Journal of Agron. 18:235-265.

Lizaso, J.L., K. J. Boote, J. W. Jones, C. H. Porter, L. Echarte, M. E. Westgate, and G. Sonohat. 2011. CSM-IXIM: A New Maize Simulation Model for DSSAT Version 4.5. Agron. J. 103: 766-779.

Ma, L., D.C. Nielsen, L.R. Ahuja, R.W. Malone, S.A. Saseendran, K.W. Rojas, J.D. Hanson, J.G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. Trans. ASAE 46:39-49.

Ma, L., G. Hoogenboom, L.R. Ahuja, D.C. Nielsen, and J.C.II. Ascough. 2005. Evaluation of the RZWQM-CROPGRO hybrid model for soybean production. Agron. J. 97: 1173-1182.

Ma, L., G. Hoogenboom, L.R. Ahuja, J.C II. Ascough, and S.A. Saseendran. 2006. Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. Agric. Syst. 87:274–295.

Ma, L., G. Hoogenboom, S. A. Saseendran, P. N. S. Bartling, L. R. Ahuja, and T. R. Green. 2009. Estimates of soil hydraulic properties and root growth factor on soil water balance and crop production. Agron. J. 101:572–583.

Ma, L., L.R. Ahuja, S.A. Saseendran, R.W. Malone, T.R. Green, B.T. Nolan, P.N.S. Bartling, G.N. Flerchinger, K.J. Boote, and G. Hoogenboom. 2011. A Protocol for Parameterization and Calibration of RZWQM2 in Field Research. p 2-64. *In*: L.R. Ahuja and L. Ma (eds.), Methods of introducing system models into agricultural research. Advances in Agricultural Systems Modeling Series 2.

Ma, L., T.J. Trout, L.R. Ahuja, W.C. Bausch, S.A. Saseendran, R.W. Malone, and D.C. Nielsen. 2012. Calibrating RZWQM2 model for maize responses to deficit irrigation. Agricultural Water Management 103:140– 149.

McCown, R.L., G.L. Hammer, J.N.G. Hargreaves, D.L. Holzworth, and D.M. Freebairn. 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research. Agric. Syst. 50:255-271.

Neumann, P.M. 1995. The role of cell wall adjustment in plant resistance to water deficits. Crop Sci 35:1258-1266.

Nimah, M.N., and R.J. Hanks. 1973. Model for estimating soil water, plant and atmospheric inter relations: I. description and sensitivity. Proceedings Soil Sci. Soc. Of America 37:523-527.

Norwood, C.A. 1999. Water use and yield of dryland row crops as affected by tillage. Agron. J. 91:108-115.

Norwood, C.A. 2001. Planting date, hybrid maturity, and plant population effects on soil water depletion, water use, and yield of dryland corn. Agron. J. 93:1034-1042.

Nouna, B.B., N. Katerji, and M. Mastrorilli. 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance. Europ. J. Agron. 13:309–322.

Rawls, W.J., D. L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Trans. ASAE 25:1316-1320, 1328.

Ritchie, J. T. 1998. Soil water balance and plant water stress. p. 42-54. *In* G. Y. Tsuji, G. Hoogenboom, and P. K. Thornton (Eds). Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Ritchie, J.T. 1981. Water dynamics in the soil-plant-atmosphere system. Plant and Soil 58: 82-96.

Salazar, M.R., J.E. Hook, A. Garcia y Garcia, J.O. Paz, B. Chaves, and G. Hoogenboom. 2012. Estimating irrigation water use for maize in the Southeastern USA: A modeling Approach. Agricultural Water Management 107:104– 111.

Saseendran S.A., L.R. Ahuja, L. Ma, D.J. Timlin, C.O. Stockle, K.J. Boote, and G. Hoogenboom. 2008a. Current Water Deficit Stress Simulations in Selected Agricultural System Simulation Models, *in* L. R. Ahuja, et al. (Eds.), Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, USA. pp. 2-38.

Saseendran, S.A., D.C. Nielsen, L.R. Ahuja, T. Trout, and L. Ma. 2008b. Simulations of limited-water irrigation management options for corn in dryland agriculture. Water Resour. Res. 44: W00E02, doi:10.1029/2007WR006181.

Saseendran, S. A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on a winter wheat cropping system using RZWQM and CERES-wheat. Agron. J. 96:615-630.

Saseendran, S. A., L. Ma, D.C. Nielsen, M.F. Vigil, and L.R. Ahuja. 2005. Simulating planting date effects on crop production using RZWQM and CERES-maize models. Agron. J. 97:58-71.

Saseendran, S.A., D.C. Nielsen, D. Lyon, L. Ma, D.G. Felter, D.D. Baltensperger, G. Hoogenboom, and L.R. Ahuja,. 2009. Modeling responses of dryland spring triticale, proso millet, and foxtail millet to initial soil water in the High Plains. Field Crops Res. 113:48-63.

Saseendran, S.A., D.C. Nielsen, L. Ma., L.R. Ahuja, and M.F. Vigil. 2010. Simulating alternative dryland rotational cropping systems in the Central Great Plains with RZWQM2. Agron. J. 102:1522-1534.

Sau, F., K. J. Boote, W. M. Bostick, J. W. Jones, and M. I. Minguez. 2004. Testing and improving evapotranspiration and soil water balance of the DSSAT crop models. Agron. J. 96: 1244-1257.

Shao H.B., L.Y. Chu, M.A. Shao, C. Abdul Jaleel, and M. Hong-Mei. 2008. Higher plant antioxidants and redox signaling under environmental stresses. Comp. Rend. Biol., 331: 433–441.

Stockle, C.O., M. Donatelli, and R. Nelson. 2003. CropSyst, a cropping systems simulation model. Europ. J. Agron. 18:289-307.

Tardieu, F., C. Granier, and B. Muller. 1999. Research review: Modeling leaf expansion in a fluctuating environment: are changes in specific leaf area a consequence of changes in expansion rate? New Phytol. 143:34-43.

Tardieu, F., M. Reymond, P. Hamard, C. Granier, and B. Muller. 2000. Spatial distributions of expansion rate, cell division rate and cell size in maize leaves: a synthesis of the effects of soil water status, evaporative demand and temperature. Journal of experimental botany 51:1505-1514.

Trout, T.J., W.C. Bausch, and G.W. Buchleiter. 2010. Water Production Functions for Central Plains Crops. An ASABE Conference Presentation. Paper Number: IRR10-9654. 5th National Decennial Irrigation CD-ROM Proceedings. ASABE Publication Number 711P0810cd. P8.

Woli, P., J. W. Jones, K. T. Ingram, and C. W. Fraisse. 2012. Agricultural Reference Index for Drought (ARID). Agron. J. 104:*287-300.*

Willmont, C.J. 1981. On the validation of models. Physical geography 2:184-194.

CHAPTER IV

DEVELOPMENT OF CROP WATER PRODUCTION FUNCTIONS FOR CORN IN COLORADO USING RZWQM2 MODEL*

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 in food production holds the key to address this challenge. Water is the most important natural resource limiting corn production in the semiarid Great Plains of USA (Halvorson et al., 2004). With the competing demands for water (agriculture vs. urban needs) as well as grains in the region (food vs. fuel), 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).

It has been observed that when only water is limiting, grain yield response of most crops 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

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than the maximum water requirement of the plant is available. Further, as water stress tolerance of crops vary considerably by genotype, soil and climate, specific CWPFs are pre-requisites for planning and managing water needs and allocation during the crop growth period and for analysis of economic outcomes (Martin et al., 1989; Geerts and Raes, 2009).

Variable responses of crops to water deficits during specific water sensitive growth stages also can influence the CWPFs. For instance, water deficit during the reproductive period (after tasseling) of corn can increase the interval from tasseling to silking and pollen-shed, increasing spikelet sterility and shorten the grain filling period, resulting in reduced grain yield (Westgate, 1994; Kefale and Ranamukhaarachchi, 2004; Cakir 2004; Moser et al., 2006). Hence, in limited-irrigation situations, it is critical that the water applied is carefully allocated between different critical water-sensitive crop growth stages considering the soil water storage, to optimize production (Klocke et al., 2004; Farre´ and Faci, 2009). However, the optimal water application strategy varies from year to year and location to location depending upon the amount and distribution of rainfall as well as crop variety. We have not addressed the issue of growth-stage specific irrigation in this study; it will be addressed in follow-up studies, where we plan to establish the principles behind the growth-stage water allocations.

The measured CWPFs of crop yield vs. ET or irrigation may vary from year to year 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 short-term experiments across long-term weather and soils (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. water for limited irrigation management. The actual irrigation water applied to meet the needed irrigation water will vary with the method of irrigation, with its water application efficiency in the field.

The objective of this study was to develop location specific CWPFs for drip, sprinkler and surface irrigation methods for planning limited irrigation of corn grown in a clay loam, silt loam and sandy loam soil at (1) Greeley, Weld County; (2) Akron, Washington County and (3) Rocky Ford, Otero County in Colorado in the central Great Plains of USA using the calibrated and validated Root Zone Water Quality Model (RZWQM2). The three counties were selected as they are spatially separated and have experimental data for model calibrations. Generalization of CWPFs across the three locations and three soils were explored to quantify essential minimum data required to obtain CWPF for a location.

MATERIALS AND METHODS

RZWQM2 Model

The RZWQM2 is a process-oriented agricultural system model that was developed to simulate the impacts of tillage, crop residue, water, fertilizers, 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 and 2009; Hoogenboom et al., 1991; Jones et al., 2003) (http://arsagsoftware.ars.usda.gov/agsoftware/). Several studies rigorously tested and integrated the RZWQM2 with short term (3 to four year) and long-term (14 to 17 year) field research conducted in the Great Plains for managing dryland and irrigated cropping systems (Ma et al., 2003; Saseendran et al., 2004; 2005a; 2005b, 2008, 2009; 2010a; 2010b). Saseendran et al. (2013) modified the water stress factor for photosynthesis related processes (SWFAC) in RZWQM2-CERES using the daily potential root water uptake (TRWUP) calculated by Nimah and Hanks (1973) approach and accounting 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 (Saseendran et al., 2013). The modified model was used for simulations of yield responses to irrigations in this study.

The model inputs include weather (driving variables), soil physical and hydraulic parameters, crop and soil management information and soil initial conditions. The 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.

The soil physical properties required are: soil profile depth and horizons (layers); soil texture, bulk density, 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, amounts and methods of irrigation and fertilizer applications. The model requires the soil water, N, and carbon contents in the profile at the start of the simulation.

In the order of importance, experimental data needed for calibration of the model for simulation of 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. In order to simulate a specific corn hybrid, the CERES-maize 4.0 model requires six cultivar parameters (Jones et al., 2003).

For simulation of a cropping system, the RZWQM requires careful iterative calibration of its 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).

Site characteristics and experiments used in calibration of RZWQM2

Data for calibration and evaluation of the model for simulations of corn in the three counties of Colorado came from experiments conducted near: (1) Greeley (40.45^{o} N, 104.64^{o} W, 1.43 km amsl), Weld county (2) Rocky Ford (38.04^{O}N, 103.70^{O}W, 1.27 km amsl), Otero county and at Akron (40.15^{O}N, 103.14^{O}W, 1.38 km amsl), Washington county.

Greeley, Weld county, Colorado

Four years of data (2008-2011) were collected in field experiments at the limited irrigation research farm (LIRF) near Greeley in the central Great Plains of Colorado, USA (Trout et al., 2010; Bausch et al., 2011) to quantify field corn (*Zea mays* L.) responses to limited irrigation. Details of the experiments and irrigation treatments at LIRF are available in Trout et al. (2010) and Ma et al. (2012). Six irrigation treatments were designed to meet certain percentages of potential crop ET (ETc) requirements during the growing seasons: 100%F (T1), 85%V (T2), 70%F (T3), 70%V (T4), 55%V (T5), and 40%V (T6) of ETc. (V denote that 20% of the estimated weekly amounts of irrigation requirement for that treatment during vegetative growth period were withheld and added to weekly amounts during the reproductive growth period; this was not done in the F treatments). The site contains three types of soils, Nunn (Fine, smectitic, mesic Aridic Argiustolls), Olney (Fine-loamy, mixed, superactive, mesic Ustic Haplargids), and Otero (Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents)) with predominant sandy loam texture, throughout the 200 cm soil profile. Weather data were recorded on site with a standard Colorado Agricultural Meteorological Network weather station http://ccc.atmos.colostate.edu/~coagmet/ at the farm. Mean annual precipitation (1993-2010) at the location was 27.2 cm out of which 19.92 cm was received during the corn growing season from May to October. Maize ('Dekalb 53-59') was planted, in a randomized block design with four replicates, at an average rate of 81,000 seeds per hectare with 0.76 m row spacing on 12 May, 11 May, 11 May and 3 May and harvested on 6 November, 12 November, 19 October and 25 October in 2008, 2009, 2010 and 2011, respectively. Fertilizer as urea-ammonium-nitrate (UAN) was applied at planting and then with irrigation water during the growing seasons as needed so that there is no N stress in the experiments. Saseendran et al.

(2013) modified RZWQM2 for better crop responses to water stresses and conducted detailed calibration and validation of the soil water, N and crop (corn 'DeKalb 53-59') parameters of the RZWQM2 for simulation of the LIRF experiments from 2008 to 2011. The plant parameters calibrated by Saseendran et al. (2013) were used in this study.

Saseendran et al. (2013) performed detailed calibrations and evaluation of RZWQM2 for simulations of the experimental data from 2008 to 2011 collected in the LIRF experiments at Greeley, Colorado with reasonable accuracy. So, detailed comparison of the simulated and measured crop growth and yield are not attempted here. Simulations of grain yields had an average RMSE of 434 kg ha^{-1} the four years under all levels of irrigations (Fig. 4-1). The yield-ET relationship or production per unit of ET differs among the years due to variability in weather, length of growing season and fertility (Martin et al., 1989). Yet, the four year simulations of grain yield responses to ET (CWPF in terms of yield vs. ET) show reasonable agreement with the measured responses (Fig. 4-2). These results provide confidence on the use of a calibrated model for developing long-term average CWPFs for corn at the location for irrigation management.

Akron, Colorado

This data set was from irrigated and rainfed corn experiments conducted at the Central Great Plains Research Station 6.4 km east of Akron, CO. Mean annual precipitation at the site is about 420 mm of which 290 mm is received during corn growing season from May to September. Soil type at the location is a Rago silt loam (fine montmorillonitic mesic Pachic Arguistoll). Details of the experiments, soil physical and hydraulic properties used in the simulations were described by Ma et al. (2003). The irrigation experiments used in the study were conducted during 1984, 1985, and 1986. Corn hybrid ‘Pioneer Brand 3732’ (101-day relative maturity) was planted under a line-source gradient irrigation system. In 1985, additional drip irrigation treatments were conducted with four irrigation levels. For the line-source irrigation experiment, three irrigation levels in 1984 and four irrigation levels in 1985 and 1986 were applied, with four replications. Maximum irrigation rate was 3.2 mm hr^{-1}. There were 5, 11, and 10 irrigation events in 1984, 1985 and 1986, respectively. Irrigation application varied from 23 to 106 mm in 1984, from 72 to 188 mm in 1985, and 46 to 299 mm in 1986, and were withheld until just before tasseling (late July). Seeding rate was uniform across the irrigation gradient (about 76,000 seeds ha^{-1}). All the experiments were fertilized with ammonium nitrate at the rate of 168 kg N ha^{-1}. Soil water measurements were made at planting, harvest, and several intermediate periods with a neutron probe. Leaf area measurements were made periodically with a leaf area meter by destructive sampling one-meter lengths of row, and the same samples were used for biomass measurements. Grain yield was measured at harvest.

The rainfed (dryland) corn experiments were part of a larger ongoing crop rotation experiment conducted at the same location since 1990. In these experiments, various tillage and crop sequences were assessed for effects on productivity, soil quality, and economic viability. Detailed descriptions of cultural practices, plot area, and experimental design were reported by Bowman and Halvorson (1997) and Anderson et al. (1999). The corn hybrid ‘Pioneer Brand 3732’ used in the irrigation studies was also used in the rainfed crop rotation study from 1993 to 1997. These experiments used a randomized complete block design with three replications. Grain yield and biomass data were collected at harvest. Fertilizer N application rates were based on annual soil tests and a corn yield goal of 4100 kg ha^{-1}. Actual fertilizer applied in different years ranged between 34 and 95 kg N ha^{-1}. Soil water measurements were made every two weeks with a neutron probe at two locations near the center of each experimental plot at depths of 0.45, 0.75, 1.05, 1.35, and 1.65 m. Time-domain reflectometry was used to measure soil water in the 0.00-0.30 m depth. Saseendran et al. (2013) simulated the Akron experiments with reasonable accuracy using the CSM-CERES-Maize 4.0 within RZWQM2. Saseendran et al. (2013) calibrated model and crop parameters were used in this study for simulations of crop yield responses to irrigations.

Saseendran et al. (2013) conducted detailed calibration and evaluation of the rainfed (1993 to 1997) and irrigated (1984-1986) corn experiments at Akron, Colorado using the CSM-CERES-Maize 4.0 in RZWQM2 with reasonable accuracy levels for irrigation applications (Fig. 4-3). The grain yield simulations had an RMSE of 472 kg ha^{-1} for the rainfed and 442 kg ha^{-1} for irrigated experiments (Fig. 4-3). The accuracy levels of simulations of the grain yields at this location provide confidence for applying the model for limited irrigation management.

Rocky Ford, Colorado

Data for this location was from a N source rate study under conventional tillage conducted from 2000 to 2003 in a silty clay soil (fine-silty, mixed, calcareous, mesic Ustic Torrithents) at the Arkansas Valley Research Center near Rocky Ford (38.04 ^{O}N, 103.670 ^{O} W, 1.274 km amsl), Colorado (Halvorson et al. 2005). Corn growing season at the location is from April through September. The long-term average precipitation for the growing period at the location is 227 mm (Halvorson et al., 2005). Corn hybrid ‘Pioneer 33A14’ was planted on 27 April 2000, ‘DeKalb 642RR’ on 24 April 2001, and Garst 8559 Bt/RR on 23 April 2002 and 29 April 2003. Plant populations were 66828 in 2000, 97103 in 2001, 90414 in 2002 and 93499 in 2003. The experiments were a randomized block design with four replications. The N rates were

0, 56, 112, 168, 224 and 280 kg ha^{-1} in 2000; no N applied in 2001; 28, 56, 84, 112 and 140 kg ha^{-1} in 2002; and 0, 34, 67, 101, 134 and 168 in 2003. However, there were no N applications in 2001. The crop was furrow irrigated and the total water applied to the crops in 2000, 2001, 2002 and 2003 were 70.47, 55.51, 64.17 and 85.03 cm, respectively. Detailed accounts of the experiments (irrigation and N schedules) and data collection procedures are available in Halvorson et al. (2005). Grain yield at harvest was collected in the experiments and was used for evaluating the model. The cultivar parameters calibrated for simulation of DeKalb 53-59' in the LIRF experiments at Greeley was used as a starting point for calibration of the 'DeKalb 642RR', 'Pioneer 33A14' and 'Garst 8559 Bt/RR' hybrids at this site.

No field irrigation treatments were conducted for corn, nor were any available in the literature, in the Otero county of Colorado for calibration of the model. So, instead, data from an N management study for irrigated corn under conventional tillage conducted by Halvorson et al. (2005) at the Arkansas Valley Research Center near Rocky Ford in the Otero county from 2000 to 2003 was used.   In 2001, pest damage reduced grain yields in the experiments (Halvorson et al., 2005). With the exception of some over simulations in 2001, simulated grain yield agreed reasonably well with the measured data giving confidence in using the model for irrigation research at the location (Fig. 4-4). Simulations of the four year experiment at various N levels (irrigation varied across the years only) were with an RMSE of 417 kg ha^{-1}, that exclude the pest damaged corn simulations in 2001. The CSM-CERES-Maize 4.0 used in the study does not simulate pest or disease impacts on growth and development of the crop (Jones et al., 2003). Hence, as expected, the 2001 grain yields were mostly over simulated by the model.

Development of CWPFs using long-term (20 yr) simulations of the model

Long-term simulations

Weather data recorded during 1993-2011 at Greeley, Akron, and Rocky Ford by the Colorado Agricultural Meteorological Network http://ccc.atmos.colostate.edu/~coagmet/) were used. Using the RZWQM2 calibrated and validated for the three locations and soils above, the crop growth was simulated from 1992 to 2011 (20 crop seasons) for each of silt loam, clay loam, and sandy loam soils. Default soil parameters for clay loam, silt loam and sandy loam soils were used. These soils were assumed of uniform properties with depth. Reference crop evapotranspiration (ET_r) for tall grass (alfalfa) was calculated based on Allen et al. (2005).

All the long-term simulations were initialized for soil water contents at field capacity in the top 30 cm and half of plant available water (field capacity - wilting point) in the layers below on 1st January of every year of simulation (20 years). The crop was planted every year on 2nd May at the three locations and weekly irrigations initiated on the same day and continued until 10th September every year. Irrigations were based on meeting crop evapotranspiration (ET) demands of 0 (dryland), 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 % accounting for precipitation on weekly intervals (Ma et al., 2012). ET in the soil-residue-canopy system is modeled using the 'extended Shuttleworth-Wallace ET model' (Farahani and Ahuja, 1996: Farahani and DeCoursey, 2000). Irrigations in the model simulations were applied with 100% efficiency by treating them as low intensity rainfall events. All simulations assumed no N stress to the crop.

Development of average crop water production functions (CWPFs)

For development of CWPFs, average and standard deviations of corn growing season precipitation, grain yield, biomass, crop evapotranspiration (ET_c), tall grass reference ET (ETr), amount of irrigation, plant available water in the soil at planting (PAW), and runoff from the 20 yearly simulations at different levels of irrigation (irrigations at 0 to 100% ET demand at weekly intervals) were computed. Effective precipitation (P_{eff}), effective irrigation (I_{eff}) and plant water supply to the crop (PWS) are calculated as:

I_{eff} = Irrigation – Runoff – Deep percolation -------------------------- [1]

P_{eff} = Precipitation – Runoff – Deep percolation -----------------------[2]

PWS = I_{eff} + Plant available soil water (PAW) at planting + P_{eff} ------[3]

The CWPFs were developed by plotting average grain yields vs. (1) irrigation and (2) ET due to irrigation ($ET_{a\text{-}d}$, ET at a particular irrigation level – ET at no irrigation). Linear relationships between grain yields and $ET_{a\text{-}d}$ were also developed.

Development of CWPFs for drip, sprinkler and surface irrigation methods.

As noted above, the CWPFs derived above from the RZWQM2 (yield vs. irrigations and $ET_{a\text{-}d}$) simulations were with irrigations at 100% efficiency (negligible losses due to runoff and deep percolation). For projection of simulated grain yields in response to the various amounts of irrigations applied at 100% efficiency by the model into 95% efficiency under drip, 85% efficiency under sprinkler and 55% efficiency under surface irrigations [average irrigation efficiencies for different irrigation methods were derived from Irmak et al. (2011)], we established functional relationships between the simulated crop yields and irrigation amounts. Such functional relationships will allow extrapolation of CWPFs for irrigation at 100%

efficiency to other methods of irrigations. Assuming Cobb-Douglas type of yield-water response function (Eq. 4), the Martin et al. (1984) recommended the functional relationship (CWPF) as given in Eq. 5.

$$f(I_r) = m - (1 - I_r)^n \qquad \text{-----------------------------------} \; [4]$$

$$Y = Y_d + (Y_m - Y_d)[1 - (1 - I_r)^{\frac{1}{\beta}}] \qquad \text{---------------------------} \; [5]$$

where, *m* and *n* are parameters of the Cobb-Douglas' response functions; *Y* is grain yield in response to a given irrigation *I*; Y_d is dryland yield for the crop; Y_m is the maximum irrigated crop yield; $I_r = \dfrac{I}{I_m}$, I_r is relative irrigation; $Y_r = \dfrac{Y}{Y_m}$, Y_r is relative irrigation; I is a given irrigation level for a given yield (Y) and I_m is the irrigation required to obtain Y_m; and

$$\beta = (ET_m - ET_d) / I_m \qquad \text{------------------------------} \; [6]$$

where, ET_m and ET_d are evapotranspiration in response to I_m and no irrigation (dryland), respectively.

Irrigation required for achieving a given yield (simulated average over 20 years in response to various irrigation amounts by different methods) can be obtained by rearranging Eq. [5] as:

$$I = I_m \left[1 - \left(1 - \frac{Y - Y_d}{Y_m - Y_d} \right)^{\beta} \right] \qquad \text{----------------------------} \; [7]$$

where, I_m in the equation for any specific irrigation method can be calculated from the maximum irrigation needed at 100% irrigation efficiency (I_{m_p}) and the irrigation efficiency (ε) of the specific method of irrigation of interest:

$$I_m = \frac{I_{m_p}}{\varepsilon} \qquad \text{------------------------ [8]}$$

Once, I_m for a specific method of irrigation is known, the corresponding β is calculated using Eq. [6].

As noted above, irrigations in the model (RZWQM2) are assumed to be at $\varepsilon = 1.0$. The ε values adopted for other methods of irrigations were 0.95 for drip, 0.85 for sprinkler and 0.55 for surface irrigations (Irmak et al., 2011). To evaluate yield based on Eq. (5), we need to find *Ym, Yd* and β at a given irrigation, I_r.

RESULTS AND DISCUSSIONS

Long-term averaged CWPFs using RZWQM2

The calibrated and evaluated model for the three locations was used to generate yield responses to weekly irrigations to meet 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100% crop ET demands using long-term weather data (20 years) collected at each location. The model was also used to obtain similar responses in different soil types at the locations by changing the soil properties. Water also interacts with fertilizers in yield production, but this was not considered in the present study, in which we assumed the nutrients were not limiting. In general, across the three soils and climates, precipitation was sufficient such that irrigation amounts required to meet ET demand up to 30% was found to be negligible; hence they were considered the dryland treatments.

At Greeley, simulated average amounts of water to meet 40 to 100% ET demands of corn in the clay loam soil was 27.5 to 72.7 cm with corresponding irrigation requirements between 7.9

and 61.3 cm (remaining ET demands that was met from stored soil water and precipitation) (Table 4-1). Similarly, average ET was between 34.3 and 77.4 cm, and irrigations between 13.3 and 68.8 cm in the silt loam soil. In the sandy loam soil, average ET amounts were between 26.6 and 63.4 cm, and irrigations between 6.8 and 51.4 cm. Dryland ET that was met from stored soil water and precipitation was 20.8 cm in the clay loam, 23.3 cm in the silt loam and 22.2 cm in the sandy loams soils. There was no dryland treatment in the LIRF experiments for comparison. Simulated dryland grain yields for the location was 2149, 2595 and 3041 kg ha^{-1} in the clay loam, silt loam and sandy loam soils, respectively (Table 4-1). Simulated grain yields in response to irrigations to meet full ET requirements were 15507, 15508 and 15507 kg ha^{-1} for the three soils at the location (Greeley).

These model irrigation applications to meet 10 to 100% ET assumed 100% efficiency (net irrigation = gross irrigation) as we adjusted the rate and amount of irrigation commensurate with the saturated hydraulic conductivity of the soil and soil water deficit to generate negligible amounts of runoff and deep percolation. However, runoff can still occur as we did not make adjustments in irrigation for anticipated precipitation occurrences following irrigations. Numerous experiments in the literature have shown a linear relationship between yield and crop evapotranspiration (ET) for many irrigated crops grown in the U.S. Great Plains (Doorenboos and Kassam, 1979; Hergert et al., 1993; Nielsen, 1995; Klocke et al., 2004; Payero et al., 2006; Tolk and Howell, 2008, Tolk et al., 1998). Solomon (1985) reviewed and summarized CWPFs for 37 crops at various locations in the world and reported the yield-ET relationships as mostly linear (there were some non-linear relationships as well), and yield-irrigation relationships were always non-linear. The linearity of the grain yield-ET function is based on the assumption that the yield/biomass ratio is either constant or decreases or increase linearly with T or ET. Tolk and

Howell (2008) identified a change in slope in the yield: ET relationship, with increased ET demand beyond an upper limit, of sorghum grown in the Great Plains of USA. In the 20-years of simulations at Greeley, average grain yield responses to ET and PWS (CWPFs) were close to linear with R^2 values of 0.98 and 0.99, respectively (Fig. 4-5). However, a change in slope was noticed towards the highest ET values (corresponding highest irrigations at 100% ET). In a two-year corn experiment in Tanzania, Igbadun, et al. (2007) fitted linear relationships between grain yield and ET but the variance in the grain yield data explained by the ET was only 71.87%.

The response of average (with ± one standard deviation from the mean) simulated grain yield over the 20 years to different levels of irrigations was in agreement with the measured grain yield responses to irrigations from 2008 to 2011 at Greeley, CO (Fig. 4-6). However, some of the measured grain yields in response to irrigations to meet 40 to 100% crop ET demands deviated substantially from the simulated long-term average grain yields. In the LIRF experiments, corn was planted in rotation with winter wheat, dry beans and sunflower, and as such was planted in different plots each year (Trout et al., 2010). Some variations in measured water retention curves across soil cores collected across the LIRF plots were reported (Ma et al., 2012). However, an average soil was used in the simulations (Ma et al., 2012). One possible reason for the larger deviations in the measured grain yields from the simulated average can be due to the varying soil properties (hydraulic and fertility levels) across the corn planted plots from year to year that was not accounted for in the simulations. However, the 3-year measured yields are well within ± 2 standard deviations of the average values.

The relationship between simulated 20-year average grain yield and $ET_{a\text{-}d}$ is shown in Fig. 4-5. Yield predicted from Yield vs. $ET_{a\text{-}d}$ relationships were comparable to long-term average yields simulated by RZWQM2 (Table 4-1).

Grain yields predicted by Eq. [5] (CWPF) in the three soils also were computed (Table 4-1; Fig. 4-7). The grain yield-ET (or irrigation) relationship as shown in Fig. 4-7 does not pass through the origin, and intercepts the yield axis at certain value around 2000 kg ha^{-1} (also in Fig. 4-5 and 4-6). This value corresponds to the dryland yield when irrigation is zero and if precipitation and stored soil water are available for plant uptake. The magnitude of the intercept depended upon evapotranspiration demand of the atmosphere as well.

Yield as functions of irrigation amounts for drip, sprinkler and surface irrigations.

Simulated grain yields in response to the various amounts of irrigations applied at 100% efficiency in the model (i.e., net irrigation) were converted to yield responses to gross irrigations at efficiencies of 95% under drip, 85% under sprinkler and 55 % under surface irrigations using Eq. [5] (e.g., in silt loam soil in Fig. 4-8). First step in this process was to convert the average net irrigation (simulated by RZWQM2) required for achieving a given average yield (simulated average over 20 years) to gross irrigations required when irrigated with lower efficiencies (drip, sprinkler and surface methods) using Eq. [7].

RZWQM2 simulated grain yields in the clay loam at Greeley ranged from 2149 kg ha^{-1} under dryland conditions to 15506 kg ha^{-1} with maximum irrigation. Maximum gross irrigation amounts computed with Eq. [7] were 54.8 cm under drip, 61.3 cm under sprinkler and 94.7 cm under surface irrigation methods (Table 4-2). Maximum gross irrigation amounts computed in silt loam soil was 61.5 cm under drip, 68.8 cm under sprinkler and 106.3 cm under surface irrigation methods. Maximum gross irrigation amounts in sandy loam soil under the three irrigation methods were 48.7, 54.5 and 84.2 cm, respectively.

Development of CWPFs for other locations and soils

The above procedure was repeated using a clay loam, silt loam and sandy loam soil in RZWQM2 and similar CWPFs for corn as shown in Fig. 4-7 were developed for the three irrigation methods (drip, sprinkler and surface) at Rocky Ford, Otero county; and Akron, Washington county (e.g., in silt loam soil in Fig. 4-8). The curves representing grain yield responses to irrigation under a given method (drip, sprinkler or surface) fitted using Eq. [5] for the clay loam, silt loam and sandy loam soils across the three locations (Greeley, Akron and Rocky Ford) did not coincide. So, in order to make use of the CWPF developed using experimental data at a location under a given irrigation method (e.g.: LIRF at Greeley) across soils and climates in the region, a scientifically sound procedure that makes use of the available information at the location of interest, needs to be developed. In this direction, the generalization of CWPFs for corn across three locations (Greeley, Akron and Rocky Ford) and soils (clay loam, silt loam and sandy loam) were explored.

Estimation of ET_d and Y_d

The PAW in the soil at planting at a location significantly modifies the shape of the crop yield responses to applied irrigations (CWPFs) (Stewart and Hagan, 1969). The PAW in the crop root zone will vary from field to field, and location to location, depending upon the crop grown prior to planting corn, length of the fallow period in between, snow and rainfall in that preceding period, as well as any pre-planting irrigation applied. Therefore, we explored some relationships to account for the effect of different initial water contents at planting, along with the amount of effective rainfall (rainfall minus runoff minus deep percolation) after planting, on the average dryland ET (ETd) and corn yield, in order to adjust the CWPFs for yield versus irrigation.

For all the three soil types and three locations of this study (pooled data), plots of ETd vs. seasonal total precipitation, ETd vs. seasonal total P_{eff} and ETd vs. PWS show good correlations. Further, there is approximately a linear relationship between ETd and PWS, with R^2=0.90, which falls slightly below the 1:1 line (Fig. 4-9a).

Above equation shows that about 97.5% of the initial soil water and effective rainfall contribute to ETd. This relation is useful for estimating the effect of varying initial plant-available soil water in the root zone (in 1 m depth in RZWQM2 calculations), as well as of effective rainfalls, on ETd.

Further, we explored various possible options available for the prediction of dryland corn grain yield (Yd) from measured and readily available data at the locations. Reliable relationships between Yd and total crop season precipitation (P), relative Yd (dryland yield/ maximum fully irrigated yield) (RelYd) and P, Yd and effective precipitation (precipitation – runoff – deep percolation, Peff), RelYd and Peff, Yd and PWS, and Yd and dryland ET (ETd) were poor, rendering them to have low predictable value. However, RelYd vs. PWS and RelYd vs. ETd showed strong enough relationships for prediction (Fig. 4-9 b and c). In the Fig. 4-9 b and c, the RelYd varies along fitted straight lines.

Thus, Fig. 4-9 allows us to estimate ETd and dryland yield from knowledge of initial soil water and effective precipitation. Thus, these relationships allow us to adjust the CWPFs of yield vs. irrigation for the various initial soil water contents at planting and/or the variable effective rainfall. The estimated value of dryland yield and dryland ETd also allow us to develop the

CWPFs for irrigation from knowledge of the long-term average fully irrigated maximum corn yield and the corresponding maximum ET and maximum irrigation in Eq. [5].

Generalization of CWPFs between yield and ET or PWS

The relationships among the corn CWPFs from three different locations in Colorado (Greeley, Akron, and Rocky Ford) and three soil types (silt loam, clay loam, and sandy loam) were explored to identify similarities in their shape and magnitude and minimum parameters to represent them. The similarities could, thus, allow us to develop reasonable CWPFs from minimum known data points for counties and locations where adequate data are not available for calibration/validation of the model to develop detailed long-term average functions.

Fig. 4-10a shows the 20-year average corn yield vs. ET CWPFs for three different soil types plotted together, for each of the three locations in Colorado. The functions for each location seem to come close, but they differ in shape and magnitudes among locations. The functions are close to linear, as commonly reported in the literature. The lower limit of ET in these graphs is the ET resulting from PWS ($I_{eff} = 0$), which could vary among the soil types and locations. The functions for yield vs. PWS, the effective irrigation water applied (initial plant available water in the top 1m of soil was considered) show similar results (Fig. 4-10b).

The linear relation between biomass (and often yield) and transpiration for a crop species is affected by the evaporative demand of the atmosphere and CO_2 concentration. For fixed CO_2 level and in the absence of severe water or N stress, the linear CWPF need to be normalized for evaporative demand of the atmosphere in order to extrapolate the function across different climate zones (Steduto et al., 2007). Tanner and Sinclair (1983) suggested that the transpiration (or approximately ET) be normalized by division with the leaf-air vapor pressure deficit (VPD) or approximately the vapor pressure deficit of the air, on daily or weekly time intervals. However, under field conditions, the canopy temperature greatly affects the relationship between VPD of the leaf stomata and the VPD of the air, and the use of the VPD is not as sensitive. Steduto and Albrizio (2005) and Steduto et al. (2007) gave evidence that the use of Penman-Monteith reference ET as a normalization factor is much more robust.

Fig. 4-11a shows the average grain yield-ET functions for the three locations plotted together for each soil type separately. Again, the functions for the three locations are fairly close together for each soil type, except that the longer duration corn variety grown at Rocky Ford had higher yield and higher ET. Fig. 4-11b shows the same functions when the grain yield is plotted as a function of ET normalized with ET_r on a daily basis. Instead of further coalescing as expected from the theory of normalization for climate across locations (Tanner and Sinclair, 1983; Steduto et al., 2007) as described in the Introduction, the functions actually separate. For a given yield, less normalized ET is required for Rocky Ford and Akron locations than for the Greeley location. This may indicate that the corn variety and the weather conditions at Rocky Ford, and to a lesser degree at Akron, are such that the crop makes more efficient use of water. However, model parameterization uncertainty at each individual location also can be a contributing factor here.

Fig. 4-11c shows functions for relative grain yield vs. relative ET (ET_R), that is the ET divided by the maximum actual ET for the crop at each location. Interestingly, the functions coalesce together for each soil type, as well as for all soil types together (Fig. 4-11d). Similar coalescence was obtained for the biomass-ET relations. This coalescence is very useful in that it allows us to estimate yield-ET functions for any location and soil type from minimum data of: multi-year average maximum yield and maximum ET under fully irrigated conditions for a given location and variety, and yield and ET for dryland conditions resulting from initial soil water and effective rainfall. In the analysis presented above, we developed relationships between the dryland yield and ET with initial soil water and effective rainfall above. The coalescence was not as compact for yield vs. PWS in the model (assumed to be applied most efficiently) (Fig. 4-12).

In Fig. 4-11d, we have fitted a liner relationship between pooled relative yield vs. relative ET (Eq. [9]) with an R^2 of 0.99.

$$Yr = 0.1761 + 0.7921\,ET_R \quad \text{--------------------------} \ [9]$$

SUMMARY AND CONCLUSIONS

Crop yield responses to applied irrigation (CWPFs) are essential information for planning allocations and management of scarce fresh water resources for optimum crop production. Annual precipitation and other weather variables are key factors affecting irrigation decisions at a location. Hence CWPFs need to be based on long-term yield responses to weather (including precipitation) and applied irrigations at a location. We combined a dynamic process-oriented cropping system simulation model with short term limited irrigation trials and long-term weather data to develop long-term average CWPFs for corn. We used the calibrated and tested RZWQM2 model for simulation of corn production at Greeley, Weld County; Akron, Washington County; and Rocky Ford, Otero County, Colorado. The model was then used to simulate crop responses to irrigation schedules in clay loam, silt loam and sandy loam soils based on weekly cumulative ET demands over a 20 yr (1993-2011) period of recorded weather at the three locations and developed average CWPFs. Generalization of the CWPFs across the three locations and soils were explored. We were able to generalize the CWPFs across the soils and locations through a linear relationship between relative grain yield (Y/Ymax) and relative ET (ET/ETmax). Linear relationships were also found to exist between dryland ET (ETd) and PWS, and relative dryland grain yield (Y/Ymax) and ETd. The estimated value of dryland yield and ETd also allow us to develop the CWPFs for irrigation from knowledge of the long-term average fully irrigated maximum corn yield and the corresponding maximum ET and maximum irrigation. The method developed can be adapted for development of similar CWPFs for other crops of interest in different soils and climates across the world.

Table 4-1. Percentage ET demand at which irrigations were applied and average seasonal amount of irrigation applied in response, and averages of evapotranspiration and grain yield simulated for corn in clay loam, silt loam and sandy loam soils at Greeley, Colorado. Grain yields due to irrigation ($Y\text{-}Y_d$) predicted by the Cobb-Douglas type response function given in Eq. [5] and using a Yield:($ET\text{-}ET_d$) linear relationships are also given.

% ET demand for irrigation	Actual Irrigation applied (cm)	ET, (cm)	Simulated grain yield Average (kg ha^{-1})	Simulated grain yield SD (kg ha^{-1})	Yield from Eq. [5] (kg ha^{-1})	Yield from $ET_{a\text{-}d}$ (kg ha^{-1})
Clay loam						
0-30	0.0	20.8	2149	1250	2149	2149
40	7.9	27.5	4289	2645	4153	3920
50	20.1	36.6	6019	1273	7151	6348
60	27.3	44.7	7699	1811	8847	8505
70	35.7	52.3	10217	2371	10749	10558
80	45.4	59.1	12254	2132	12797	12353
90	51.2	64.6	14185	1751	13926	13817
100	61.3	72.7	15506	2030	15507	15999
Silt loam						
0-30	0.0	23.3	2595	1458	2595	2595
40	13.3	34.3	4880	3094	5678	5386
50	25.2	43.9	7252	3149	8242	7829
60	34.4	51.9	9592	2831	10103	9849
70	42.8	58.4	11896	2246	11679	11506
80	50.5	64.4	13122	1927	13001	13030
90	59.1	71.0	14648	1886	14285	14691
100	68.8	77.4	15508	2029	15508	16323
Sandy loam						
0-30	0.0	22.2	3041	1883	3041	3041
40	6.8	26.6	3900	1782	5052	4458
50	13.9	34.0	6500	2467	7103	6839
60	24.3	40.5	9048	2358	9887	8906
70	30.4	47.5	10696	2121	11420	11155
80	36.2	52.6	12922	2089	12784	12801
90	42.1	58.1	14828	1898	14028	14548
100	51.4	63.4	15507	2029	15507	16258

Table 4-2. Irrigation amounts derived for drip, sprinkler, and surface irrigation methods, using the irrigation-yield responses (CWPFs) simulated by RZWQM2 with 100% irrigation efficiency (€), in clay loam, silt loam and sandy loam soils at Greeley, Weld county, Co. I_m is maximum irrigation needed for achieving maximum yield.

Irrigation schedule (Weekly %ET demand)	Average grain yields simulated (kg ha^{-1})	Irrigation amounts (cm)		
		Drip (€ = 95%)	Sprinkler (€ = 85%)	Surface (€ = 55%)
		Clay loam		
0-30(dry land)	2149	0.0	0.0	0.0
40	4289	25.8	28.8	44.6
50	6019	32.2	36.0	55.7
60	7699	41.9	46.9	72.4
70	10217	48.4	54.1	83.6
80	12254	51.6	57.7	89.1
90	14185	52.9	59.1	91.3
100(maximum)	15506	54.8	61.3	94.7
		Silt loam		
0-30	2595	0.0	0.0	0.0
40	4880	29.0	32.4	50.0
50	7252	36.2	40.5	62.5
60	9592	47.1	52.6	81.3
70	11896	54.3	60.7	93.8
80	13122	57.9	64.7	100.1
90	14648	59.4	66.4	102.6
100	15508	61.5	68.8	106.3
		Sandy loam		
0-30	3041	0.0	0.0	0.0
40	3900	21.7	24.2	37.4
50	6500	27.1	30.3	46.8
60	9048	35.2	39.3	60.8
70	10696	40.6	45.4	70.1
80	12922	43.3	48.4	74.8
90	14828	44.4	49.6	76.7
100	15507	48.7	54.5	84.2

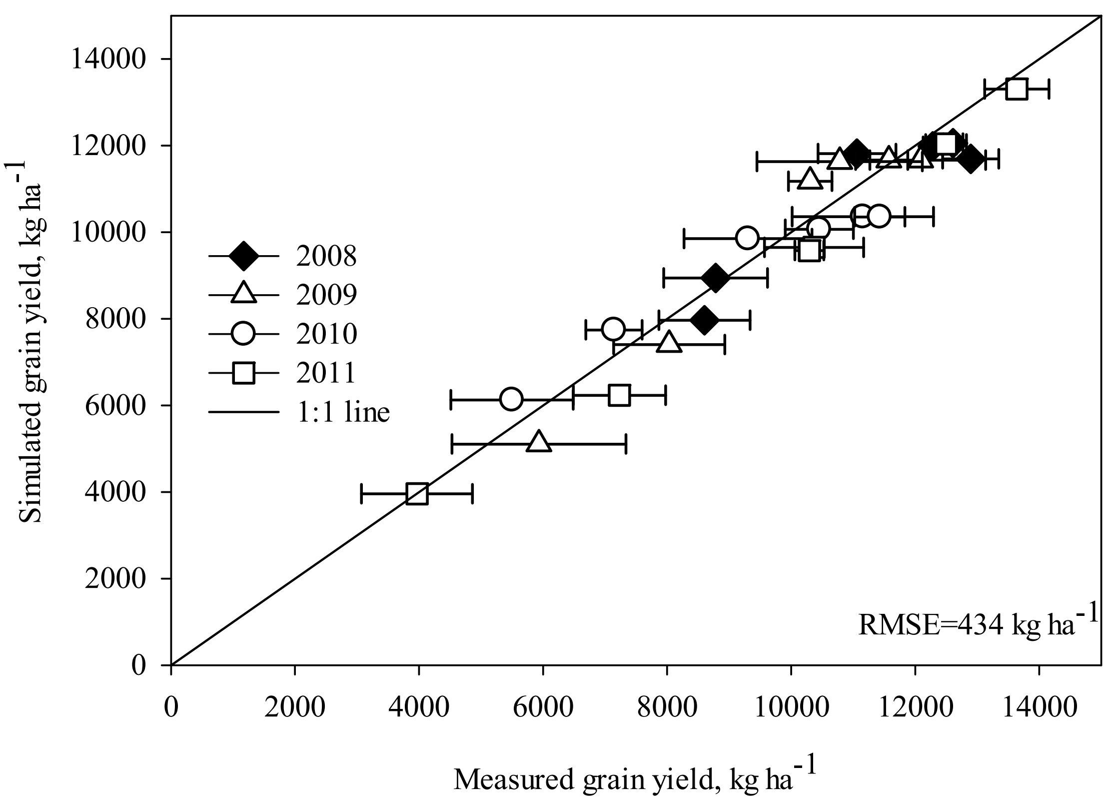

Fig. 4-1. Comparison between measured and simulated grain yields from 2008 to 2011 in the LIRF experiments. Error bars indicate one standard deviation in the measured data.

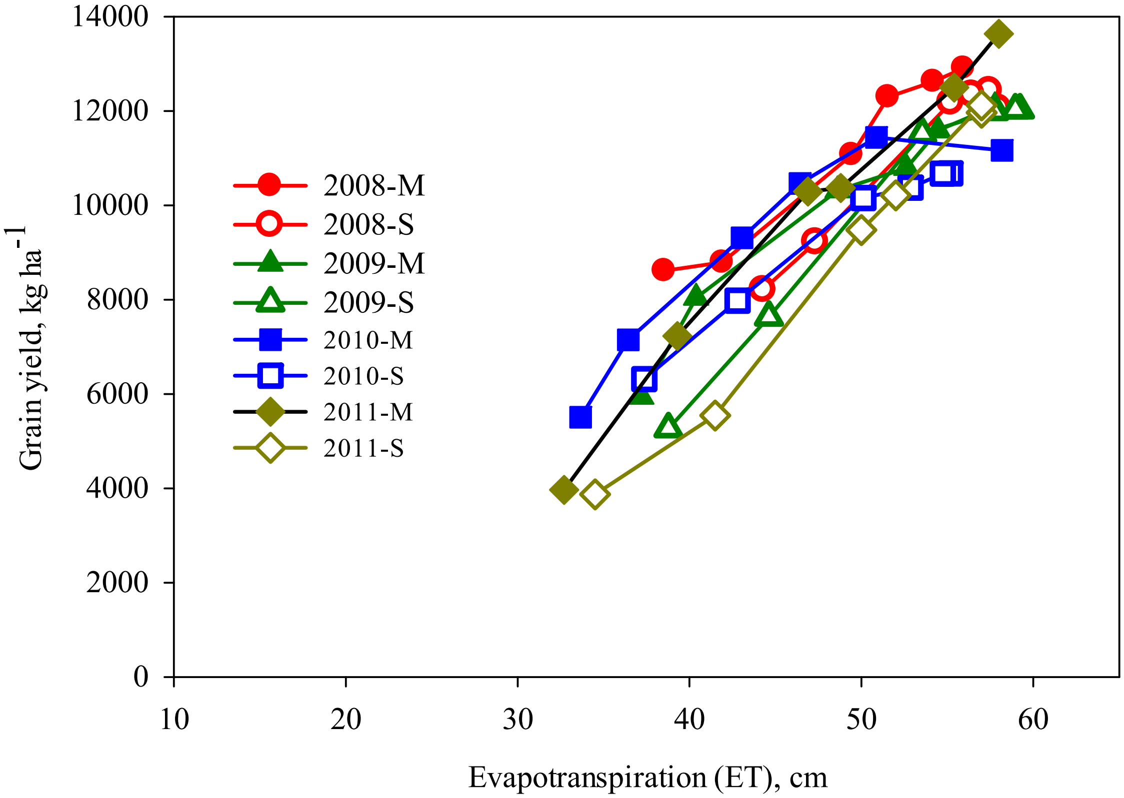

Fig. 4-2. Comparisons of measured and simulated corn grain yield responses to evapotranspiration in the LIRF experiments. M = measured, S = Simulated.

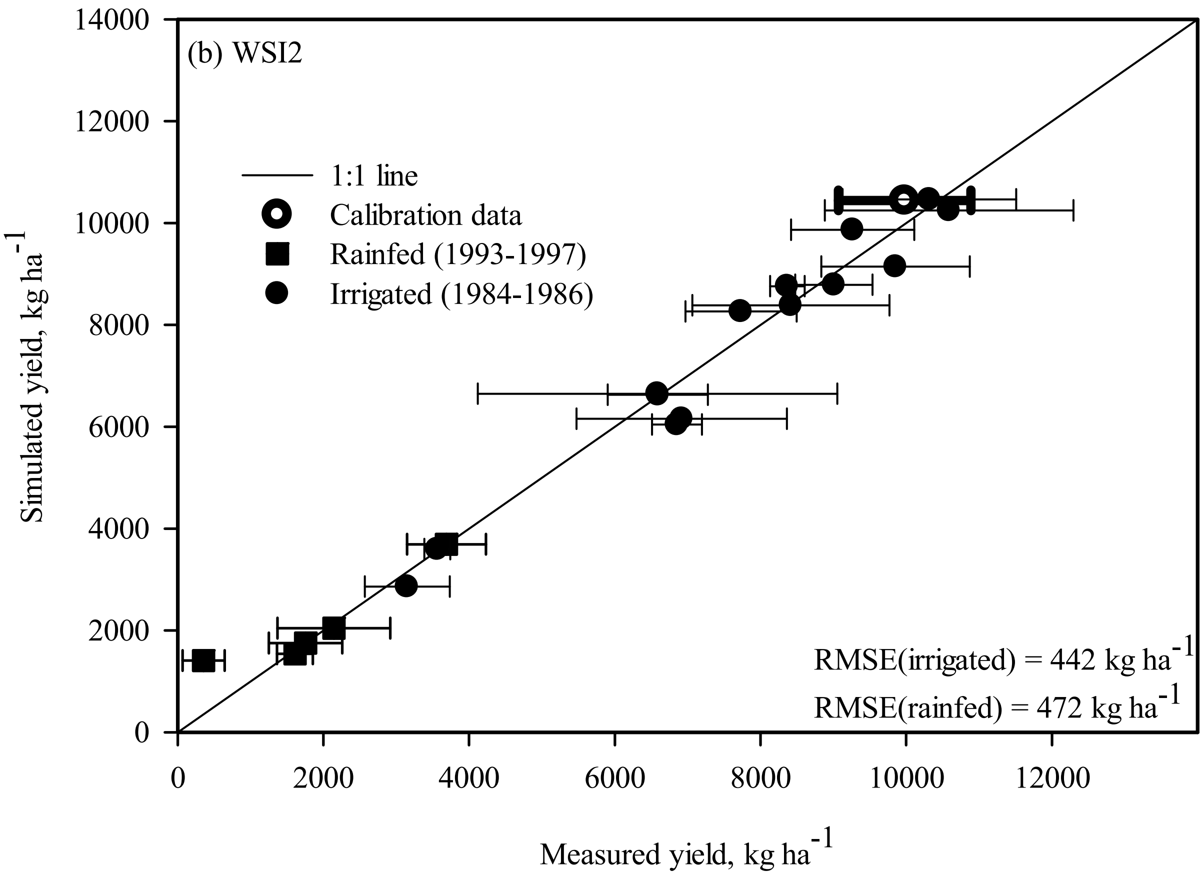

Fig. 4-3. Comparison between measured and simulated rainfed (1994-1996) and irrigated (1984-1986) corn grain yields at Akron, Washington County, Colorado. Error bars indicate one standard deviation in the measured data.

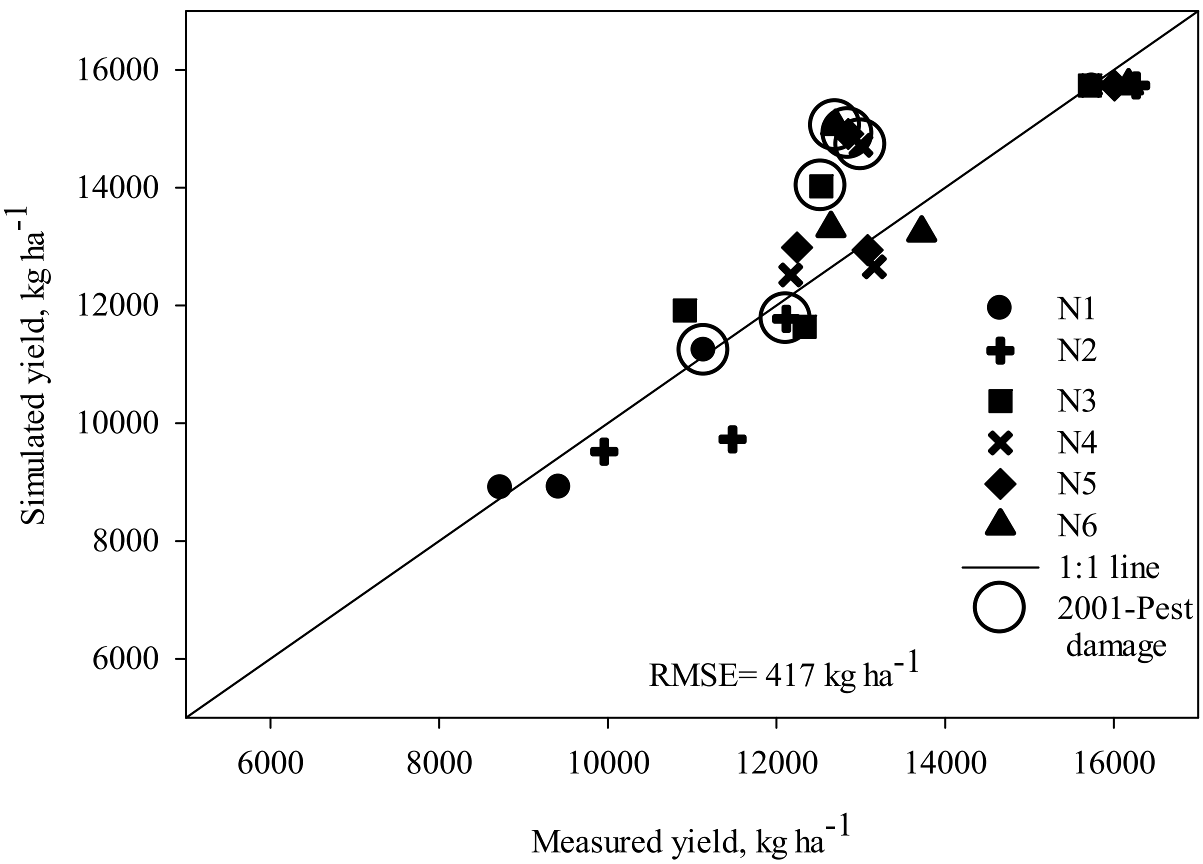

Fig. 4-4. Measured and simulated corn grain yields in the N source and rate study conducted at Rocky Ford during 2000-2003. N1, N2, N3, N4, N5 and N6 represent the six N levels used in the experiments. Pest damaged corn yields in 2001 was not used in calculation of RMSE.

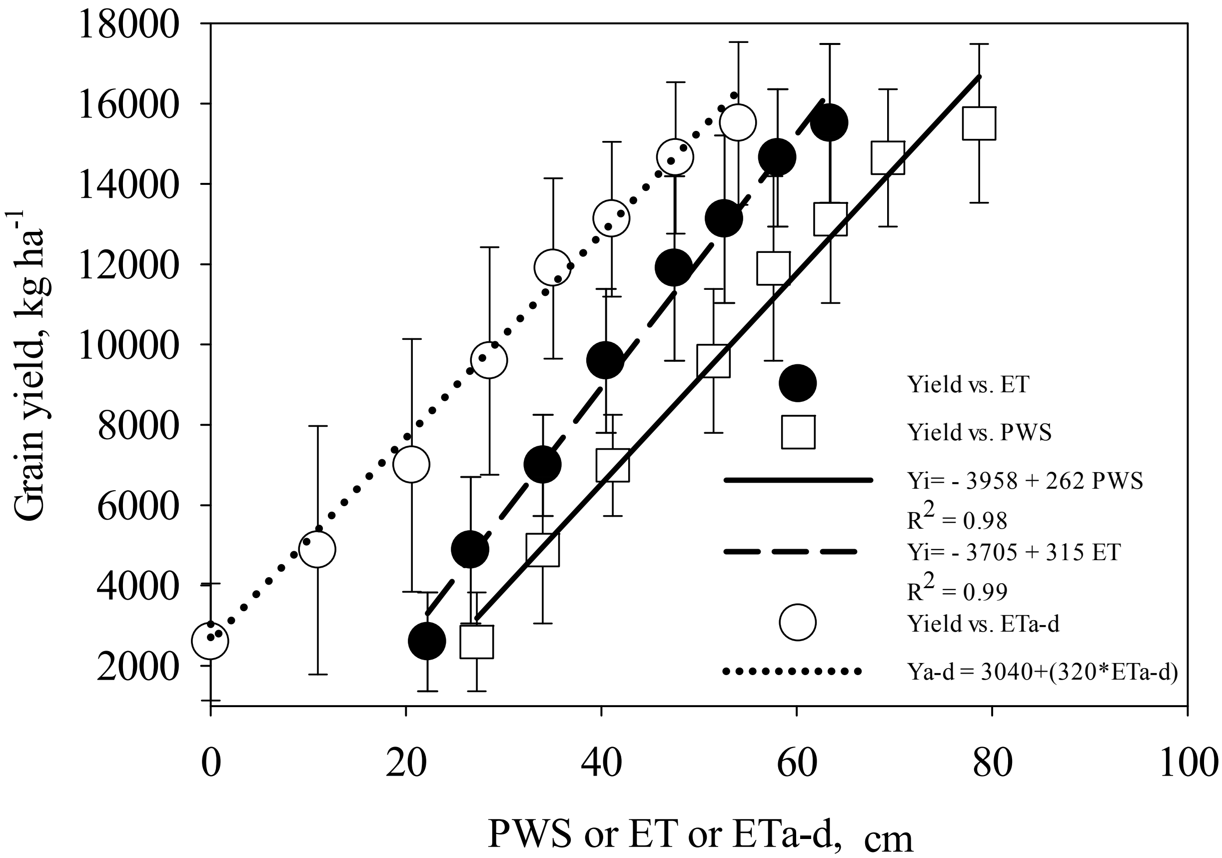

Fig. 4-5. Simulated long-term average corn yield (Yi) response to plant water supply (PWS) (effective rainfall + plant available water in the soil profile at planting + applied irrigation), evapotranspiration (ET), and Eta-d (ET due to irrigation) in silt loam soil at Greeley, Colorado. Error bars indicate one standard deviation in the 20 yrs of simulated grain yield. Ya-d is yield due to irrigation. Linear equations representing the yield vs. ET, $ET_{a\text{-}d}$ and PWS are also shown.

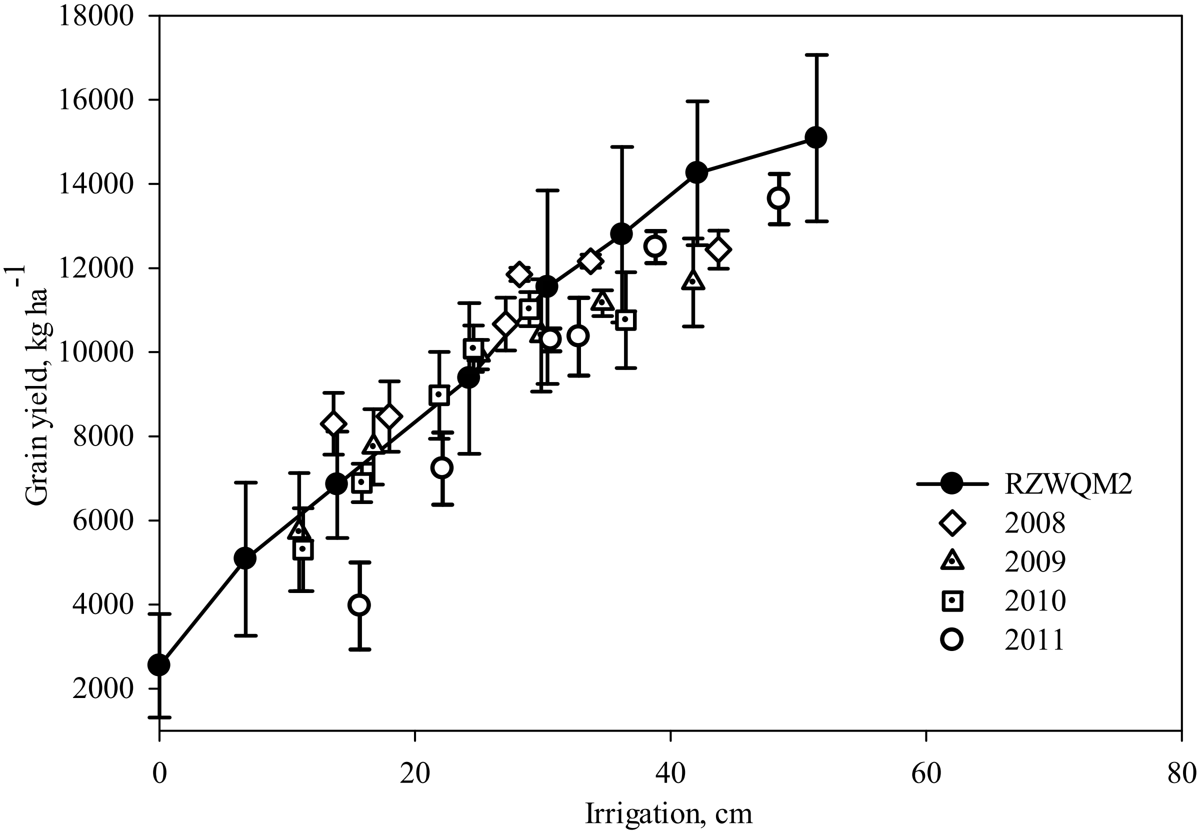

Fig. 4-6. Comparison of simulated 20-years average grain yield responses to irrigation with field measured data for 2008, 2009, 2010 and 2011 for corn at Greeley, Colorado. Error bar indicate one standard deviation from the mean of the long-term simulations.

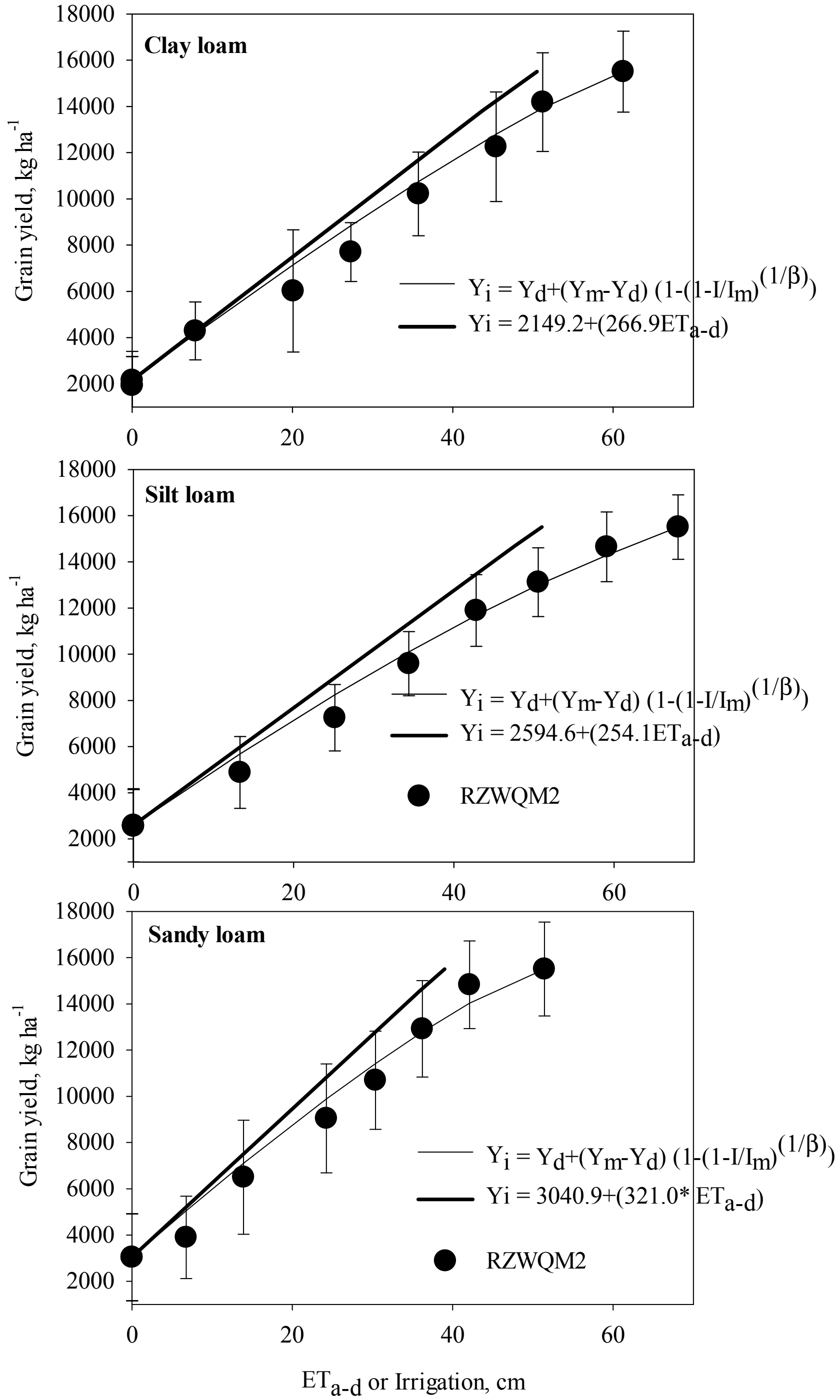

Fig. 4-7. Simulated average corn yield responses to gross irrigations and ET in clay loam, silt loam and sandy loam soils at Greeley, Colorado. Black filled circle represent the yield responses to irrigation (RZWQM2), and the thin curve represents the yield response fitted using the Cobb-Douglas (power) function (Eq.[5]). The thick straight line represents the yield response to Et_{a-d} fitted assuming a linear relationship. Error bar is one standard deviation from the mean of 20 year simulated grain yields.

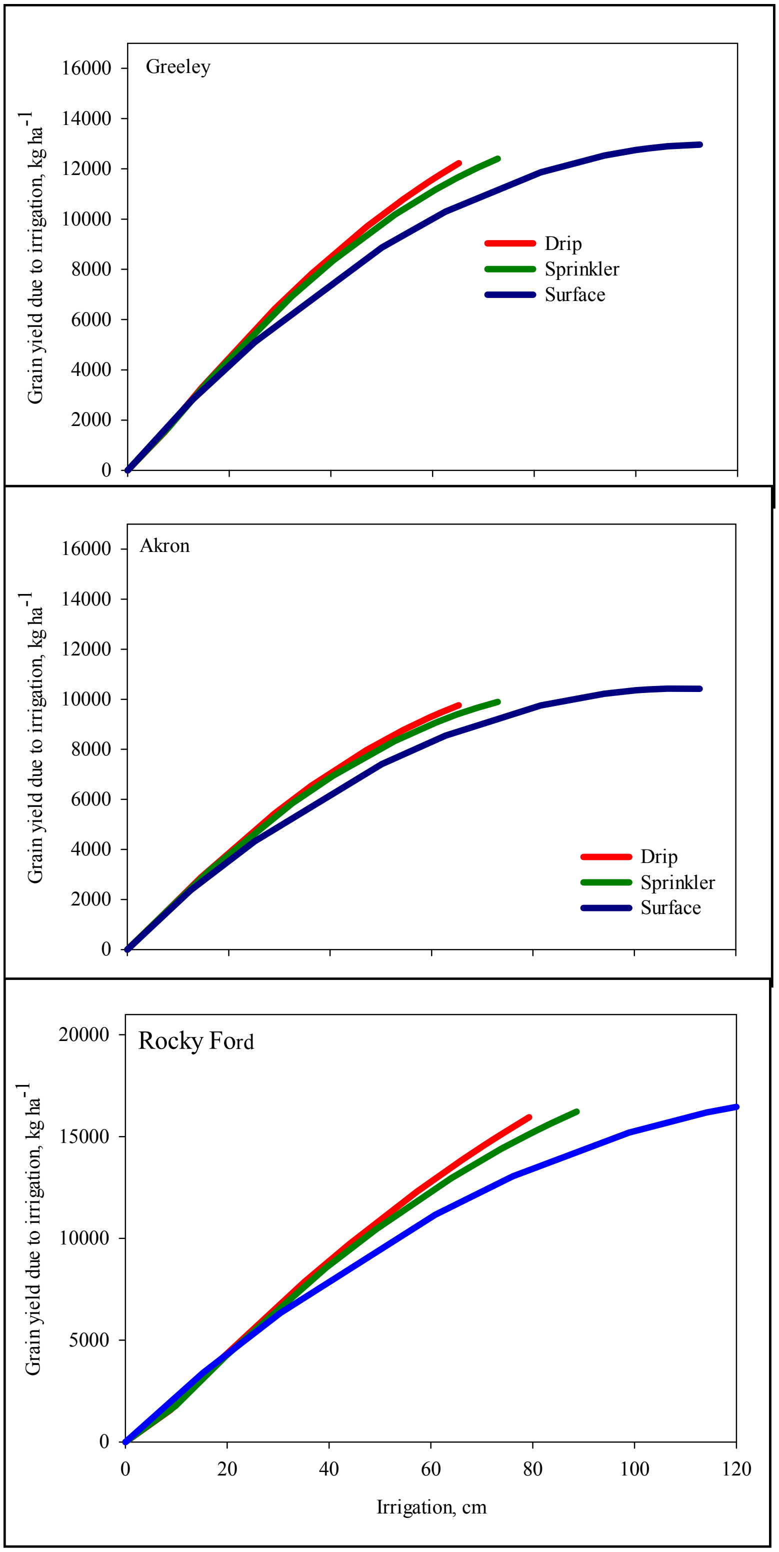

Fig. 4-8. Corn yield responses to gross irrigations, fitted using the Martin et al. (1984) function (Eq. [5]), under drip, sprinkler and surface irrigations in silt loam soils at Greeley, Weld county; Akron, Washington county; and Rocky Ford, Otero county, Colorado.

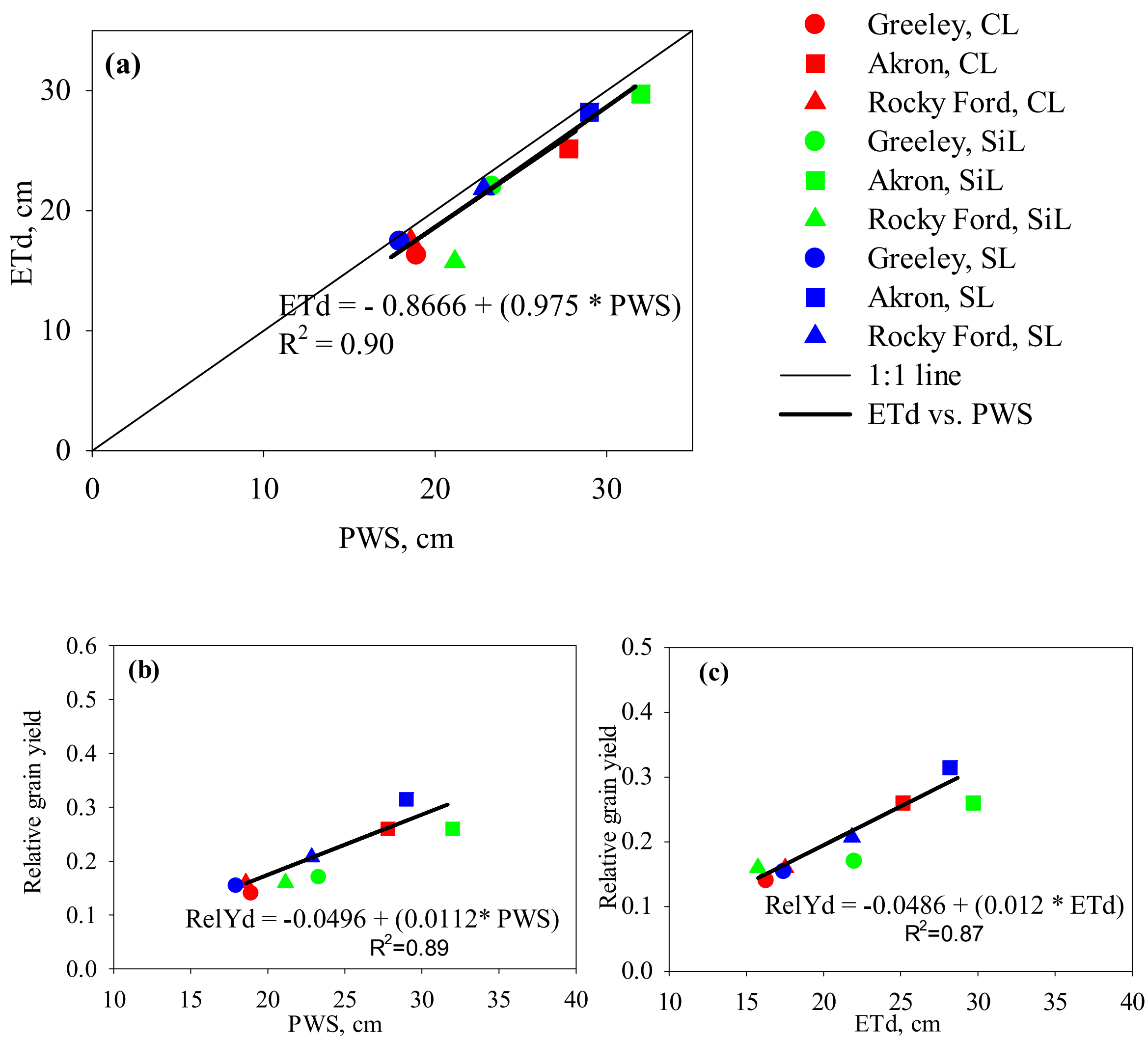

Fig. 4-9. (a) Relationships between average seasonal dryland evapotranspiration (ETd) and plant water supply (PWS, effective precipitation and plant available water in the soil at planting), (b) relative grain yield (i.e., *RelYd=Yd/Ym*, *Yd* is dryland grain yield and *Ym* is the average maximum fully irrigated grain yield) responses to PWS, and (c) RelYd responses to ETd. Linear functions fitted between ETd and PWS, RelYd and PWS, and RelYd and ETd are shown.

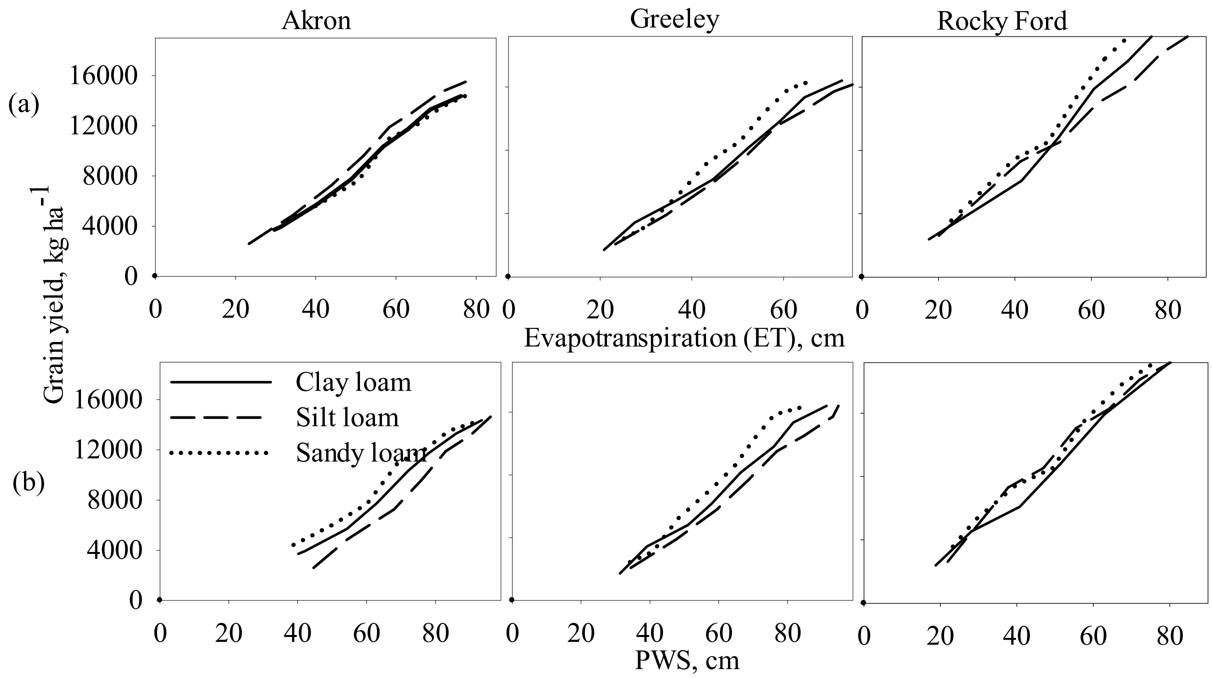

Fig. 4-10. (a) Corn grain yield-ET relations across three soil types at each location and (b) yield-plant water supply (PWS) (effective precipitation + applied irrigation + plant available water in the 1 m soil profile at planting) relations across three soil types at each location.

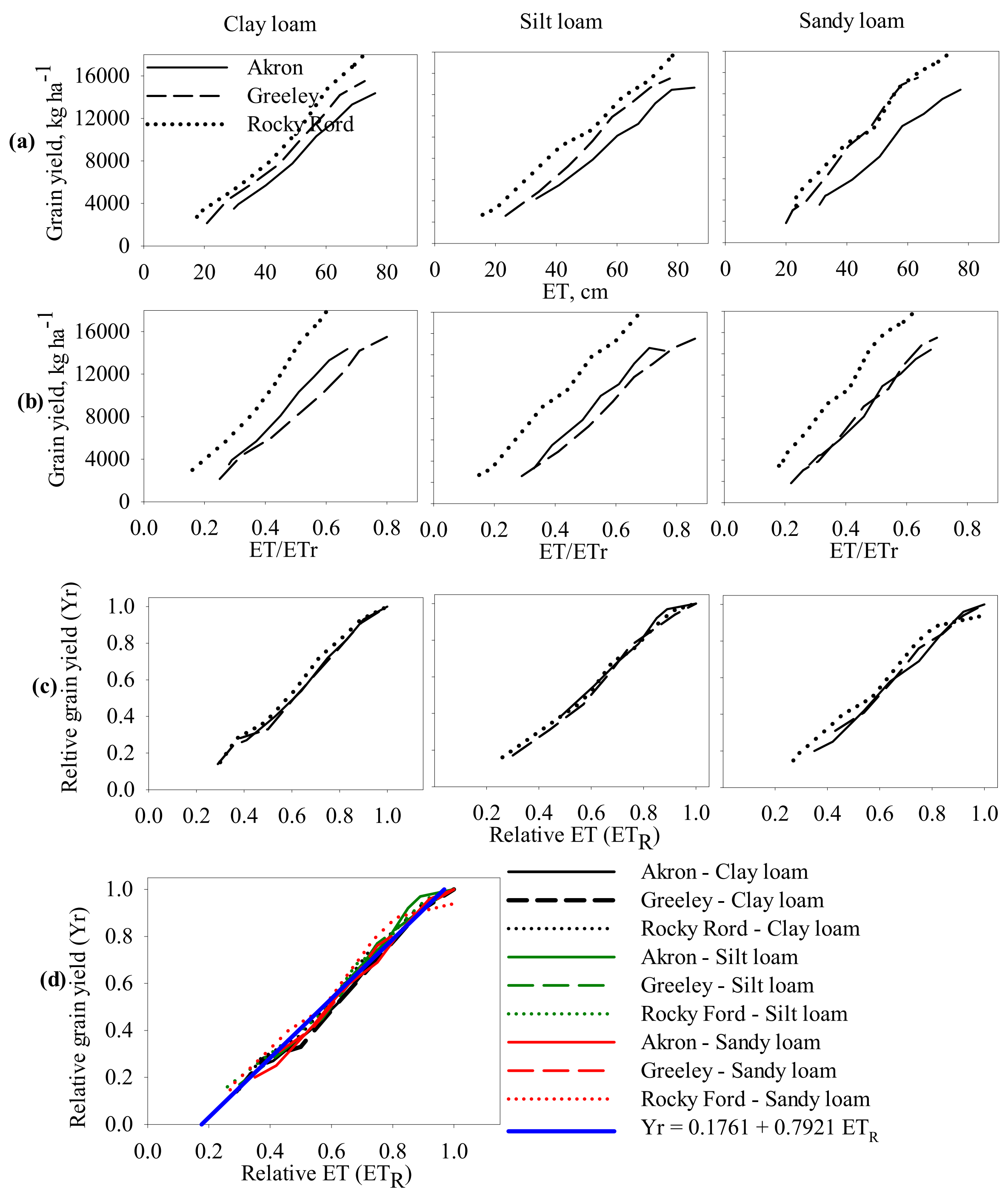

Fig. 4-11. (a) Grain yield- ET relationships across the three locations by soil type soils, (b) Yield - ET normalized with reference crop evapotranspiration (ET_r) across locations by soil type, (c) Relative Yield (Yr)-relative ET (ET_R=ET/ETmax, ETmax=maximum ET) across the three locations by soil type, and (d) Y - ET_R relationships between the three locations and the three soil. The linear relationship fitted to the Yr - ET_R relationships pooled across the three locations and soils in (d) was: $Yr = 0.1761 + 0.7921\, ET_R$ with an R^2 of 0.99

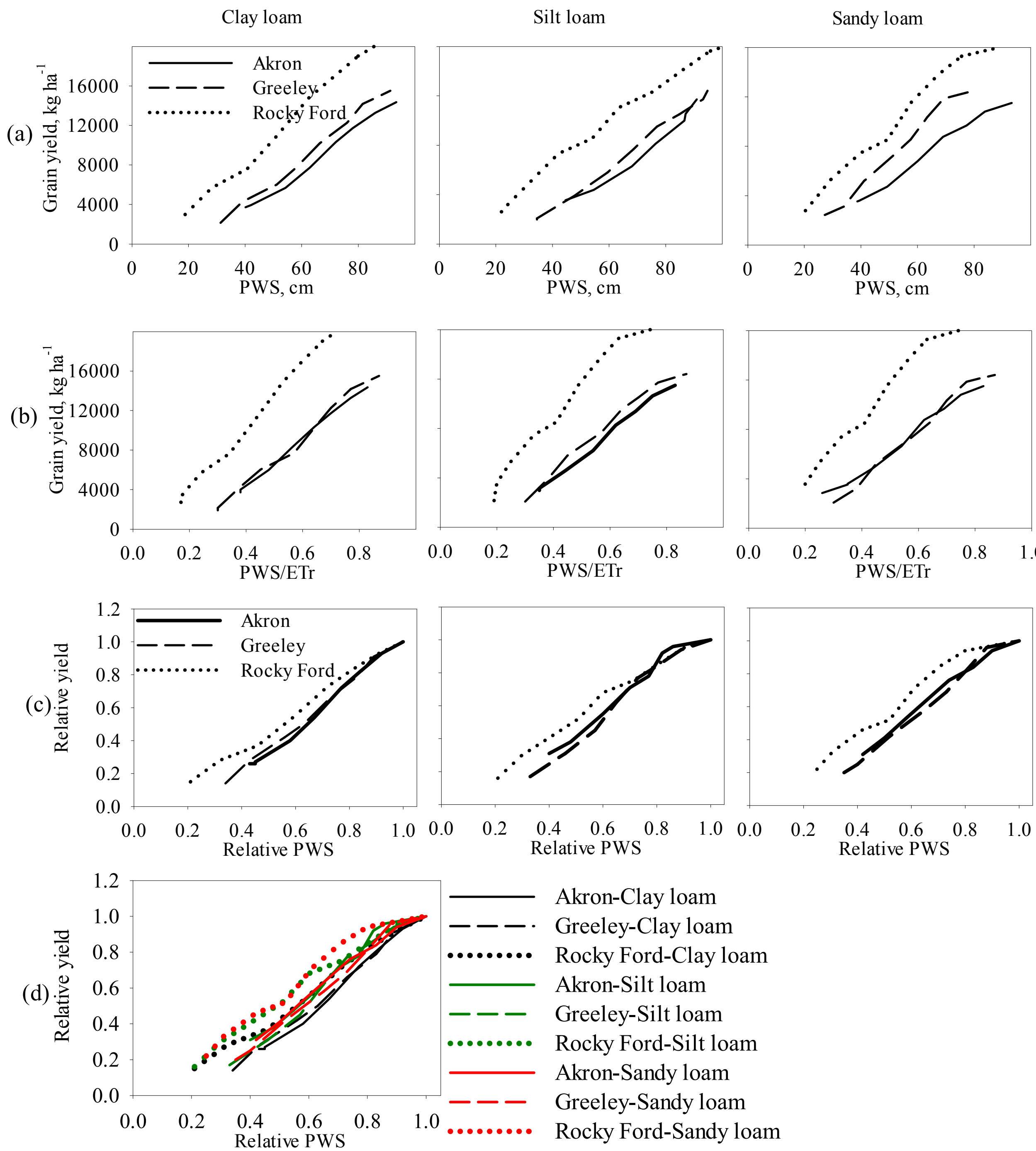

Fig. 4-12. (a) Corn grain yield – plant water supply (PWS) (effective precipitation + applied irrigation + plant available water in the 1 m soil profile at planting) relationships across three locations by soil type; (b) yield - PWS normalized with reference crop evapotranspiration (ET_r) across the three locations by soil type; (c) relative yield (Yr) - relative PWS relationships across the three locations by soil type; and (d) Yr - relative PWS relationships across the three locations and the three soils.

REFERENCES

Ahuja, L. R., Rojas, K. W., Hanson, J. D., Shafer, M. J., Ma, L. (Eds.), 2000. Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water resources publications, LLC, Colorado, USA. 372p.

Allen, R. G., I.A, Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder. 2005. The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers. Reston, VA.

Anderson, R.L., R.A. Bowman, D.C. Nielsen, M.F. Vigil, R.M. Aiken, and J.G. Benjamin. 1999. Alternative crop rotations for the central Great Plains. J. Prod. Agric. 12:95-99.

Bausch, W., T. Trout, and G. Buchleiter. 2011. Evapotranspiration adjustments for deficit-irrigated corn using canopy temperature: a concept. Irrig. and Drain. 60: 682–693.

Bowman, R.A., and A.D. Halvorson. 1997. Crop rotation and tillage effects on phosphorus distribution in the central Great Plains. Soil Sci. Soc. Am. J. 61:1418-1422.

Cakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res. 89:2-16.

Dorenboos J., and A.H. Kassam. 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33. Rome, Italy: FAO.

Farahani, H. J., and DeCoursey, D. G. 2000. Potential evapotranspiration processes in the soil-crop-residue system. p52-80. *In* L.R. Ahuja, K.W. Rojas, J. D. Hanson, M.J. Shafer, L. Ma (eds.). Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resources Publications, LLC, Highlands Ranch, CO.

Farahani, H.J., and L.R. Ahuja. 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Trans. ASAE 39:2052-2064.

Farre´ , I., and J.M. Faci. 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. Agric. Water Manage. 96:383–394.

Fereres, E., and Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. Special issue on ‘Integrated approaches to sustain and improve plant production under drought stress’. J. Exp. Bot. 58: 147–159.

Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96: 1275–1284.

Halvorson, A.D., D.C. Nielsen, and C.A. Reule. 2004. Nitrogen fertilization and rotation effects on no-till dryland wheat production. Agron. J. 96:1196-1201.

Halvorson, A.D., F.C. Schweissing, M.C. Bartolo, and C.A. Reule. 2005. Corn response to nitrogen fertilization in a soil with high residual nitrogen. Agron. J. 97:1223-1229.

Hergert, G.W., N.L. Klocke, J.L. Petersen, P.T. Nordquist, R.T. Clark, and G.A. Wicks. 1993. Cropping systems for stretching limited irrigation supplies. J. Prod. Agric. 6: 520–528.

Hoogenboom, G., J.W. Jones, and K.J. Boote. 1991. A decision support system for prediction of crop yield, evapotranspiration, and irrigation management. In: Proc. 1991 Irrig. and Drainage. ASCE, Reston, VA, pp. 198–204.

Igbadun H.E., A.K.P.R. Tarimo, B.A. Salim, and H.F. Mahoo. 2007. Evaluation of selected crop water production functions for an irrigated maize crop. Agric. Water Manage. 9 4:1–10.

Irmak, S., L.O. Odhiambo, W.L. Kranz, and D.E. Eisenhauer. 2011. Irrigation efficiency and uniformity, and crop water use efficiency. University of Nebraska-Lincoln extension. http://ianrpubs.unl.edu/epublic/live/ec732/build/ec732.pdf.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. European Journal of Agron. 18:235-265.

Kefale, D., and S.L. Ranamukhaarachchi. 2004. Response of maize varieties to drought stress at different phenological stages in Ethiopia. Trop. Sci. 44: 61–66.

Klocke, N.L., J.P. Schneekloth, S.R. Melvin, R.T. Clark, and J.O. Payero. 2004. Field scale limited irrigation scenarios for water policy strategies. Applied Engineering in Agriculture 20: 624-631.

Ma, L., D.C. Nielsen, L.R. Ahuja, R.W. Malone, S.A. Saseendran, K.W. Rojas, J.D. Hanson, J.G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. Trans. ASAE 46:39-49.

Ma, L., G. Hoogenboom, L.R. Ahuja, D.C. Nielsen, and J.C.II. Ascough. 2005. Evaluation of the RZWQM-CROPGRO hybrid model for soybean production. Agron. J. 97: 1173-1182.

Ma, L., G. Hoogenboom, L.R. Ahuja, J.C. II. Ascough, and S.A. Saseendran. 2006. Evaluation of RZWQM-CERES-maize hybrid model for maize production. Agric. Systems. 87:274-295.

Ma, L., G. Hoogenboom, S. A. Saseendran, P. N. S. Bartling, L. R. Ahuja, and T. R. Green. 2009. Estimates of soil hydraulic properties and root growth factor on soil water balance and crop production. Agron. J. 101:572–583.

Ma, L., L.R. Ahuja, S.A. Saseendran, R.W. Malone, T.R. Green, B.T. Nolan, P.N.S. Bartling, G.N. Flerchinger, K.J. Boote, and G. Hoogenboom. 2011. A Protocol for Parameterization and Calibration of RZWQM2 in Field Research. p 2-64. *In*: L.R. Ahuja and L. Ma (eds.), Methods of introducing system models into agricultural research. Advances in Agricultural Systems Modeling Series 2.

Ma, L., T.J. Trout, L.R. Ahuja, W.C. Bausch, S.A. Saseendran, R.W. Malone, D.C. Nielsen. 2012. Calibrating RZWQM2 model for maize responses to deficit irrigation. Agric. Water Manage. 103:140– 149.

Martin, D. L., D.G. Watts, and J.R. Gilley. 1984. Model and production function for irrigation management. J. Irrig. and Drain. ASCE 110:149-164.

Martin, D.L., J. R. Gilley, and R.J. Supalla. 1989. Evaluation of irrigation planning decisions. Journal of Irrigation and Drainage Engineering 115: 58-77.

Moser, S.B., B. Feil, S. Jampatong, and P. Stamp. 2006. Effects of pre-anthesis drought, nitrogen fertilizer rate, and variety on grain yield, yield components, and harvest index of tropical maize. Agric. Water Manage. 81: 41–58

Nielsen, D. C. 1995. Conservation Tillage Fact Sheet #3-95. Water use/yield relationships for central Great Plains corps. Akron, Colo.: Colorado Conservation Tillage Association.

Nimah, M.N., and R.J. Hanks. 1973. Model for estimating soil water, plant and atmospheric inter relations: I. description and sensitivity. Proceedings Soil Sci. Soc. Of America 37:523-527.

Payero, J.O., S.R. Melvin, S. Irmak, and D. Tarkalson. 2006. Yield response of corn to deficit irrigation in a semiarid climate. Agric. Water Manage. 84:102-112.

Saseendran, S. A., Nielsen, D.C., Ma, L., Ahuja, L.R. 2010a. RZWQM2 simulations of alternative cropping systems with and without summer crops in the Central Great Plains. Agron. J. 102:1522-534.

Saseendran, S.A., D.C. Nielsen, L. Ma, and L.R. Ahuja. 2010b. Adapting CROPGRO for simulating canola growth in RZWQM2 and DSSAT. Agron. J. 102:1606-621.

Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-wheat. Agron. J. 96:615-630.

Saseendran, S.A., L. Ma, D.C. Nielsen, M.F Vigil, and L.R. Ahuja. 2005a. Simulating planting date effects on corn production using RZWQM and CERES-Maize. Agron. J. 97:58-71.

Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, M.F. Vigil, and A.D. Halvorson. 2005b. Effectiveness of RZWQM for simulating alternative Great Plains cropping systems. Agron. J. 97: 1184-1193.

Saseendran, S.A., L.R. Ahuja, D.C. Nielsen, T.J. Trout, and L. Ma. 2008. Use of crop simulation models to evaluate limited irrigation management options for corn in a semiarid environment. Water Res. Res. 44, W00E02, doi:10.1029/2007WR006181.

Saseendran, S.A., D.C. Nielsen, D. Lyon, L. Ma, D.G. Felter, D.D. Baltensperger, G. Hoogenboom, and L.R. Ahuja,. 2009. Modeling responses of dryland spring triticale, proso millet, and foxtail millet to initial soil water in the High Plains. Field Crops Res. 113:48-63.

Saseendran, S.A, L.R. Ahuja, L. Ma, T.J. Trout, G.S. McMaster, A.A. Andales, J. Chavez, and J. Ham. 2013. Enhancing RZWQM2 for water stress responses of corn (*Zea mays*. L.). Agronomy J. (under review).

Solomon, K.H. 1985. Typical crop water production functions. ASAE paper No. 85-2596.

Steduto P, and R. Albrizio. 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea II. Water use efficiency and comparison with radiation use efficiency. Agricultural and Forest Meteorol. 130:269–281.

Steduto, P., T.C. Hsiao, and E, Fereres. 2007. On the conservative behavior of biomass water productivity. Irrig Sci. 25:189–207.

Stewart, J. I., and R.M. Hagan. 1969. Predicting effects of water shortage on crop yield. Journal of the Irrigation and Drainage Division, ASCE 95: 92-104. No. IR1, Proc. Paper 6443.

Stewart, J.I., and R.M. Hagan. 1973. Functions to predict effects of crop water deficits. Journal of the irrigation and drainage division 99: 422-439.

Tanner C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: research or re-search? In: Taylor H.M., Jordan W.R., Sinclair T.R., eds. Limitations to efficient water use in crop production. Madison, WI: ASA, CSSA, SSSA, 1–27.

Tolk, J.A., and T.A. Howell. 2008. Field water supply: Yield relationships of grain sorghum grown in three USA Southern Great Plains soils. Agricultural Water Management 95(12):1304-1313.

Tolk, J.A., T.A. Howell, and S.R. Evett. 1998. Evapotranspiration and yield of corn grown on three high plains soils. Agron. J. 90:447-454.

Trout, T.J., W.C. Bausch, and G.W. Buchleiter. 2010. Water Production Functions for Central Plains Crops. An ASABE Conference Presentation. Paper Number: IRR10-9654. 5th national Decennial Irrigation CD-ROM Proceedings. ASABE Publication Number 711P0810cd. P8.

Westgate, M.E. 1994. Water status and development of the maize endosperm and embryo during drought. Crop Sci. 34:76-83.

CHAPTER V

GENERAL CONCLUSIONS

As the demand for fresh water increases with growing human population, there is a necessity for making agriculture water use more efficient by bringing in innovative state-of-the-art, science-based technologies in the irrigation science arena. Simulation models can synthesize and integrate knowledge across disciplines to a whole system level, and present a way to develop new irrigation management strategies for managing limited water. One constraint in simulation modeling is the requirement for defining the water stress (WS) factors based on commonly measured and simulated soil or plant parameters. Once a system model is built, methodologies need be developed that use it effectively for evolving new irrigation management strategies for adoption by farmers, consultants and policy makers for water management.

In the Root Zone Water Quality Model (RZWQM2), WS factors were calculated as the ratio of potential root water uptake to potential transpiration demand to modify leaf expansion (TURFAC) and carbon assimilation (SWFAC) processes. Several past studies reported inadequate performances of these stress factors in simulations of crops under water limited conditions. For sufficient quantifications of WS for better crop simulations, in this study, we investigated several ways of expressing WS based on soil water measurements and their relationship with grain yield, biomass and canopy cover of corn (*Zea Mays* L), winter wheat (*Triticum aestivium* L.) and dry (pinto) bean (*Phaseolus vulgaris* L.). There were six irrigation treatments for each crop, designed to meet 40 to 100% of potential crop ET (ETc) requirements during the growing season. Experiments were conducted from 2008 to 2011 near Greeley, Colorado in a sandy loam soil (LIRF experiments). Water available for plant uptake (PAW) and the maximum PAW (MAW) in the soil were calculated from 45 days after planting till maturity. SWFAC and TURFAC were calculated as ratios of (1) PAW to alfalfa reference crop evapotranspiration (ETr) (WSF1), (2) PAW to MAW (WSF2), and (3) WSF2 to ETr (WSF3). Stability of the relationship between the three stress factors and relative responses of grain yield, biomass and fraction canopy was best for WSF3 followed by WSF2 and WSF1. A single linear relationship between WSF3 and combined relative grain yield and biomass of the three crops had an R^2 of 0. 8259. Similar relationship between WSF3 and canopy cover had an R^2 of 0.856. The study also revealed that, on average, the three crops can extract water from the soil without suffering water stress for photosynthesis and leaf expansion growth until 38% and 34%, respectively, of the PAW in the soil root zone is depleted.

Use of the above soil water based WS factors in the RZWQM2 for simulation of specific crops will necessitate accurate measurements and specification of water in the soil profile at planting, sometimes limiting its applications in experiments where these are not measured. In this context, we further defined and explored suitability of three more stress factors for crop simulations that do not directly use soil water in its quantifications. Therefore, three additional WS factors (WSI1, WSI2 and WSI3) were developed as modifications of the default WS factors in the RZWQM2 using potential root water uptake (TRWUP) calculated by Nimah and Hanks (1973) approach and with accounting for stress due to heating of canopy from unused energy, when soil evaporation falls below the potential evaporation. These were incorporated in RZWQM2 and tested for simulation of corn in the LIRF experiments using CSM-CERES-Maize (v 4.0) module. Simulations with the new stress factors showed that the simulations of crop responses to water can be substantially improved by incorporation of soil evaporation in both the supply and demand terms in the water stress quantifications in the model. Out of the three water stress factors tested, WSI2 was found to be better than others in simulations of corn grain yield, biomass and LAI. It was noteworthy, in the simulations with the WSI2 stress factor, that grain yield and biomass were improved simultaneously and the magnitudes of the errors were reasonable for model applications in water management. When WSI1 and WSI2 gave comparable grain yield simulations, WSI2 gave better accuracies in biomass and LAI as well.

Superior simulations of RZWQM2 enhanced with WSI2 over other WS factors of corn under both rained and irrigated conditions at Akron, Colorado, USA; and two irrigation experiments in two contrasting soils, a sandy loam soil at, Zaragoza, Spain and a sandy soil at Gainesville, Florida, USA, verified the capability of the enhanced model for simulations across soils and climates.

The next task in the study was to use the RZWQM2 to evolve a methodology and develop long-term average crop water production functions (CWPFs) for corn by combining it with limited experimental and long-term weather data at Greeley, Weld County; Akron, Washington County; and Rocky Ford, Otero County, Colorado, and test the generalization of the functions across soils and locations. Corn grain yield responses to irrigation schedules or CWPFs in clay loam, silt loam and sandy loam soils based on weekly cumulative ET demands at the three locations were developed. We were able to generalize the CWPFs across the soils and locations through a linear relationship between relative grain yield (Y/Ymax) and relative ET (ET/ETmax). Linear relationships were also found to exist between dryland ET (ETd) and plant water supply (PWS), and relative dryland grain yield (dryland grain yield/maximum grain yield with irrigation) and ETd. The estimated value of dryland yield and ETd also allow us to develop the CWPFs for irrigation from knowledge of the long-term average fully irrigated maximum corn yield and the corresponding maximum ET and maximum irrigation. The methodology developed can be adapted to generate CWPFs for other crops in different soils and climates across the world.

VISION FOR THE FUTURE

Based on the studies presented in this dissertation, I envision the following for the further improvement and application of the RZWQM2 models.

1. In this study, the stress factors developed have only been tested for simulating corn at three locations (climates and soils). Hence, further evaluation of the stress factors are needed to assess the robustness and accuracy for simulating corn and other crops in different soils and environments.
2. Water and heat stress in plants are interrelated, however for lack of information on these interactions, they are modeled independently in RZWQM2. Improved quantification of these interactions in experiments and RZWQM2 may perhaps better predict water stress responses of crops.
3. The processes of carbon assimilation (photosynthesis), transpiration, stomatal behavior, canopy temperature, CO_2 concentration effects, and overall energy balance are coupled. The radiation use efficiency (RUE) approach used to simulate carbon assimilation in RZWQM2 does not explicitly simulate leaf temperature, leaf energy balance, and stomatal conductance, or their interaction/coupling. Such coupled approaches in simulating the photosynthesis and transpiration processes can improve the RZWQM2 capabilities in simulating crop growth and development under climate change and associated drought conditions.

4. In this study, LAI and biomass were simulated less accurately than grain yields. Better collaboration between model developers and field scientists can help in appropriate experimental data collection for further improvement of the models for their simulations [e.g., dates of important growth stages, LAI and biomass data at weekly to biweekly intervals, N content in various plant components, rooting depths and root densities in different soils layers].