Agricultural Water Management 157 (2015) 65–77

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

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

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ARTICLE INFO

Article history:
Available online 27 September 2014

Keywords:
Cropping system model
Limited irrigation
Water management
Crop water production function

ABSTRACT

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

1. Introduction

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

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

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http://dx.doi.org/10.1016/j.agwat.2014.09.002
0378-3774/

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

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

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

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

2. Materials and methods

2.1. RZWQM2 model

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

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

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

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

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

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

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

2.2.1. Greeley, Weld County, Colorado

Four years of data (2008–2011) were collected 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 responses to limited irrigation. Experimental details and irrigation treatments at LIRF are available in Trout et al. (2010) and Ma et al. (2012). Six drip irrigation treatments were designed to meet certain percentages of potential crop *ET* (ET_c) requirements during the growing seasons: 100%F, 85%*V*, 70%F, 70%*V*, 55%*V*, and 40%*V* of ET_c. *V* denotes 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 sandy loam texture. Weather data were recorded on site with a standard Colorado Agricultural Meteorological Network weather station http://ccc.atmos.colostate.edu/ coagmet/. Mean annual precipitation (1992–2010) at the location was 27 cm out of which 20 cm was received during the corn growing season from May to October. Corn ('Dekalb 52–59') with 102-day relative maturity was planted in a randomized complete 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. Nitrogen applications were based on soil samples taken for soil fertility status. Fertilizer as urea–ammonium–nitrate (UAN) was applied at planting and then with irrigation water during the growing seasons as needed to eliminate N stress in the experiments.

2.2.2. Akron, Colorado

Both irrigated and rainfed corn field experiments conducted at the Central Great Plains Research Station 6.4 km east of Akron, CO was used. Mean annual precipitation at the site is about 420 mm of which 290 mm is received during the corn growing season from May through September. Soil type at the location is a Rago silt loam (fine montmorillonitic mesic Pachic Arguistoll). Details of the irrigation treatments in the experiment including soil physical and hydraulic properties used in the simulations were described in 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.

There were 5, 11, and 10 irrigation events in 1984, 1985 and 1986, respectively. Irrigation applications were withheld until just before tasseling (late July) and varied from 23 to 106 mm in 1984, from 72 to 188 mm in 1985, and 46 to 299 mm in 1986. Seeding rate was uniform across the irrigation gradient at about 76,000 seeds ha^{-1}. All experiments were fertilized prior to planting with ammonium nitrate at the rate of 168 kg N ha^{-1}. Soil water measurements were made at planting, harvest, and several intermediate times 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 above ground biomass measurements. Grain yield was measured at harvest using plot combine.

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 using plot combines. 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 (TDR) was used to measure soil water in the 0.00–0.30 m depth. The neutron probe and TDR were calibrated for the site soils and calibration verified annually. The calibrated model and crop parameters determined for simulation of the experiment by Saseendran et al. (2014) were used in this study for simulations of crop yield responses to irrigations.

2.2.3. Rocky Ford, Colorado

A randomized complete block design with four replications examining N-source rate under conventional tillage was conducted from 2000 to 2003 on a silty clay soil (fine-silty, mixed, calcareous, mesic Ustic Torrithents) at the Arkansas Valley Research Center near Rocky Ford, Colorado (Halvorson et al., 2005). The long-term average precipitation for the growing period (April through September) at the location is 227 mm (Halvorson et al., 2005). Corn hybrids 'Pioneer 33A14' (113 day relative maturity) was planted on 27 April 2000, 'DeKalb 642RR' (114 day relative maturity) on 24 April 2001, and Garst 8559 Bt/RR (110 day relative maturity) on 23 April 2002 and 29 April 2003. Final plant populations were 67,000 in 2000, 97,000 in 2001, 90,000 in 2002, and 93,000 plants ha^{-1} in 2003. There were six N treatments (designated as N1, N2, N3, N4, N5 and N6, where N1 is the minimum and N6 the maximum rate) every year. N fertilization 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. The crop was furrow irrigated and the total water applied to the crops in 2000, 2001, 2002, and 2003 were 70.5, 55.5, 64.2, and 85.0 cm, respectively. Detailed accounts of the experiments (irrigation and N schedules) and data collection procedures are available in Halvorson et al. (2005). Grain yield collected at harvest was used for evaluating the model. Grain yields were determined by harvesting ears from a 11.6 m^2 or larger area of each plot in 2000 and 2001, and using plot combine in 2002 and 2003. The cultivar parameters calibrated for simulation of DeKalb 52–59′ 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. Highest N treatment in 2000 was used for calibration and rest of the data used in validation of the model.

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

2.3.1. Long-term simulations

Using the RZWQM2 calibrated and validated for the three locations and soils as described above, crop growth was modeled from 1992 to 2011 (20 crop seasons) for silt loam, clay loam, and sandy loam soils. Default texture-based soil parameters for the three soils were used (Rawls et al., 1982). These soils were assumed to have uniform properties with depth. Weather data recorded from 1992–2011 at Greeley, Akron, and Rocky Ford by the Colorado Agricultural Meteorological Network http://ccc.atmos.colostate.edu/ coagmet/) were used in the simulations. Alfalfa reference crop evapotranspiration (ET_r) was calculated based on Allen et al. (2005).

All long-term simulations were initialized with soil water content at field capacity in the top 30 cm and half of plant available water (field capacity – wilting point) in the layers below 30 cm on 1 January for each year simulated. In earlier studies at Akron, CO, we found that if we started the model a few months before planting (on January 1 of each year), the precipitation during this early period tended to equilibrate the soil water and reproduce close to the initial soil water at planting.

The simulated crop was planted every year on 2 May at the three locations and weekly irrigations continued until 10 September every year. Irrigations were based on meeting crop evapotranspiration (ET) demands of 0 (dryland or no irrigation), 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100% accounting for precipitation at weekly intervals (Ma et al., 2012). Evapotranspiration 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 (effective irrigation, I_{eff} = applied irrigation, I). Effective irrigation represents the amount of applied irrigation water entering into the soil, taking into account the runoff and canopy interception losses. Water interacts with fertilizer in dry matter accumulation, but this was not considered in the present study, as we assumed the nutrients were not limiting for all treatments.

2.3.2. Development of four 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), alfalfa reference ET (ET_r), 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}, cm), effective irrigation (I_{eff}, cm), and plant water supply to the crop (*PWS*, cm) were calculated as:

$$I_{\text{eff}} = \text{Irrigation} \quad (I) \tag{1}$$

(runoff and deep percolation due to model irrigations were negligible).

$$P_{\text{eff}} = \text{precipitation} - \text{runoff} - \text{deep} \quad \text{percolation} \tag{2}$$

(3)$PWS = I_{\text{eff}} + \text{plant available soil water } (PAW) \text{ at planting} + P_{\text{eff}}$

Four CWPFs were developed by plotting 20-years' average simulated grain yields vs. 20-years' averages of (1) *PWS*, (2) irrigation, (3) *ET*, and (4) *ET* due to irrigation (ET_{a-d}, *ET* at a particular irrigation level – *ET* at no irrigation).

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

As noted above, the CWPFs derived above from RZWQM2 simulations for yield vs. irrigation water applied were based on simulated irrigation applications having 100% efficiency. For projection of simulated grain yields in response to the various amounts of irrigation water applied at 100% efficiency (ε) by the model into 95% of full irrigation with drip, 85% of full irrigation under sprinkler, and 55% of full irrigation under surface irrigations (average ε at full irrigation level for different irrigation methods were derived from Irmak et al., 2011). We established functional relationships between the simulated crop yields and irrigation amounts which allowed extrapolation of CWPFs for irrigation at 100% efficiency to other methods of irrigation. Assuming Cobb–Douglas type of yield-water response function (Eq. (4)), Martin et al. (1984) recommended the functional relationship (CWPF) as given in Eq. (5).

$$f(I_r) = m - (1 - I_r)^n \tag{4}$$

$$\frac{Y - Yd}{Ym - Yd} = 1 - (1 - I_r)^{\frac{1}{\beta}} \tag{5}$$

where f is relative increase in yield as a function of relative irrigation I_r, and m and n are parameters of the Cobb–Douglas' response function, Y is grain yield in response to a given irrigation I, Y_d is dryland yield for the irrigated crop, Y_m is the maximum irrigated crop yield,$I_r = I/I_m$, where I_r is relative irrigation and I_m is the irrigation required to obtain Y_m; and

$$\beta = \frac{(ET_m - ET_d)}{I_m} \tag{6}$$

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:

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

Eqs. (5) and (6) can be used to obtain Y at any given I, knowing Y_m, Y_d, I_m, ET_m and ET_d. The Y_m, Y_d, ET_m, and ET_d do not change with the irrigation method for a given crop and location. Only the I_m changes. The I_m for any specific irrigation method can be calculated from the modeled maximum irrigation needed at 100% efficiency (I_{m_p}) and the ε of the specific method of irrigation of interest as a fractional value:

$$I_m = \frac{I_{m_p}}{\varepsilon} \tag{8}$$

3. Results and discussion

3.1. Model development, calibration and validation

3.1.1. Evaluation of RZWQM2 for simulation of corn at Greeley, Akron and Rocky Ford

Saseendran et al. (2014) modified RZWQM2 for better crop responses to water stresses and conducted detailed calibration and validation of the soil water, N, and crop parameters of the RZWQM2 for simulation of the LIRF experiments from 2008 to 2011. The results showed reasonable accuracy, simulated grain yields had a 4-yr average RMSE of 626 kg ha^{-1} under all levels of irrigations (Fig. 1). The detailed comparison of the simulated and measured crop growth and yield results are not repeated in this paper. The observed yield–*ET* relationship or production per unit of *ET* (CWPF) differed among the years due to variability in weather, length of growing season, and fertility. Yet, the four year simulations of grain yield responses to *ET* (CWPF in terms of yield vs. *ET*) as well as the field estimated *ET*-grain yield responses were close to each other (Fig. 2). These results provide reasonable confidence in the use of a calibrated model for developing long-term average CWPFs for corn at the location for irrigation management. The plant parameters calibrated and evaluated in the above study by Saseendran et al. (2014) were used in this study for developing long-term CWPFs (Table 1).

Saseendran et al. (2008) 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

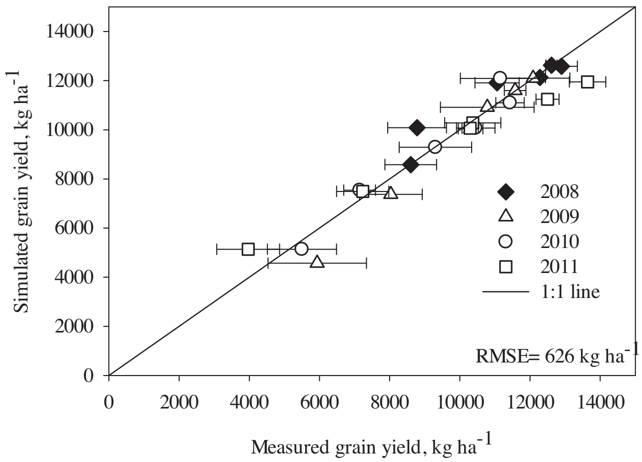

Fig. 1. Measured and simulated grain yield from 2008 to 2011 in the LIRF experiments at Greeley, CO. Error bars indicate one standard deviation in the measured data. (Adapted from Saseendran et al., 2014 with permission).

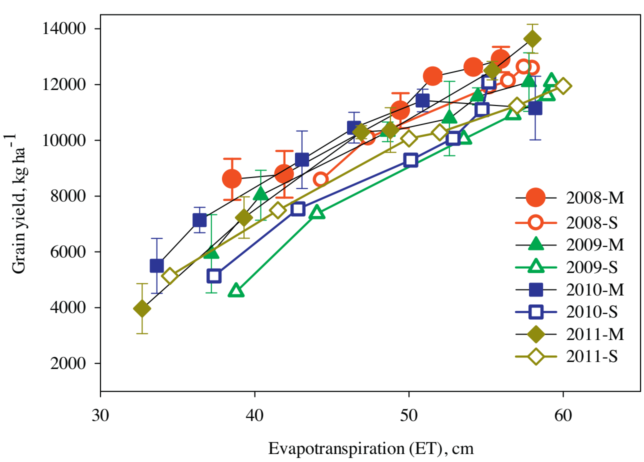

Fig. 2. Measured and simulated corn grain yield responses to evapotranspiration (*ET*) in the LIRF experiments at Greeley, CO. M = measured grain yield with *ET* estimated from soil water balance for a 1 m soil profile, S = simulated *ET* and grain yields. Error bars indicate one standard deviation from the mean of measured grain yields.

4.0 in DSSAT with reasonable accuracy levels for irrigation applications. Saseendran et al. (2014) fine tuned the cultivar parameters of Saseendran et al. (2008) for accurate simulation of the experiments using CSM-CERES-Maize 4.0 within RZWQM2 (Table 1, Fig. 3a). The soil water and N routines of RZWQM2 are more detailed compared to DSSAT, and the simulated water and N interactions with crop

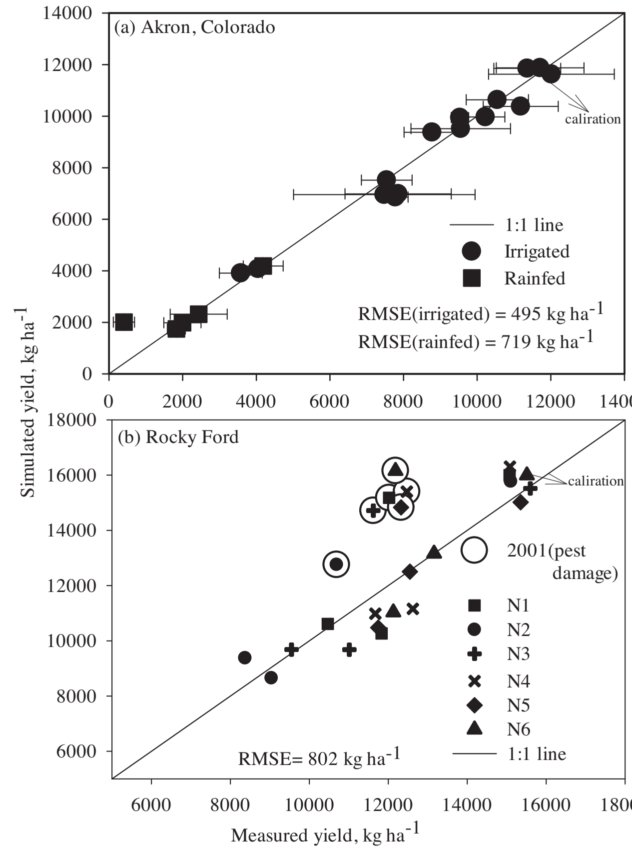

Fig. 3. Measured and simulated corn grain yields in (a) rainfed (1993–1996) and irrigated (1984–1986) corn grain yields at Akron, Colorado, and (b) N source and rate study conducted at Rocky Ford during 2000–2003 (N1 through N6 represent the six N levels used in the experiments, N1 represent the minimum and N6 the maximum rate each year). Pest damaged corn yields in 2001 at Rocky Ford were not used in calculation of RMSE. Error bars indicate one standard deviation in the measured data. Circled data points are pest damaged grain yields in 2001.

necessitated the fine tuning of the crop parameters (Ahuja et al., 2000). Notwithstanding, the accuracy levels of all the soil and crop variables simulated had comparable accuracy levels of Saseendran et al. (2008), we did not attempt further comparisons of simulated and measured data here. In brief, the grain yield simulations were with an RMSE of 495 kg ha^{-1} for the rainfed and 719 kg ha^{-1} for irrigated experiments (Fig. 3). Accordingly, accuracy levels of simulations of the grain yields at this location also have reasonable accuracy for applying the model for limited irrigation management.

Table 1
Corn cultivar parameters calibrated for simulations at Akron, Greeley and Rocky Ford Colorado.

Parameter values calibrated for			
Acronyms used and definitions of traits.	'DeKalb 52-59' at Greeley	Pioneer Brand 3732 at Akron	'Pioneer 33A14', 'DeKalb 642RR' and 'Garst 8559 Bt/RR' at Rocky Ford
P1—Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (thermal degree days)	260	290	330
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]	0.6	0.8	0.3
P5—Degree days (base temperature of 8 °C) from silking to physiological maturity (thermal degree days)	620	615	920
G2—potential kernel number	1000	930	740
G3—potential kernel growth rate (mg (kernel d)$^{-1}$)	6.9	6.9	6.0
PHINT—Degree days required for a leaf tip to emerge (phyllochron interval) (thermal degree days)	43.0	38.9	40.0

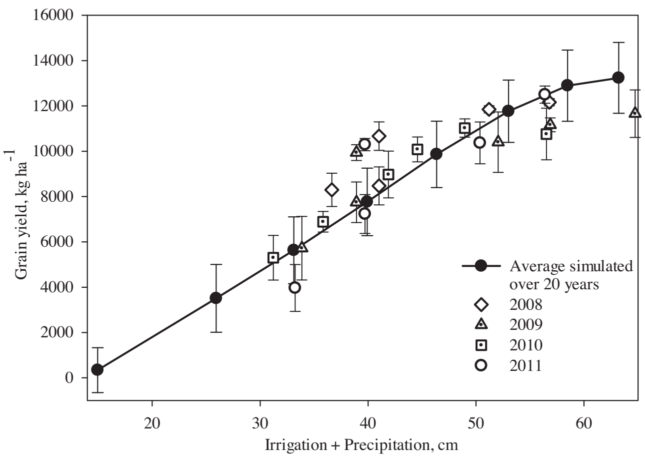

Fig. 4. Measured, and simulated long-term average CWPFs at Greeley, Colorado. Measured corn grain yields were from 2008 through 2011 and simulated were the 20-years average grain yield responses to precipitation and irrigations at 7-day intervals simulated by RZWQM2. Error bar indicate one standard deviation from the mean of the long-term simulations. In addition to precipitation and applied irrigation, stored soil water at planting also contribute to grain yields.

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, an N management study of 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, as presented in the materials and methods section. In 2001, pest damage reduced grain yields in the experiments (Halvorson et al., 2005). With the exception of some over simulations (model over estimated grain yield) 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. 3b). Simulations of the four year experiment at various N levels (irrigation varied across the years only) were with an RMSE of 802 kg ha^{-1} against an average measured value of 1029 kg ha^{-1} (i.e., the simulations deviated by 7.35% from the average measured mean yield), 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).

3.1.2. Long-term averaged CWPFs at Greeley, Colorado

The CWPF (response function) of 20-yr averaged simulated grain yields in response to different levels of *ET*-based weekly irrigation water applications (irrigations and precipitation received) during the crop period is shown in Fig. 4, along with the measured CWPFs (grain yield responses to precipitation plus irrigations) from 2008 to 2011 in the LIRF experiments at Greeley, CO. The average response passed through the experiment data for the 4 years. As expected, measured grain yields deviated from the simulated long-term average grain yields because weather conditions other than water can vary the yield from year to year. In addition, in the LIRF experiments, corn was planted in a four year rotation with winter wheat, dry beans, and sunflower, and thus, was planted in a different plot each year (Trout et al., 2010). Although considerable variation in measured water retention curves across soil cores collected across the LIRF plots were reported (Ma et al., 2012), an average soil was used in the simulations (Ma et al., 2012). Therefore, some deviation in the measured grain yields from the simulated average could also be due to varying soil properties (hydraulic and fertility levels) across the plots from year to year that was not accounted for in the simulations.

The relationship of average simulated grain yield with ET_{a-d} and *ET* (CWPFs) for all locations were close to linear with R^2 values of 0.99 and 0.96, respectively (Fig. 5). However, slight reduction in slope was noticed near the highest ET_{a-d} and *ET* values (corresponding to the highest irrigations at 100% *ET* recharge). This slope reduction has significance in that meeting slightly less than the 100% *ET* demand may reduce the yield less than irrigation demand. On the other hand, the relationships between yield with *PWS* and irrigation amounts were non-linear and cubic polynomials fitted well to these data (R^2 value of 0.99 for both; Fig. 5). Yields estimated from the fitted linear yield vs. ET_{a-d} relationships were comparable to long-term average yields simulated by RZWQM2 (Table 2).

Numerous experiments in the literature have shown a linear relationship between yield and crop evapotranspiration (*ET*) for many irrigated crops (Klocke et al., 2004; Payero et al., 2006; Tolk and Howell, 2008; Nielsen et al., 2010). Solomon (1985) had reviewed and summarized the CWPFs for 37 crops at various locations in the world and reported the yield–*ET* relationships to be mostly linear. He also reported that the 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 increases linearly with plant transpiration (*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.

The average grain yield relationships shown in Figs. 4 and 5 intercept the yield axis at values between 1000 and 2000 kg ha^{-1}. This value corresponds to the dryland yield when irrigation is zero but precipitation and stored soil water are available for plant uptake. The magnitude of the intercept depended upon the amount of precipitation during the season and PAW at beginning of the season, as well as evapotranspiration demand of the atmosphere.

Dryland *ET* that was met from stored soil water and precipitation was 20 cm in the clay loam, 23 cm in the silt loam, and 21 cm in the sandy loams soils. There was no dryland treatment in the LIRF experiments for comparison. Simulated dryland grain yields for the location were between 1500 and 2000 kg ha^{-1} for the three soils (Table 2). Simulated grain yields in response to irrigations to meet full *ET* requirements were 13251, 13274 and 13265 kg ha^{-1} for the three soils at the location (Greeley). Table 2 also gives the grain yields due to irrigation ($Y_i - Y_d$) predicted by the Cobb–Douglas type response function given in Eq. (5) and using a Yield: ET due to irrigation (ET_{a-d}) linear relationships.

The extrapolation of model simulated CWPFs with 100% water application efficiency to drip, sprinkler, and surface methods of irrigation is shown in Table 3. This Table gives irrigation amounts needed to obtain the simulated yields at each level of *ET*-based irrigation for each of the methods of irrigation, using Eq. (7). For the three soils, the maximum gross irrigation amounts needed to obtain the maximum simulated yield were about 50 cm under drip (ε = 0.95), 56 cm under sprinkler (ε = 0.85), and 87 cm under surface irrigation (ε = 0.55), methods. Surface and sprinkler irrigation methods with less irrigation efficiencies than drip required more irrigation water for a given *ET* recharge level. Maximum gross irrigation amount computed in silt loam soil was 49 cm under drip, 55 cm under sprinkler and 85 cm under surface irrigation methods. Maximum gross irrigation amounts in sandy loam soil under the three irrigation methods were 50, 56 and 86 cm, respectively.

3.2. CWPFs for Akron and Rocky Ford locations

The simulated long-term average for each of the four CWPFs for Akron and Rocky Ford are presented in Fig. 5b and c. Owing to differences in climate variables, especially precipitation and temperature, and differences in grain yield traits of the corn hybrids

Table 2
Simulated percentage *ET* demand at which irrigations were applied and average seasonal amount of irrigation applied in response, and averages of evapotranspiration and grain yield (ε = 1.0), for corn in clay loam, silt loam and sandy loam soils at Greeley, Colorado. Grain yields due to irrigation ($Y_i - Y_d$) predicted by the Cobb–Douglas type response function given in Eq. (5) and using a Yield: *ET* due to irrigation (ET_{a-d}) linear relationships are also given. SD (standard deviation) was computed for the 20 yr RZWQM2 simulated yield.

Irrigation schedule (weekly %*ET* demand)	Irrigation applied (cm)	*ET* (cm)	Simulated grain yield		Yield from Eq. (5) (kg ha^{-1})	Yield from ET_{a-d} using linear interpolation (kg ha^{-1})
			Average (kg ha^{-1})	SD (kg ha^{-1})		
Clay loam						
0–30 (dryland)	0.0	19.8	1563	1029	1563	1563
40	11.0	30.9	4217	1271	4438	4662
50	18.2	37.9	6426	1248	6280	6638
60	25.0	44.3	8604	1211	7981	8438
70	31.4	50.3	10,576	1341	9552	10,103
80	38.1	56.4	12,235	1359	11,120	11,836
90	43.5	61.2	13,017	1504	12,331	13,159
100	48.3	63.9	13,251	1524	13,251	13,924
Silt loam						
0–30	0.0	23.2	2190	1434	2190	2190
40	10.0	32.7	4560	1489	4803	4852
50	17.0	39.6	6979	1402	6564	6800
60	23.8	46.0	9201	1379	8236	8615
70	30.1	52.0	11,258	1229	9756	10,307
80	36.7	57.5	12,642	1471	11,252	11,873
90	41.8	62.3	13,176	1507	12,347	13,215
100	47.0	65.2	13,274	1523	13,274	14,046
Sandy loam						
0–30	0.0	21.4	1919	1362	1919	1919
40	9.8	31.5	4618	1469	4498	4691
50	16.5	38.1	6902	1443	6209	6521
60	23.9	45.5	9406	1497	8075	8545
70	29.2	50.4	11,002	1177	9349	9916
80	39.4	59.8	12,590	1421	11,708	12,512
90	41.2	60.9	13,149	1426	12,095	12,813
100	47.3	64.1	13,265	1522	13,265	13,676

Table 3
Irrigation amounts derived for drip, sprinkler, and surface irrigation methods, using the irrigation-yield responses (CWPFs) simulated by RZWQM2 with 100% irrigation efficiency (ε), 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)			
		(ε = 100%)	Drip (ε = 95%)	Sprinkler (ε = 85%)	Surface (ε = 55%)
Clay loam					
0–30(dry land)	1563	0.0	0.0	0.0	0.0
40	4217	11.0	20.3	22.7	35.1
50	6426	18.2	25.4	28.4	43.9
60	8604	25.0	30.5	34.1	52.6
70	10,576	31.4	35.6	39.7	61.4
80	12,235	38.1	40.6	45.4	70.2
90	13,017	43.5	45.7	51.1	79.0
100 (maximum)	13,251	48.3	50.8	56.8	87.7
Silt loam					
0–30	2190	0.0	0.0	0.0	0.0
40	4560	10.0	19.8	22.1	34.1
50	6978	17.0	24.7	27.6	42.7
60	9200	23.8	29.7	33.1	51.2
70	11,257	30.1	34.6	38.7	59.8
80	12,641	36.7	39.5	44.2	68.3
90	13,176	41.8	44.5	49.7	76.8
100	13,273	47.0	49.4	55.2	85.4
Sandy loam					
0–30	1919	0.0	0.0	0.0	0.0
40	4618	9.8	19.9	22.3	34.4
50	6902	16.5	24.9	27.8	43.0
60	9406	23.9	29.9	33.4	51.6
70	11,001	29.2	34.9	39.0	60.2
80	12,590	39.4	39.8	44.5	68.8
90	13,149	41.2	44.8	50.1	77.4
100	13,265	47.3	49.8	55.7	86.0

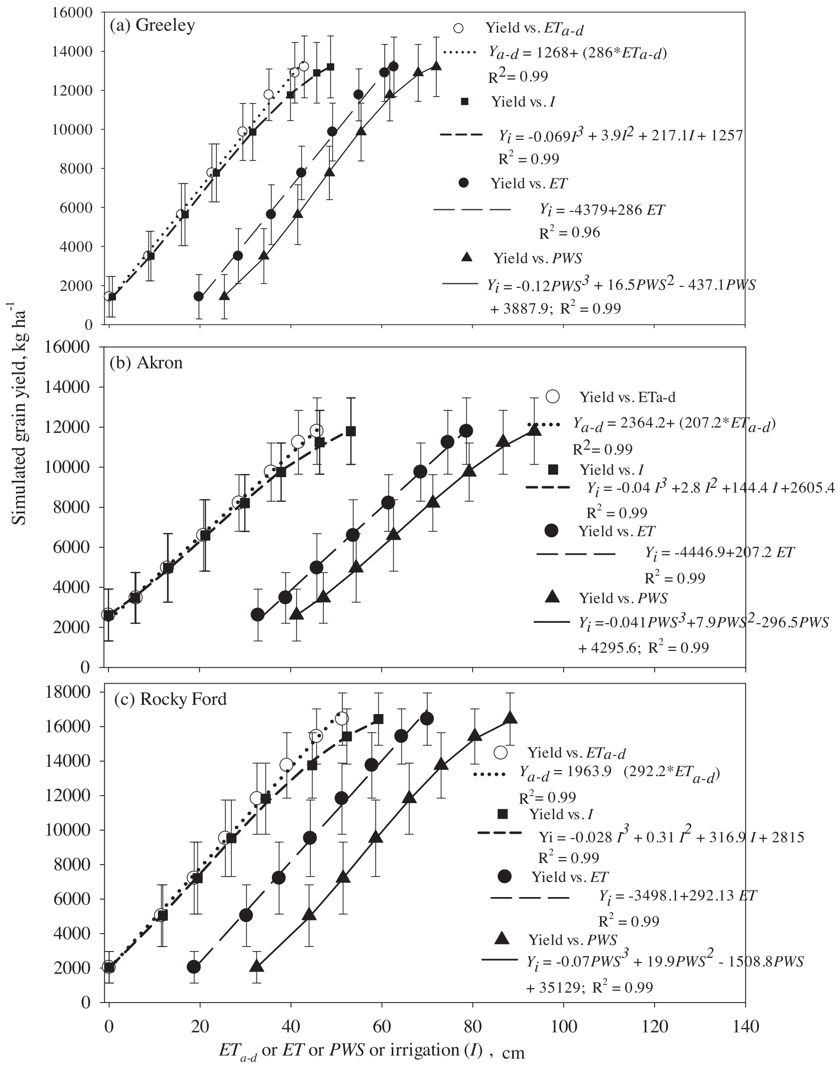

Fig. 5. Simulated long-term average corn grain yield (Y_i) response to *ET* due to irrigation (ET_{a-d}), irrigation (*I*), evapotranspiration (*ET*), and plant water supply (*PWS* = effective rainfall + plant available water in the soil profile at planting + applied irrigation) at Greeley, Akron and Rocky Ford, Colorado. Error bars indicate one standard deviation in the 20 yrs of simulated grain yields. Y_{a-d} is yield due to irrigation. Linear equations representing the yield vs. *ET*, ET_{a-d} and *PWS* are also shown.

used at Greeley, Akron and Rocky Ford locations, the simulated grain yields in response to irrigations at 0 (dryland) to 100% *ET* ranged between 1425 and 13200, 2616 and 11799, and 2043 and 16429 kg ha^{-1}, respectively (Fig. 5a–c). Effective 20-yr average growing season P_{eff} at Greeley, Akron and Rocky Ford were 15.0, 27.6 and 13.6 cm, respectively; largely explains the differences in dryland yield between the locations. Average irrigations applied at the locations were 47.2, 52.2 and 57.2, respectively.

Similar to Greeley, the average grain yield vs. ET_{a-d} and *ET* CWPFs were close to linear, and average grain yield vs. *PWS* CWPFs were non-linear (cubic polynomials were fitted) with R^2 values > 0.99. Notwithstanding, the slope of the CWPFs differed between the locations (Fig. 5a–c). In Fig. 5a–c, the grain yield vs. irrigation CWPFs represent the irrigation water productivity (IWP = increase in yield above dryland yield per unit of irrigation water), and the grain yield vs. *ET* CWPFs represent the *ET* water productivity (WP = increase in yield per unit of *ET*) (Tolk and Howell, 2008). The difference in slope between the two CWPF (WP vs. IWP) lines with increase in irrigation amounts indicates water losses to other than *ET*. These water losses can be due to runoff, deep percolation and change in soil water storage in the soil profile.

Percentage *ET* demand at which irrigations were applied and average seasonal (growing period) amount of irrigation applied in response, and averages of *ET* and grain yield simulated for corn in clay loam, silt loam and sandy loam soils at Akron and Rocky Ford, Colorado are presented in Tables 4 and 5 (similar to Table 2). Grain yields due to irrigation ($Y_i - Y_d$) predicted by the Cobb–Douglas type response function given in Eq. (5) and using a Yield: *ET* due to irrigation (ET_{a-d}) linear relationships are also given. We also extrapolated these functions to different methods of irrigation, as in Table 3 for the Greeley location. However, because of the similarity of approach and values they are not shown here.

The CWPFs representing grain yield responses to irrigation under a given method (drip, sprinkler, or surface) for the clay loam, silt loam, and sandy loam soils (all the three soil texture types were assumed to occur at all the three locations) across the three locations (Greeley, Akron, and Rocky Ford) differed among each other considerably (e.g., shown in Fig. 5a–c). Therefore, in order to make use of the CWPF developed using experimental data at one of the locations under a given irrigation method (e.g.,: drip irrigation at LIRF, Greeley) across soils and climates in other locations (we designated this problem as 'normalization' of the CWPF) in the region (e.g., Akron or Rocky Ford), a scientifically sound procedure that makes use of the available information at the locations of interest needs to be developed. In this direction, the normalization of CWPFs for corn across three locations (Greeley, Akron and

Table 4
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 Akron, Colorado. Grain yields due to irrigation ($Y_i - Y_d$) predicted by the Cobb–Douglas type response function given in Eq. (5) and using a Yield: ET due to irrigation (ET_{a-d}) linear relationships are also given. SD (standard deviation) was computed for the 20 yr RZWQM2 simulated yield.

Irrigation schedule (weekly %*ET* demand)	Actual irrigation applied (cm)	*ET* (cm)	Simulated grain yield		Yield from Eq. (5) (kg ha^{-1})	Yield from ET_{a-d} (kg ha^{-1})
			Average (kg ha^{-1})	SD (kg ha^{-1})		
Clay loam						
0–30 (dryland)	0.0	28.8	3380	1356	3380	3380
40	4.0	32.7	4222	1204	4378	4431
50	8.8	37.2	5321	1535	5568	5625
60	15.6	43.3	7264	1793	7181	7219
70	22.5	49.4	9011	1925	8745	8858
80	28.8	55.1	10,581	1666	10,103	10,368
90	35.2	60.2	11,725	1467	11,366	11,717
100 (maximum)	40.9	64.0	12,262	1505	12,262	12,712
Silt loam						
0–30	0.0	33.9	4333	1793	4333	4333
40	4.5	38.5	5439	1529	5311	5389
50	9.7	43.3	6870	1907	6425	6497
60	16.8	49.7	8761	2059	7885	7971
70	23.6	55.7	10,406	1916	9204	9369
80	30.6	61.9	11,642	1519	10,501	10,793
90	37.5	67.5	12,281	1565	11,645	12,075
100	43.6	70.8	12,426	1544	12,426	12,843
Sandy loam						
0–30	0.0	33.0	4627	1944	4627	4627
40	3.6	36.7	5509	1477	5464	5548
50	8.1	40.7	6637	1749	6496	6534
60	14.4	46.5	8513	2149	7887	7963
70	20.5	52.3	10,154	2248	9180	9405
80	27.3	58.1	11,377	1939	10,519	10,818
90	33.6	63.1	12,197	1724	11,649	12,071
100	38.6	65.8	12,340	1618	12,340	12,738

Table 5
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 Rocky Ford, Colorado. Grain yields due to irrigation ($Y_i - Y_d$) predicted by the Cobb–Douglas type response function given in Eq. (5) and using a Yield: ET due to irrigation (ET_{a-d}) linear relationships are also given. SD (standard deviation) was computed for the 21 yr RZWQM2 simulated yield.

Irrigation schedule (weekly %*ET* demand)	Actual irrigation applied (cm)	*ET* (cm)	Simulated grain yield		Yield from Eq. [5] (kg ha^{-1})	Yield from ET_{a-d} (kg ha^{-1})
			Average (kg ha^{-1})	SD (kg ha^{-1})		
Clay loam						
0–30 (dryland)	0.0	22.6	2874	1373	2874	2874
40	11.3	34.0	6202	1792	5997	6235
50	18.5	40.9	8605	1922	7956	8273
60	25.8	47.7	11,022	2025	9873	10,251
70	33.2	54.6	13,160	1773	11,773	12,276
80	40.3	60.9	14,972	1530	13,539	14,136
90	47.2	67.1	16,299	1398	15,176	15,963
100 (maximum)	54.4	71.8	16,649	1486	16,649	17,328
Silt loam						
0–30	0.0	26.3	3794	1996	3794	3794
40	10.6	37.3	7404	1884	6773	7021
50	17.3	43.8	9994	1688	8612	8932
60	24.2	50.4	12,144	1512	10,457	10,871
70	31.3	56.6	14,256	1287	12,293	12,725
80	38.3	63.0	15,816	1274	14,013	14,590
90	45.2	68.5	16,609	1477	15,604	16,231
100	50.7	71.7	16,688	1484	16,688	17,158
Sandy loam						
0–30	0.0	24.6	3539	2030	3539	3539
40	10.0	35.5	6895	1850	6401	6824
50	16.8	42.1	9329	1711	8307	8814
60	23.6	48.6	11,766	1447	10,191	10,807
70	30.7	55.3	13,832	1173	12,111	12,823
80	37.4	61.4	15,658	1160	13,877	14,675
90	43.9	67.2	16,606	1461	15,491	16,409
100	49.3	70.0	16,685	1484	16,685	17,270

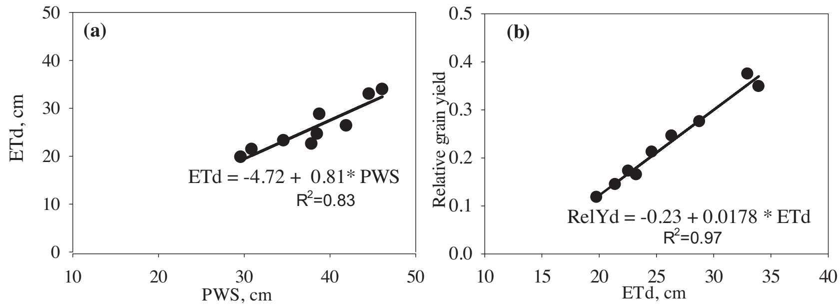

Fig. 6. (a) Relationship between average simulated plant water supply (*PWS* = effective precipitation + plant available water in the 1 m soil profile at planting) and seasonal dryland evapotranspiration (ET_d), and (b) relationship between ET_d and relative grain yield (i.e., RelY_d = Y_d/Y_m, Y_d is dryland grain yield and Y_m is the average maximum fully irrigated grain yield) responses to ET_d. Simulated data at all the three locations (Greeley, Akron and Rocky Ford) have been used. Lines represent least squares linear functions fitted to the data.

Rocky Ford) and soils (clay loam, silt loam and sandy loam) were explored.

3.3. 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, or CWPFs (Stewart and Hagan, 1969). The PAW in the crop root zone will vary among fields, locations, and years depending on the crop prior grown, soil texture, length and precipitation of the non-cropped period prior to planting, as well as any pre-plant irrigation. 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* (ET_d) and corn yield, in order to adjust the CWPFs for yield vs. irrigation.

For all three soil types and three locations of this study (pooled data from Tables 2, 4 and 5), relationships between simulated ET_d vs. seasonal total precipitation, ET_d vs. seasonal total P_{eff}, and ET_d vs. *PWS*1 (P_{eff} + available soil water at planting) were explored for regression relationships. The relationship between ET_d and *PWS*1 was found to be linear with R^2 = 0.83 (Fig. 6a). The data displayed in Fig. 6a indicate about 81% of the initial soil water and effective rainfall contributed to ET_d. This relationship is useful for estimating the effect of varying initial plant-available soil water in the root zone (1 m depth in RZWQM2 simulations), as well as of effective rainfalls, on ET_d.

Further, we explored various possible options available for predicting dryland corn grain yield (Y_d) from measured and readily available data at the locations from relationships between Y_d and total crop season precipitation (*P*), relative Y_d (dryland yield/maximum fully irrigated yield, RelY_d) and *P* and P_{eff}, Y_d and *PWS*1, Y_d and dryland *ET* (ET_d), and RelY_d and ET_d. The regression between RelY_d vs. ET_d showed strong enough relationships (R^2 = 0.97) for prediction (Fig. 6b).

Thus, Fig. 6a and b allows us to estimate ET_d and dryland yield from knowledge of initial soil water and effective precipitation. These relationships allow us to adjust the CWPFs of yield vs. irrigation for the various initial soil water contents at planting and/or the effective seasonal rainfall. The estimated values of dryland yield and dryland ET_d 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).

3.4. Normalization 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. 7a 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 relationships for each location are similar, but they differed in magnitudes of grain yields among locations. The relationships obtained were close to linear, as commonly reported in the literature (e.g., Klocke et al., 2004; Nielsen et al., 2010). 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. Unlike the yield–*ET* relationships, the yield–*PWS* (the effective irrigation water applied in which initial plant available water in the top 1 m of soil was considered) across soils and locations differed both in magnitudes of grain yields and *ET* (Fig. 7b).

Fig. 8a shows the average simulated grain yield–*ET* relationships for the three locations plotted together for each soil type separately. Again, the functions for the three locations are fairly similar for each soil type, except that the longer duration corn variety grown at Rocky Ford had higher yield and higher *ET*. Fig. 8b shows the same functions when 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) described above, 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 (water use efficiency is higher). Similar results were obtained for grain yield–*PWS* relationships (Fig. 9a and b).

Fig. 8c shows functions for relative grain yield (*Yr*) 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. 8d). Similar coalescence was obtained for the biomass-*ET* relations (data not shown) and for the relationship between yield and relative *PWS*. Whereas the *Yr* vs. *ET* relationship was close to linear for the whole range of *ET*, the *Yr* vs. *PWS* relationship was close to linear at lower PWS initially and deviated from linearity gradually with higher *PWS* values. These observed relationships are very useful in that they allow us to estimate yield–*ET* functions for any location and soil type from knowledge of one point on the relationship, such as the multi-year average maximum yield and maximum *ET* or *PWS* under fully irrigated conditions for a given location and variety. In Fig. 6,

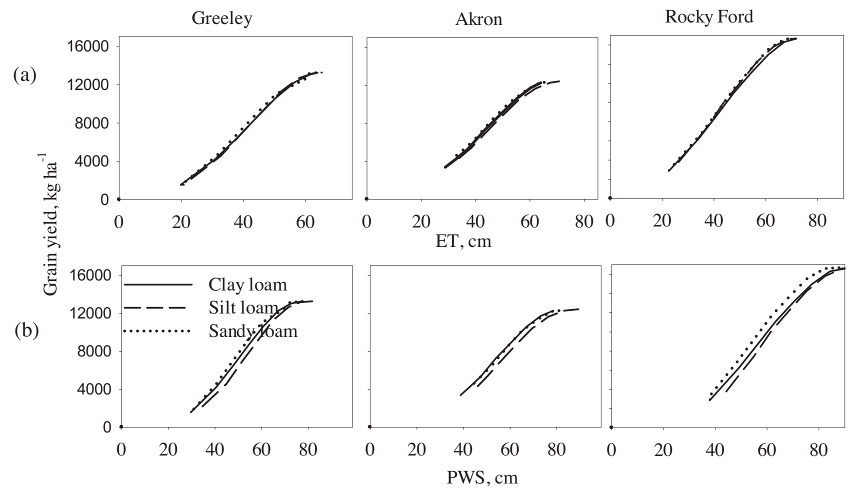

Fig. 7. (a) Simulated corn grain yield–*ET* relationships across three soil types at Akron, Greeley and Rocky Ford, and (b) yield–plant water supply (*PWS;* effective precipitation + applied irrigation + plant available water in the 1 m soil profile at planting) relations across three soil types at three locations.

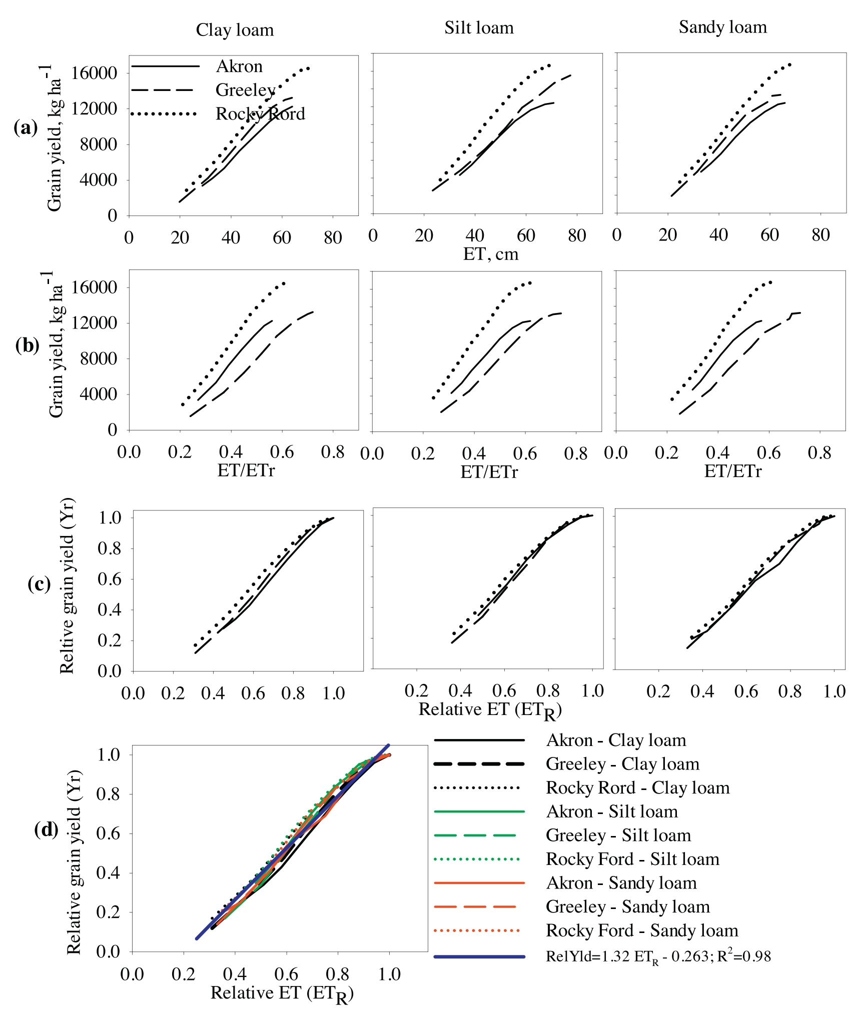

Fig. 8. (a) Grain yield–*ET* relationships across the three locations by soil type, (b) yield–*ET* normalized with alfalfa reference crop evapotranspiration (ET_r) across locations by soil type, (c) relative yield (*Yr*)–relative *ET* ($ET_R = ET/ET_{max}$, ET_{max} = maximum *ET*) relationships across the three locations by soil type, and (d) *Y*–ET_R relationships between the three locations and three soil types. A liner equation was fitted to the *Yr*–ET_R relationships pooled across the three locations and soils in (d).

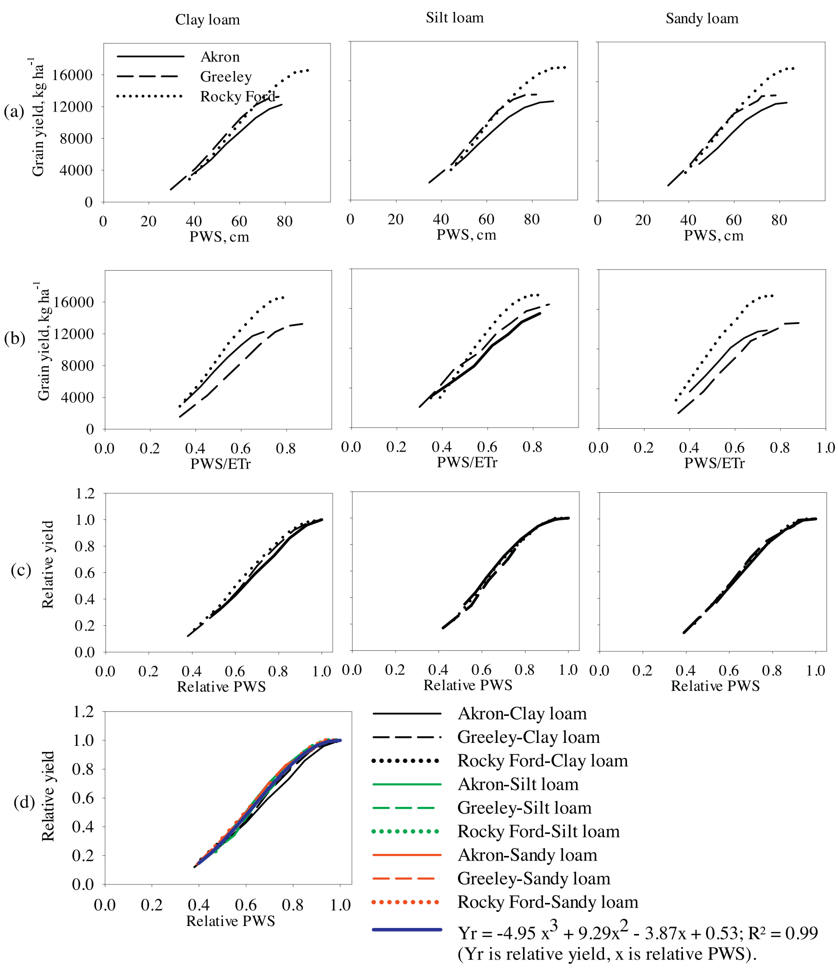

Fig. 9. (a) Corn grain yield–plant water supply (*PWS*) (effective precipitation + applied irrigation + plant available water in the 1 m soil profile at planting) relationships across three locations by soil type; (b) yield–*PWS* normalized with reference crop evapotranspiration (ET_r) across the three 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. A liner cubic equation fitted to the *Yr*–relative *PWS* relationships pooled across the three locations and soils in (d) is also shown.

we developed relationships between dryland yield and *ET* with initial soil water and effective rainfall. These relationships can refine the response functions at the dry end.

In Fig. 8d, we have fitted a linear relationship between pooled relative yield vs. relative *ET* (Eq. (9)) with an R^2 of 0.98, and in Fig. 9d, we fitted a cubic polynomial relationship between pooled relative yield vs. relative *PWS* (Eq. (10)) with R^2 of 0.99.

$$Yr = 1.32ETR - 0.263 \quad (9)$$

$$Yr = -4.95PWS^3 + 9.29PWS^2 - 3.87PWS + 0.53 \quad (10)$$

3.5. *Transferability of the CWPF developed in the study across the world.*

We have irrigated corn production data collected in experiments conducted at the Yuncheng Integrated Agricultural Experimental Station (36.57°N, 116.36°E, 28 m amsl) in the North China Plain for comparison with the CWPF depicted by the relative grain yield vs. relative *ET* relationship (Eq. (9)) developed in the study (Fig. 10). We also simulated the experiments using the RZWQM2 model. As can be seen in Fig. 10, all of the simulated and all except one of the measured data fell close to the CWPF represented by Eq. (9) above. Two outliers (below the generalized line) in the measured data, probably is caused by factors other than water and nutrients in corn production at the location. The measured CWPFs in the experiments conducted at Greeley, Colorado during 2008–2011 also fell reasonably close to the normalized CWPF developed using Eq. (9) in Fig. 9.

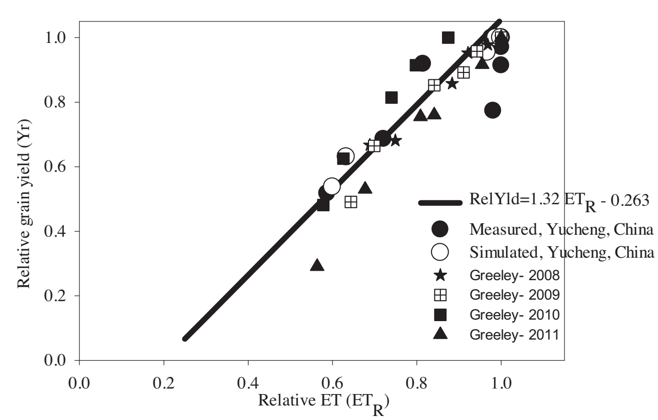

Fig. 10. Comparison of the relative grain yield (*Yr*)–relative *ET* (ET_R) relationship developed in Fig. 8 with measured and simulated corn water production data from Greeley, Colorado and Yucheng, China.

4. Conclusions

Crop yield responses to water use or applied irrigation (CWPFs) can provide essential information for planning limited irrigations and allocations of the limited water resources for optimum crop production. However, the annual precipitation and other weather factors greatly vary the irrigation requirements from year to year at a location. Therefore, for planning purposes, the 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 at Greeley, Weld County; Akron, Washington County; and Rocky Ford, Otero County, Colorado. We were able to normalize the CWPFs across the soils and the three locations through a linear relationship between relative grain yield (Y/Y_{max}), and relative ET (ET/ET_{max}) and relative PWS (PWS/PWS_{max}). Linear relationships were also found to exist between dryland ET (ET_d) and PWS, and relative dryland grain yield (Y/Y_{max}) and ET_d. The estimated value of dryland yield and ET_d 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. However, the RZWQM2 does not simulate salinity effects on crop growth, so the conclusions of this paper many not represent soils with salinity related issues.

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, Highlands Ranch, CO.

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

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

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

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

Briggs, L.J., Shantz, H.L., 1917. The water requirement of plants as influenced by environment. Proceedings Second Pan American Scientific Congress 3, 95–107.

De Wit, C.T., 1958. Transpiration and Crop Yield. Instituut voor Biologisch en Scheikusdig Ondergoek van Landvouwgewassen, Wageningen (Wededeling, No. 59).

Farahani, H.J., DeCoursey, D.G., 2000. Potential evapotranspiration processes in the soil-crop-residue system. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 51–80.

Farahani, H.J., Ahuja, L.R., 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Trans. ASAE 39, 2051–2064.

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

Halvorson, A.D., Schweissing, F.C., Bartolo, M.C., Reule, C.A., 2005. Corn response to nitrogen fertilization in a soil with high residual nitrogen. Agron. J. 97, 1222–1229.

Hanks, R.J., 1983. Yield and water-used relationships: an overview. In: Taylor, H.M. et al. (Ed.), Imitations to Efficient Water Use in Crop Production. American Society of Agronomy, Madison, WI, pp. 393–411.

Hanks, R.J., 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66, 660–665.

Hoogenboom, G., Jones, J.W., Boote, K.J., 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.

Irmak, S., Odhiambo, L.O., Kranz, W.L., Eisenhauer, D.E., 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⟩ (checked on 06 June 2013).

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

Klocke, N.L., Schneekloth, J.P., Melvin, S.R., Clark, R.T., Payero, J.O., 2004. Field scale limited irrigation scenarios for water policy strategies. Appl. Eng. Agric. 20, 623–631.

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

Ma, L., Hoogenboom, G., Ahuja, L.R., Nielsen, D.C., Ascough, J.C., 2005. Evaluation of the RZWQM–CROPGRO hybrid model for soybean production. Agron. J. 97, 1172–1182.

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

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

Ma, L., Ahuja, L.R., Saseendran, S.A., Malone, R.W., Green, T.R., Nolan, B.T., Bartling, P.N.S., Flerchinger, G.N., Boote, K.J., Hoogenboom, G., 2011. A Protocol for Parameterization and Calibration of RZWQM2 in field research. In: Ahuja, L.R., Ma, L. (Eds.), Methods of Introducing System Models into Agricultural Research. ASA-SSSA-CSSA, Madison, WI, pp. 1–64.

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

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

Martin, D.L., Gilley, J.R., Supalla, R.J., 1989. Evaluation of irrigation planning decisions. J. Irrig. Drain. Eng. 115, 58–77.

Nielsen, D.C., Vigil, M.F., Benjamin, J.G., 2010. Evaluating decision rules for dryland rotation crop selection. Field Crops Res. 120, 254–261.

Nimah, M.N., Hanks, R.J., 1973. Model for estimating soil water, plant and atmospheric inter relations: I. Description and sensitivity. Proc. Soil Sci. Soc. Am. 37, 522–527.

Payero, J.O., Melvin, S.R., Irmak, S., Tarkalson, D., 2006. Yield response of corn to deficit irrigation in a semiarid climate. Agric. Water Manage. 84, 101–112.

Rawls, W.J., Brakensiek, D.L., Saxton, K.E., 1982. Estimation of soil water properties. Trans. ASAE 25, 1316–1320 (1328).

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

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

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

Saseendran, S.A., Nielsen, D.C., Lyon, D.J., Ma, L., Felter, D.G., Baltensperger, D.D., Hoogenboom, G., Ahuja, L.R., 2009. Modeling responses of dryland spring triticale, proso millet and foxtail millet to initial soil water in the High Plains. Field Crops Res. 10, 48–63.

Saseendran, S.A., Ahuja, L.R., Ma, L., Trout, T.J., McMaster, G.S., Andales, A.A., Chavez, J., Ham, J., 2014. Enhancing RZWQM2 for water stress responses of corn (*Zea mays* L.). Agron. J. 106 (1), 81–94.

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

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

Stewart, J.I., Hagan, R.M., 1969. Predicting effects of water shortage on crop yield. J. Irrig. Drain. Div., ASCE 95, 91–104 (No. IR1, Proc. Paper 6443).

Stewart, J.I., Hagan, R.M., 1973. Functions to predict effects of crop water deficits. J. Irrig. Drain. Div. 99, 421–439.

Tanner, C.B., Sinclair, T.R., 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. ASA, CSSA, SSSA, Madison, WI, pp. 1–27.

Tolk, J.A., Howell, T.A., 2008. Field water supply: yield relationships of grain sorghum grown in three USA Southern Great Plains soils. Agric. Water Manage. 95 (12), 1303–1313.

Trout, T.J., Bausch, W.C., Buchleiter, G.W., 2010. Water production functions for central plains crops. An ASABE conference presentation. Paper number: IRR10-9654. In: Fifth National Decennial Irrigation CD-ROM Proceedings, p. 8 (ASABE Publication Number 711P0810cd).