Modeling of Full and Limited Irrigation Scenarios for Corn in a Semiarid Environment

K. C. DeJonge, A. A. Andales, J. C. Ascough II, N. C. Hansen

Abstract. *Population growth in urbanizing areas such as the Front Range of Colorado has led to increased pressure to transfer water from agriculture to municipalities. In some cases, farmers may remain agriculturally productive while practicing limited or deficit irrigation, where substantial yields may be obtained with reduced water applications during non-water-sensitive growth stages, and crop evapotranspiration (ET) savings could then be leased by municipalities or other entities as desired. Site-specific crop simulation models have the potential to accurately predict yield and ET trends resulting from differences in irrigation management. The objective of this study was to statistically determine the ability of the CERES-Maize model to accurately differentiate between full and limited irrigation treatments in northeastern Colorado in terms of evapotranspiration (ET), crop growth, yield, water use efficiency (WUE), and irrigation use efficiency (IUE). Field experiments with corn were performed near Fort Collins, Colorado, from 2006 to 2008, where four replicates each of full (100% of ET requirement for an entire season) and limited (100% of ET during reproductive stage only) irrigation treatments were evaluated. Observations of soil profile water content, leaf area index, leaf number, and grain yield were used to calibrate (2007) and evaluate (2006 and 2008) the model. Additionally, ET and water use efficiency (WUE) were calculated from a field water balance and compared to model estimates. Over the three years evaluated, CERES-Maize agreed with observed trends in anthesis date, seasonal cumulative ET (Nash-Sutcliffe efficiency E_{NS} = 0.966 for full irrigation and 0.835 for limited irrigation), leaf number in 2007 (E_{NS} = 0.949 for full irrigation and 0.900 for limited irrigation), leaf area index in 2008 (E_{NS} = 0.896 for full irrigation and 0.666 for limited irrigation), and yield (relative error RE = 4.1% for full irrigation and -3.4% for limited irrigation). Simulation of late-season leaf area index in limited irrigation was underestimated, indicating model overestimation of water stress. Simulated cumulative ET trends were similar to observed values, although CERES-Maize showed some tendency to underpredict for full irrigation (RE = -7.2% over all years) and overpredict for limited irrigation (RE = 12.7% over all years). Limited irrigation observations showed a significant increase in WUE over full irrigation in two of the three years; however, the model was unable to replicate these results due to underestimation of ET differences between treatments. While CERES-Maize generally agreed with observed trends for full and limited irrigation scenarios, simulation results show that the model could benefit from a more robust water stress algorithm that can accurately reproduce plant responses such as those observed in this study.*

Keywords. *CERES-Maize, Crop modeling, Deficit irrigation, Evapotranspiration, Limited irrigation.*

In several areas of the U.S., including the Front Range of Colorado, large urban population growth is occurring despite limited availability of water resources. Agricultural uses currently account for more than 85% of the total water consumed in Colorado, and agricultural users hold most of the senior water rights (CDM, 2007). Furthermore, population in the South Platte River basin of northeast Colorado is expected to increase by 65% from 2000 to 2030 (CDM, 2007). To deal with large municipal growth, cities have purchased water rights from farmers. In many cases, this transfer involves all water rights and often the land, leading to dry-up of large areas and adverse ecological and socioeconomic consequences for rural communities (Colorado Water, 2010). CDM (2007) predicts that nearly 37% of the irrigated area in the South Platte River basin (54,000 ha) will be lost between 2000 and 2030. In addition to potential economic losses to farmers and smaller communities that depend on agriculture, this loss could cause negative environmental impacts from leaving land fallow, such as erosion by wind, weed invasion, lack of management (Skidmore et al., 1979), and soil carbon loss (Paustian et al., 1997). Current Colorado water law is based on the prior appropriation system of water allocation, the main components of which place high emphasis on return flow conservation and quantification of consumptive use or evapotranspiration (ET) (Colorado Water, 2010; Smith et al., 1996). Current water rights transfers allow only for complete transfer of consumptive use, but some researchers note that changes in water law are likely as irrigators find increased pressure to use their water more economically (Smith et al., 1996; English et al., 2002). En-

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glish et al. (2002) suggest that a fundamental change is necessary in the way that producers approach irrigation management. They propose that irrigated agriculture adopt a new paradigm based on the maximization of net benefits, instead of simply the biological objective of maximizing yields.

One example of this proposed change is limited irrigation of crops. Limited irrigation practices incorporate water management under restricted water application and minimize water stress during critical crop growth stages in order to maximize yields (Schneekloth et al., 2009). Older field studies have addressed maize response to growth-timing of irrigation (e.g., Barrett and Skogerboe, 1978; Doorenbos and Kassam, 1979; Gilley et al., 1980). More recent studies have supported this idea, e.g., Klocke et al. (2004) achieved 93% of fully irrigated corn yield using 76% of the water applied. In a separate study, Klocke et al. (2007) achieved limited irrigation yields of 80% to 90% of fully irrigated yields while using about half the applied water compared to full irrigation. More recent studies regarding the importance of growth-stage directed irrigation timing include Payero et al. (2006), Igbadun et al. (2008), Farre and Faci (2009), Ko and Piccinni (2009), Payero et al. (2009), and Mansouri-Far et al. (2010).

Accurate crop simulation models, such as those found in the Decision Support System for Agrotechnology Transfer (DSSAT v4.0), can play a role in assessing the costs and benefits of limited irrigation and the interactions of timing and amount of irrigation (Hoogenboom et al., 2004). The DSSAT Cropping System Model (CSM)-CERES-Maize model (Jones and Kiniry, 1986; Ritchie et al., 1998; Jones et al., 2003) has been widely used to assess cropping and management strategies for corn (both rainfed and irrigated) for well over two decades. Adapted versions of CERES-Maize were successfully used in Kenya to simulate dry land and irrigated maize grain yields for plant populations of 1 to 9 plants m^{-2} (Keating et al., 1988). Kiniry et al. (1997) and Kiniry and Bockholt (1998) both evaluated CERES-Maize yield response to rainfed climate, with simulated grain yields within 5% and 10% of measured grain yields, respectively. More recent studies have evaluated crop models specifically in terms of limited water availability. Cabelguenne et al. (1995) used the EPIC model to simulate limited irrigation of maize in southwestern France, finding that simulated results agreed with known effects of drought stress during critical growth periods. Vazifedoust et al. (2008) used the Soil Water Atmosphere Plant (SWAP) model for fodder maize in Iran to evaluate water production functions in terms of limited irrigation water supply. They found that deficit irrigation scheduling can increase water production (the ratio of yield and total applied irrigation) by a factor of 1.5. Katerji et al. (2010) used the Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS) model to evaluate corn yield and WUE for varying inputs including soil type and water supply. They determined that soil water holding capacity played an important part in deficit irrigation and water stress, and noted that the plant reproductive growth stage was particularly sensitive to water deficit. Ma et al. (2002) evaluated the Root Zone Water Quality Model (RZWQM) for water stress responses of corn grown under various limited irrigation treatments and concluded that the model correctly simulated relative increase in yield with irrigation amount.

Recent studies using CERES-Maize have raised concerns about model accuracy in water-limited scenarios. For example, Xie et al. (2001) found that simulated vegetative growth and kernel weight were extremely sensitive to growth stress. Additionally, López-Cedrón et al. (2008) evaluated CERES-Maize for rainfed and irrigated treatments with the intent to improve model ability in predicting biomass and yield under water-limited conditions. They found that the model adequately predicted yield from irrigated treatments but under-predicted yield from rainfed treatments. Other researchers have found that CERES-Maize overestimated the effects of water stress on vegetative growth and subsequently adjusted the stress functions and improved simulation results (Nouna et al., 2000; Mastrorilli et al., 2003). Recent studies have emphasized management of crops under stressed conditions, with some researchers suggesting a need for increased understanding and development of accurate simulations of water stress on various growth and development processes (e.g., Saseendran et al., 2008b). Limited water resources and increasing pumping costs have caused farmers in Colorado to consider limited irrigation as an alternative to full irrigation practices. Alternatively, farmers may consider either a reduction in planted area or schedule irrigation events so that plants do not encounter stress during sensitive growth stages. For example, Saseendran et al. (2008a) simulated various water allocations and irrigation amounts in northeastern Colorado using CERES-Maize and found that split irrigation applications of 20% of the total water applied during vegetative growth stages and 80% of the total water applied during reproductive growth stages obtained the highest yield for a given irrigation allocation (ranging from 100 to 700 mm of total irrigation).

Additional research is needed to assess the effects of limited irrigation practices on corn grain yield and ET. While there is a need for controlled field research, valuable information can come from modeling studies of limited irrigation practices because models such as CERES-Maize can evaluate several alternatives much more quickly and efficiently than experimental research. However, literature containing detailed statistical evaluations of CERES-Maize for yield and ET is sparse, especially with respect to limited irrigation. Therefore, the objective of this study was to statistically determine the ability of CERES-Maize to accurately differentiate between full and limited irrigation treatments in northeastern Colorado in terms of grain yield, leaf area index (LAI), leaf number, ET, water use efficiency (WUE), and irrigation use efficiency (IUE). The study utilizes an integrated experimental design and modeling approach whereby the tested CERES-Maize model can be used in future studies to guide irrigation management decisions, e.g., defining yield-ET and yield-irrigation relationships for varying irrigation amounts as well as maximizing economic return with limited water resources.

Materials and Methods

Field Experiment

This study compares output responses from the CERES-Maize crop growth model with results from an on-going field experiment of limited irrigation cropping systems near Fort Collins, Colorado (40° 39′ 19″ N, 104° 59′ 52″ W). Two irrigation treatments of continuous corn (the dominant irrigated crop in northeast Colorado) were studied during the 2006 through 2008 growing seasons: full irrigation (ET re-

Table 1. Soil properties at the Fort Collins limited irrigation experimental site.

Depth from Surface (mm)	Wilting Point (mm^3 mm^{-3})	Field Capacity (mm^3 mm^{-3})	Saturation (mm^3 mm^{-3})	Available Water (mm)	Sat. Hyd. Cond. (mm d^{-1})	Bulk Density (g cm^{-3})	Sand (%)	Clay (%)	Initial NH_4 (g N per Mg soil)	Initial NO_3 (g N per Mg soil)
0 - 150	0.100	0.320	0.461	33.0	200	1.28	37.4	31.0	8.8	17.6
150 - 300	0.150	0.280	0.461	19.5	345	1.25	37.4	31.0	6.0	15.1
300 - 450	0.150	0.325	0.461	26.2	79	1.46	36.0	31.0	3.4	11.3
450 - 600	0.179	0.262	0.466	12.5	273	1.34	34.2	31.2	3.4	11.3
600 - 900	0.169	0.400	0.445	69.3	66	1.38	40.3	31.7	1.3	6.3
900 - 1200	0.160	0.420	0.425	78.0	40	1.45	48.6	27.1	0.4	3.5
1200 - 1500	0.180	0.400	0.419	66.0	39	1.47	46.4	29.2	0.4	3.5
1500 - 1780	0.180	0.420	0.429	67.2	39	1.44	44.4	30.4	0.4	3.5

quirement supplied throughout the season) and limited irrigation (no irrigation before the V12 reproductive stage unless necessary for emergence, and then full irrigation afterwards). There were four replications of each treatment, arranged in a randomized complete block design. Each plot consisted of 12 rows spaced 76 cm apart, with a row length of 26 m. All data were taken from the middle four rows, with the outer eight rows serving as buffers to minimize boundary effects from adjacent treatments. Irrigation water was applied through a linear-move sprinkler system. Both treatments were monitored for crop growth (total leaf number, LAI, crop height, and biomass), crop development (phenology stages), soil water content (SWC), ET by water balance, and final grain yield.

Model Input Data and Calculation of Evapotranspiration

An on-site weather station (station FTC03; 40° 39′ 09″ N, 105° 00′ 00″ W; elevation 1557.5 m) within the Colorado Agricultural Meteorological Network (CoAgMet, http://ccc.atmos.colostate.edu/~coagmet/) continually recorded daily precipitation, solar radiation, minimum and maximum temperature, vapor pressure (which was converted to dew point temperature), and wind run. A tornado struck near the field site in Windsor, Colorado, on 22 May 2008, causing damage to the weather station. Missing data from 20 May through 16 June 2008, as well as any other missing weather data, were replaced by data from the Wellington, Colorado, station (station WLT01; 40° 40′ 34″ N, 104° 59′ 49″ W; elevation 1567.9 m) approximately 2 km north of the FTC03 station.

The soil at the study site is a Fort Collins Loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalf). When possible, field capacity and permanent wilting point were estimated from respective high and low field observations of gravimetric SWC, as Ritchie (1998) suggests, using field observations of these values for DSSAT model parameterization. Additionally, samples taken from two plots were used for all bulk density measurements and any missing field capacity and permanent wilting point values (based on pressure plate analysis). Saturated hydraulic conductivity was estimated from soil texture, field capacity, and permanent wilting point values using the Rosetta version 1.2 pedotransfer function model (Schaap et al., 2001). Soil characteristics were assumed uniform across all plots and are shown in table 1.

Management and yield data, as well as other experimental observations, were available from 2006 through 2008 (table 2). However, the most intensive data collection occurred in 2008, which included weekly gravimetric soil water (to a depth of 40 cm) and neutron moisture meter (NMM) measurements, and LAI based on length and width measurements of each leaf taken by hand. On 14 August 2008, a hailstorm occurred at the study site, significantly reducing yields. Final 2008 crop yields were measured and adjusted to levels if hail damage had not occurred, based on LAI reductions and the growth stage (Vorst, 1993).

Soil water content was measured on a weekly basis, typically the day before irrigations occurred. Soil water content was measured at each plot by NMM in 30 cm intervals to a depth of 180 cm (although data were sparse at depths below 1 m). NMM measurements used two separate calibrations for the top 30 cm and all depths below 30 cm. Initial SWC conditions in all years were determined by NMM and used as initial conditions for CERES-Maize modeling. Assuming an effective root zone of 1 m, the total SWC in the top 1.0 m of soil was used in the analyses. Calculations were restricted to the top 1.0 m of soil because NMM observations were sparse at deeper depths, observed SWC differences below 1.0 m were minimal (e.g., ET calculated using deeper observations was less than 5% higher than when calculated for the top 1.0 m),

Table 2. Experimental management data and grain yield.

	2006		2007		2008	
	Limited Irrigation	Full Irrigation	Limited Irrigation	Full Irrigation	Limited Irrigation	Full Irrigation
Hybrid	Garst 8827	Garst 8827	Garst 8827	Garst 8827	Pioneer 38P	Pioneer 38P
Planting date	10 May	10 May	10 May	8 May	30 April	30 April
Planting population (seeds m^{-2})	5.9	7.9	5.9	8.0	7.9	7.9
Nitrogen application date(s) (kg ha^{-1})	29 June (67)	29 June (157)	27 June (67)	27 June (157)	30 April (52), 23 June (157)	30 April (52), 23 June (191)
Anthesis date	Not collected	Not collected	3 August	27 July	30 July	30 July
Average yield (kg ha^{-1})	8916	11107	7576	10891	10451	10863
Harvest date	4 November	4 November	14 November	14 November	19 November	19 November

Note: 2008 yields measured and adjusted based on LAI reductions at the growth stage when hail damage occurred (Vorst, 1993).

Table 3. Irrigation schedule and amount for both full and limited irrigation treatments (2006-2008).

Year	Date	Irrigation Amount (mm) Limited	Full
2006	18 May	--	38.1
	1 June	38.1	0.0
	15 June	--	38.1
	22 June	--	38.1
	3 July	--	76.2
	13 July	--	50.8
	21 July	50.8	50.8
	27 July	55.9	55.9
	3 August	38.1	38.1
	10 August	--	38.1
	18 August	38.1	38.1
	24 August	38.1	38.1
	Total	259.1	500.4
2007	25 May	38.1	38.1
	20 June	44.5	44.5
	28 June	--	50.8
	11 July	--	50.8
	19 July	50.8	50.8
	25 July	38.1	38.1
	16 August	38.1	38.1
	23 August	--	25.4
	29 August	--	25.4
	Total	209.6	362.0
2008	11 May	38.1	38.1
	4 June	38.1	38.1
	12 June	--	25.4
	26 June	--	38.1
	3 July	--	38.1
	10 July	--	38.1
	17 July	--	38.1
	24 July	38.1	38.1
	31 July	38.1	38.1
	7 August	25.4	25.4
	Total	177.8	355.6

and observed root density dropped off dramatically after 60 cm depth (N. Hansen, personal communication, 18 October 2010).

Total leaf number per plant was sampled in 2007. This was done by counting open leaves on ten representative plants per plot. LAI was taken by non-destructive sampling in 2008. Two representative plants were selected in each plot, and subsequent samples were done on the same exact plants. Length and width of each leaf was measured, and the sum of all these areas was multiplied by 0.74 to estimate the total leaf area (Kang et al., 2003). LAI was estimated by dividing total leaf area by the average ground area per plant, based on observed plant population. Both field experiments and simulations had sufficient available nitrogen (N) to assume negligible N stress. Soil N samples were taken on 21 May 2007 only (13 days after planting). These values were assumed to represent initial N conditions for all treatments in the three years modeled by CERES-Maize (table 1). Additional N was applied during planting in 2008 and in mid-season for all years (table 2).

Irrigation was applied by a linear-move sprinkler system, generally at a weekly interval, and irrigations were applied equally to each replication for the desired treatment. Irrigation amounts were determined by crop need and supported

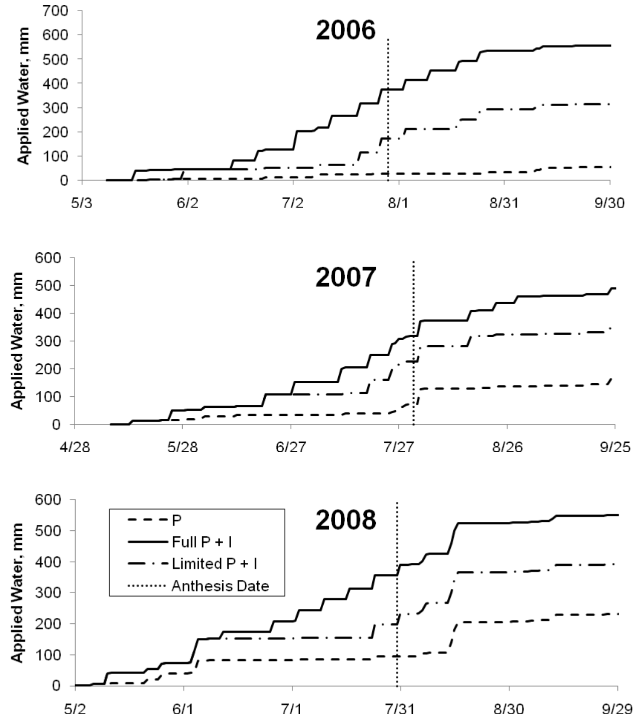

Figure 1. Cumulative precipitation (P) and total water applied as precipitation and irrigation (P + I), for both limited and full irrigation treatments, 2006-2008.

by potential ET estimates from the on-site weather station. Because of flow limitations on the linear sprinkler, irrigations occurred over a two-day period, with the southernmost two replicates being irrigated the first day and the remainder being irrigated the following day. No runoff was observed in irrigations, as application rates did not exceed infiltration capacity and the field had negligible slope. Irrigation schedules for all treatments between 2006 and 2008 are given in table 3.

Irrigation management for a fully irrigated crop typically ensures that the crop experiences no water stress during any stage of growth. Where limited irrigation differs is not only in the total amount irrigated, but also in the timing. Limited irrigation for corn may allow some visually observable (e.g., wilting and discoloring of leaves) stress of the crop during the vegetative stages but avoids stress during the reproductive stages, which are the most water-sensitive (Nielsen et al., 1996). In all three years, irrigation was applied early in the season to all treatments to encourage germination and avoid total loss of the crop. Additionally, some irrigations were applied late in the vegetative stage to ensure no stress at the beginning of the reproductive stage (i.e., irrigations on 19 and 25 July in 2007). This management strategy dictates that limited irrigation should closely match full irrigation beginning at (or slightly before) the anthesis date and continuing through the rest of the reproductive phase (fig. 1).

Observed ET values were calculated using a water balance for the top 1.0 m of soil:

$$ET = P + I - RO \pm \Delta SW \quad (1)$$

where ET is evapotranspiration (mm), P is precipitation (mm), I is irrigation (mm), RO is runoff (mm), and ΔSW is the change in SWC in the soil profile (mm). Runoff was calculated by the SCS curve number method (SCS, 1972) and was insignificant in both observations and simulations. Drainage, or deep percolation below the effective 1.0 m root zone, was assumed to be zero, as all NMM measurements below this zone were less than field capacity. Cumulative observed ET was calculated weekly based on days that soil water content was measured. Daily cumulative potential ET values for a fully irrigated crop were also calculated using the Penman-Monteith model and input data from the on-site weather station (Allen et al., 1998).

Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated as:

$$WUE = \frac{Y}{ET} \quad (2)$$

where Y is grain dry mass yield (kg ha^{-1}), and ET is cumulative evapotranspiration (mm). Because ET is calculated based on water balance, this method is analogous to the "benchmark" WUE calculated by Howell (2001). ET values typically provided in the literature indicate seasonal or total water use. However, because of data limitations, both observed and simulated values for WUE were calculated using cumulative ET values based on the latest SWC observation for each season (ranging from 27 August to 30 September). Because cumulative ET for each growing season was evaluated using different lengths of growth time, treatment comparisons can only be made within individual years but not across years. Additionally, irrigation use efficiency (IUE, kg ha^{-1} mm^{-1}) was calculated as:

$$IUE = \frac{Y}{TI} \quad (3)$$

where TI is total seasonal irrigation (mm). This is similar to the method suggested by Bos (1985), but in this case the yield component is the total grain yield and not yield improvement above dryland only yield.

Model Description

CERES-Maize is a process-oriented corn growth model that simulates the following: biomass accumulation based on light interception; partitioning of accumulated biomass to leaves, stems, roots, and grain; environmental stresses; soil water balance; soil N transformations and uptake; and crop growth and development including phenological states, biomass production, and yield. Required model inputs include soil characteristics, daily weather, cultivar parameters, fertilizer applications, irrigations, planting date, plant population, and other management practices. This model is available as part of the DSSAT v4.0 suite of crop models designed to estimate production, resource use, and risks associated with crop production practices (Tsuji et al., 1994; Jones et al., 1998; Jones et al., 2003). A complete description of the model can be found in Ritchie et al. (1998). Four discrete functions of simulated leaf-tip number are used for predicting plant canopy leaf area in CERES-Maize (Jones and Kiniry, 1986). The calculated canopy leaf area is subjected to senescence coupled with plant development. Calculated senescence rate is modified to account for population and leaf-shading effects. In addition, deficits of N and water accelerate senescence. Final LAI is calculated from the canopy leaf area balance available each day as a function of plant population.

To facilitate use of a minimum data set, CERES-Maize uses a simple water balance algorithm following a layered soil and a "tipping-bucket" approach to calculate yield reductions related to water stress (Ritchie, 1998). The USDA curve number technique (SCS, 1972) is used to calculate runoff and infiltration amounts resulting from rain and irrigation. The FAO-56 Penman-Monteith method (Allen et al., 1998), available as an option in DSSAT, was used to calculate crop ET. This method requires daily solar radiation, minimum and maximum temperature, daily average dew point temperature, and wind speed. These inputs are used in combination with energy balance and mass transfer to calculate reference crop ET. CERES-Maize partitions the potential ET into potential soil evaporation and potential plant transpiration, and actual soil evaporation and plant transpiration rates depend on the soil water availability to meet the potential values (López-Cedrón et al., 2008). In CERES-Maize, crop development rates are calculated based only on temperature and photoperiod (Ritchie et al., 1998). Biomass partitioned to grain in CERES-Maize can be affected by daily minimum temperature (Singh, 1985). Soil organic matter in CERES-Maize consists of fast-decaying "fresh organic matter" and slowly decaying "soil humus fraction." Volatilization loss of N is not simulated for dryland conditions (Godwin and Singh, 1998). N uptake is simulated based on the crop N demand and potential N uptake rate, as described by Godwin and Singh (1998).

Model Calibration

Data taken from the 2007 growing season were used for calibration. Six cultivar coefficients (table 4) were adjusted to match observed growth. First, coefficients P1 and P2 were adjusted to match the anthesis date observed in the field experiments (Boote, 1999), and P5 was matched to the growing degree day units for the hybrids planted in this study (Pioneer, 2008). Next, the PHINT coefficient (phylochron interval, or thermal time between successive leaf tip appearances) was adjusted to match the number of total leaves for each plant throughout the vegetative phase in 2007. Reproductive growth parameters G2 and G3 were also adjusted to closely match yield. Cultivar parameter values were within reasonable limits compared to those found in the literature and also within maize cultivar input files distributed with the DSSAT v4.0 software. Finally, the soil root growth weighting factor ($0 \leq SRGF \leq 1$) was adjusted for each soil layer to find a reasonable root growth distribution (similar to the approach used by Ma et al., 2002, and Saseendran et al., 2008a), as well as adequately simulating SWC and cumulative ET.

Using the calibrated model from the 2007 season, the same parameters were used to simulate the 2006 and 2008 growing seasons. Data available from these seasons were used to statistically evaluate the accuracy of the CERES-Maize model's ability to differentiate between the model response to the full and limited irrigation treatments. These datasets included grain yield, LAI, SWC, and ET estimates.

Model Statistical Evaluation

Four statistical evaluation criteria were used to evaluate the CERES-Maize model. The criteria are quantitative statistics that measure the agreement between simulated and observed values and include the Nash-Sutcliffe efficiency (E_{NS}; Nash and Sutcliffe, 1970), root mean square deviation (RMSD), normalized objective function (NOF), and relative error (RE). The E_{NS}, RMSD, NOF, and RE statistics are defined as follows:

Table 4. Cultivar growth coefficients and soil root growth weighting factor calibrated for CERES-Maize.

Parameter	Description	Units	Value(s)
P1	Thermal time from seedling emergence to the end of juvenile phase during which the plants are not responsive to changes in photoperiod.	degree-days	265
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h.	days	0.4
P5	Thermal time from silking to physiological maturity.	degree-days	589
PHINT	Phylochron interval.	degree-days	45
G2	Maximum possible number of kernels per plant.	unitless	908
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions.	mg d^{-1}	10.0
SRGF	Soil root growth weighting factor for top five soil layers from the surface downward (table 1).	unitless	1, 1, 0.61, 0.22, 0.12

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (4)$$

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad (5)$$

$$NOF = \frac{RMSD}{\overline{O}} \quad (6)$$

$$RE = \frac{\sum_{i=1}^{n}(P_i - O_i) \times 100.0}{\sum_{i=1}^{n} O_i} \quad (7)$$

where O_i is the observed value, P_i is the CERES-Maize predicted value, n is the total number of observations, and $\overline{O}$ is the mean of all observed values. E_{NS} indicates how well the plot of observed versus simulated values fits a 1:1 line. The value of E_{NS} in equation 4 may range from $-\infty$ to 1.0, with 1.0 representing a perfect fit of the data. The normalized objective function (NOF) in equation 6 is based on the root mean square deviation (RMSD), which shows the average deviation between predicted and observed values, regardless of sign. The NOF should be interpreted as a relative value to compare model performance of simulating different data sets. NOF = 0 indicates a perfect fit between experimental data and simulated results; NOF < 1 may be interpreted as a simulation error of less than 1 standard deviation around the experimental mean. RE is a measure of the average tendency of the simulated values to be larger or smaller than the observed values. The optimal RE value is 0.0; a positive value indicates a model bias toward overestimation, whereas a negative value indicates a model bias toward underestimation.

Results and Discussion

Model Calibration

For the 2007 calibration data, CERES-Maize indicated an anthesis date of 2 August for both treatments, while field observations showed that fully irrigated corn had an anthesis

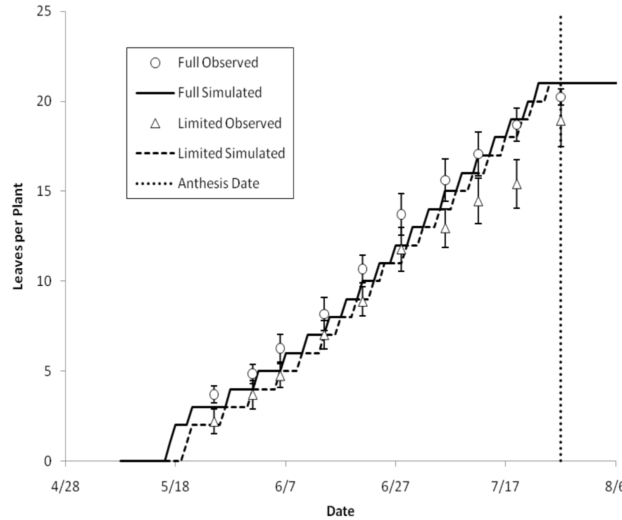

Figure 2. Total observed and simulated leaves per plant in 2007 for the full and limited irrigation treatments. Error bars on observed data indicate one standard deviation from the mean. Planting date was 8 May for full irrigation and 10 May for limited irrigation.

date around 27 July, and limited irrigation corn had an anthesis date around 3 August (table 2). Vegetative growth in terms of total leaves per plant was adequately simulated (fig. 2). Total leaf number had an E_{NS} value of 0.949 for the full irrigation treatment and 0.900 for the limited treatment, indicating excellent agreement in both cases (table 5). Limited irrigation corn was planted two days later than full irrigation corn; this was entirely the cause for the differences in the simulated treatments but only partially the cause for the difference between observed treatments. The CERES-Maize model simulates leaf number strictly as a function of thermal time and the PHINT parameter (table 4) and does not take into account any treatment differences, such as water or nutrient stress. Toward the end of the vegetative growth phase, the model overestimated the leaves per plant for limited irrigation (the last four simulations compared were the only ones outside of one standard deviation of the mean and RE = 7.3% despite all earlier simulations being very close to observed). Peak total leaf number on the anthesis date (27 July) was overestimated for both treatments, although the error was greater for limited irrigation.

The model performed well in simulating yield for the two irrigation treatments in 2007 (table 6). Observed values for full and limited irrigation yield in 2007 had very little variability, with mean yields ±1 standard deviation of 10891

Table 5. CERES-Maize statistical evaluation criteria for total leaf number (2007 calibration) and leaf area index (2008 evaluation).

Statistics[a]	Total Leaf Number		Leaf Area Index	
	Full	Limited	Full	Limited
N	390	370	70	70
$\overline{P}$	11.51	11.22	2.59	1.79
$\overline{O}$	12.12	10.46	2.25	1.56
E_{NS}	0.949	0.900	0.896	0.666
RMSD	1.284	1.663	0.691	0.841
NOF	0.106	0.159	0.307	0.537
RE (%)	-5.0	7.3	15.1	14.5

[a] N = number of observations, $\overline{P}$ = predicted mean, $\overline{O}$ = observed mean, E_{NS} = Nash–Sutcliffe efficiency, RMSD = root mean square deviation, NOF = normalized objective function, and RE = relative error.

±856 kg ha^{-1} and 7576 ±917 kg ha^{-1}, respectively. Simulated full and limited irrigation yields were 9925 and 8164 kg ha^{-1}, respectively, which gives a good representation of the differences between treatments. Observations of total 1.0 m soil water content (SWC) in 2007 (table 6) were slightly underestimated by CERES-Maize for full irrigation (RE = -2.7%) but were underestimated more in the limited irrigation treatment (RE = -13.7%). Cumulative evapotranspiration (ET) (table 6) had high model efficiency for both treatments (E_{NS} = 0.947 for full irrigation and 0.805 for limited irrigation). The model slightly underestimated cumulative ET for the full irrigation treatment, while limited irrigation was slightly overestimated (RE = -5.9% and 4.0%, respectively).

In 2007, water use efficiency (WUE) showed little difference between treatments for both mean observed (full WUE = 24.2 kg ha^{-1} mm^{-1}, limited WUE = 23.7 kg ha^{-1} mm^{-1}) and simulated (full WUE = 22.0 kg ha^{-1} mm^{-1}, limited WUE = 20.5 kg ha^{-1} mm^{-1}) values, and for both treatments simulated WUE was less than observed. Irrigation use efficiency (IUE) for the full irrigation treatment had a mean observed value of 30.1 kg ha^{-1} mm^{-1}, while CERES-Maize simulated 27.4 kg ha^{-1} mm^{-1}. Limited irrigation showed a notable increase in IUE, with 36.1 kg ha^{-1} mm^{-1} for mean observed and 38.9 kg ha^{-1} mm^{-1} for simulated IUE.

Model Evaluation

Using model parameters calibrated with 2007 data, the CERES-Maize model was evaluated using 2006 and 2008 data. The model accurately simulated leaf area index (LAI) for 2008 (table 5 and fig. 3), although the model performed better in the full irrigation treatment than in the limited irrigation treatment (full E_{NS} = 0.896, limited E_{NS} = 0.666). It is interesting to note that observed LAI values are delayed approximately ten days relative to simulated LAI in both treatments. The observed lag in LAI development was likely due to a tornado that occurred in nearby Windsor, Colorado, on 22 May 2008. While the corn did not show any direct visible damage as a result of the tornado, field observations indicated that the corn remained stunted for nearly two weeks, delaying the observed vegetative growth. In both irrigation treatments, CERES-Maize statistically overestimated LAI over the entire season (full irrigation RE = 15.1%, limited irrigation RE = 14.5%); however, the model underestimated LAI during the reproductive stage only. In the limited irrigation treatment the underestimation was greater, indicating that the model was simulating too much LAI reduction due to water stress during the late vegetative and early reproductive stages. López-Cedrón et al. (2008) observed similar trends of growth reduction in terms of biomass when comparing irrigated and rainfed treatments. Additionally, Castrignano et al. (1998) found that CERES-Maize performed well under ideal conditions but underpredicted biomass and LAI when subjected to salinity stress. Results from Xie et al. (2001) indicate that simulated LAI and kernel weight appeared to be overly sensitive to drought stress. Nouna et al. (2000) found that LAI under water stress was underestimated by CERES-Maize and suggested that functions describing leaf growth and soil water deficit be adjusted. A later study

Table 6. CERES-Maize statistical evaluation criteria for soil water content (SWC), evapotranspiration (ET), and grain yield. Results for 2007 are model calibration; results for 2006 and 2008 are model evaluation.

		2006		2007		2008		All Years	
		Full	Limited	Full	Limited	Full	Limited	Full	Limited
Total 1.0 m SWC (mm)	N	50	46	44	44	72	72	166	162
	$\overline{P}$	257	205	317	266	289	236	287	235
	$\overline{O}$	253	232	326	309	313	296	298	281
	RMSD (mm)	55	62	44	72	32	71	43	69
	NOF	0.217	0.268	0.134	0.234	0.102	0.239	0.144	0.245
	RE (%)	1.6	-11.7	-2.7	-13.7	-7.8	-20.3	-3.9	-16.3
Cumulative ET (mm)	N	50	46	44	44	72	72	166	162
	$\overline{P}$	294	198	189	163	265	215	254	196
	$\overline{O}$	297	174	200	157	286	184	273	174
	E_{NS}	0.751	0.759	0.947	0.805	0.977	0.884	0.966	0.835
	RMSD (mm)	96	55	37	54	31	44	61	50
	NOF	0.323	0.313	0.186	0.343	0.110	0.241	0.222	0.289
	RE (%)	-1.0	13.5	-5.9	4.0	-7.4	16.7	-7.2	12.7
Yield (kg ha^{-1})	N	4	4	4	4	4	4	12	12
	$\overline{P}$	11421	7491	9925	8164	12872	10371	11406	8675
	$\overline{O}$	11107	8916	10891	7575	10863	10451	10954	8981
	RMSD (kg ha^{-1})	2321	2633	1218	989	2591	2001	2128	1992
	NOF	0.209	0.295	0.112	0.131	0.239	0.191	0.194	0.222
	RE (%)	2.8	-16.0	-8.9	7.8	18.5	-0.8	4.1	-3.4

[a] N = number of observations, $\overline{P}$ = predicted mean, $\overline{O}$ = observed mean, E_{NS} = Nash–Sutcliffe efficiency, RMSD = root mean square deviation, NOF = normalized objective function, and RE = relative error.

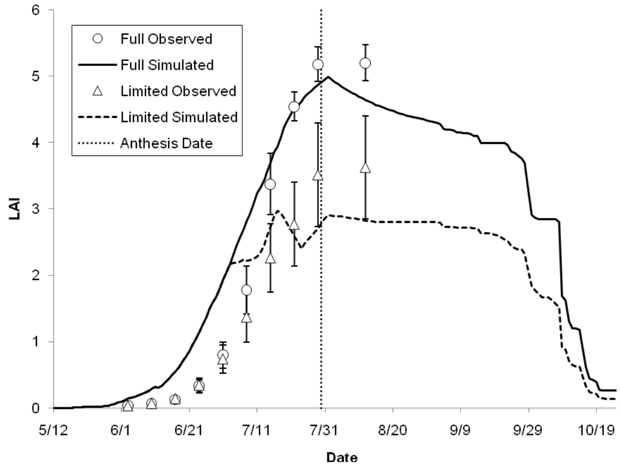

Figure 3. Leaf area index (LAI) in 2008 for both irrigation treatments. Error bars on observed data indicate one standard deviation from the mean.

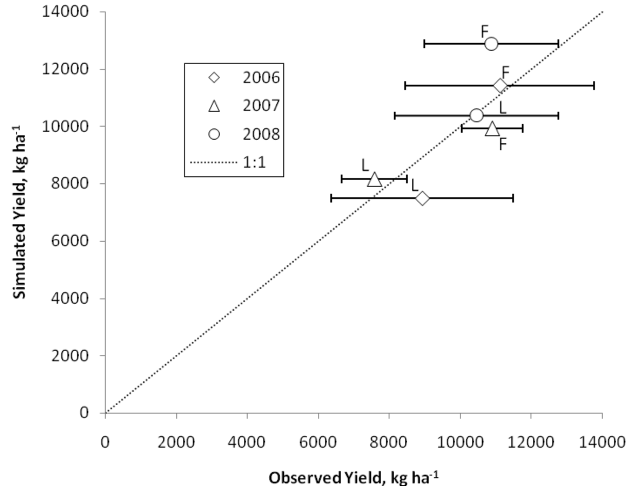

Figure 4. Simulated and observed mean yield for full (F) and limited (L) treatments (2006-2008). Error bars on observed data indicate one standard deviation from the mean. Results for 2007 are model calibration; results for 2006 and 2008 are model evaluation.

by Mastrorilli et al. (2003) simultaneously adjusted the leaf growth and soil water deficit functions in CERES Maize v 3.0 and found that simulation results were significantly improved. The above examples indicate that CERES-Maize water stress factors may have too great of an effect on simulated plant growth, and that the model could benefit from further evaluation under water-stressed conditions.

Similar to other yield studies using CERES-Maize (e.g., Saseendran et al., 2008a), simulated yields were in agreement with observations for 2006 and 2008 (table 6). Simulated yield for 2006 full irrigation and 2008 limited irrigation nearly matched mean observed values (RE = 2.8% and -0.8%, respectively), whereas yield was overestimated for full irrigation in 2008 (RE = 18.5%) and underestimated for limited irrigation in 2006 (RE = -16.0%). Observed treatment differences in yield for 2008 were minimal (412 kg ha^{-1}) and could be partially due to 2008 being the only year with no difference in planting population. However, as previously mentioned, a late-season hailstorm hindered the ability to obtain completely accurate yield estimates, so caution should be exercised when considering yield results from this year.

In 2006, total 1.0 m SWC (table 6) was simulated more effectively for full irrigation (NOF = 0.217, RE = 1.6%) than for limited irrigation (NOF = 0.268, RE = -11.7%). Overall, the model underestimated SWC under limited irrigation. In 2008, similar results were found for full irrigation (NOF = 0.102, RE = -7.8%) and limited irrigation (NOF = 0.239, RE = -20.3%). These results for total 1.0 m SWC were consistent with overestimations of cumulative ET under limited irrigation (table 6). In 2006, results were fairly similar between treatments (i.e., full E_{NS} = 0.751 and limited E_{NS} = 0.759), but limited ET was overestimated (RE = 13.5%) along with the underestimation of total 1.0 m SWC. A similar trend in results occurred in 2008, with simulated full irrigation having excellent agreement with observed values (E_{NS} = 0.977).

Both 2006 and 2008 showed higher values of mean observed WUE for limited irrigation (27.9 kg ha^{-1} mm^{-1} in 2006 and 24.6 kg ha^{-1} mm^{-1} in 2008) in comparison with full irrigation (18.1 kg ha^{-1} mm^{-1} in 2006 and 12.9 kg ha^{-1} mm^{-1} in 2008). However, the model simulated minimal differences in WUE between treatments for both years. For observed data and CERES-Maize simulations, IUE increased in both 2006 (full observed mean = 22.2 kg ha^{-1} mm^{-1}, full simulated = 22.8 kg ha^{-1} mm^{-1}, limited observed mean = 34.4 kg ha^{-1} mm^{-1}, and limited simulated = 28.9 kg ha^{-1} mm^{-1}) and 2008 (full observed mean = 30.5 kg ha^{-1} mm^{-1}, full simulated = 36.2 kg ha^{-1} mm^{-1}, limited observed mean = 59.0 kg ha^{-1} mm^{-1}, and limited simulated = 58.6 kg ha^{-1} mm^{-1}) when comparing limited to full irrigation.

Summary of All Years

Regarding vegetative growth, no direct comparisons could be made between years due to data availability. The yield observations for 2006 and 2008 (evaluation) were much more scattered than in 2007 (calibration), as indicated by larger standard deviations from the mean and smaller RMSD and NOF statistics in both 2007 treatments (table 6 and fig. 4). Although yields in general were correctly simulated by CERES-Maize, the model had a slight tendency to overestimate high observed yields and underestimate low observed yields, a trend noted by other studies (e.g., Xie et al., 2001; Panda et al., 2004; López-Cedrón et al., 2008). Dogan et al. (2006) reported the opposite trend; however, this study had very poor correlation between simulated and observed yield values (R^2 = 0.16).

Past studies have shown good agreement between CERES-Maize simulated and observed SWC (e.g., Panda et al., 2004; Saseendran et al., 2008a), but detailed statistical evaluation criteria for soil water are rarely presented. In this study, total 1.0 m SWC on a weekly basis was not simulated as well as other CERES-Maize output response variables (table 6). For example, all values of E_{NS} for total 1.0 m SWC were negative (data not shown), indicating that on days sampled the mean of all observations would be a better predictor than the predicted value (Legates and McCabe, 1999). However, this interpretation is not representative of the entire SWC, as data collection immediately following irrigation was avoided to circumvent compaction issues in the soils, thereby limiting the ability to determine model accuracy following wetting. Again, CERES-Maize performed better (for all statistical evaluation criteria) in predicting total 1.0 m SWC for the full irrigation treatment than for limited irrigation , but across all years the comparisons to observed values were reasonable (RE = -3.9% for full irrigation and -16.3% for limited). A recent study by Soler et al. (2007) found good agreement between simulated and observed soil water content, where all NOF values were < 0.15. For this study, NOF was 0.144 for full irrigation and 0.245 for limited irrigation over the three years considered. The CERES-Maize model underestimated total 1.0 m SWC in all years and treatments except full irrigation in 2006. On average, full irrigation total 1.0 m SWC was underestimated by 11 mm, and limited irrigation total 1.0 m SWC was underestimated by 46 mm (table 6). Regarding the mean difference between treatments, observed total 1.0 m SWC was 17 mm higher for full irrigation than for limited, while CERES-Maize predicted a much larger difference of 52 mm.

Despite the variability of the total 1.0 m SWC simulations, the overall SWC trends were simulated correctly. Calculated from the water balance (eq. 1), simulated and observed ET is the direct result of the SWC trends (fig. 5). It is important to note that potential ET (PET) predictions (also included in fig. 5) can only be compared with the full irrigation treatment, as PET calculations are based on a non-stressed (non-water-limiting) crop using data collected by the on-site weather station. ET statistics in table 6 were calculated using weekly observations derived from water balance. The model performed much better in simulating cumulative ET than in simulating total 1.0 m SWC, with all values of E_{NS} greater than 0.75. Simulated cumulative ET was most accurate in 2008 (full E_{NS} = 0.977, limited E_{NS} = 0.884), which was also the year with the best simulation of total 1.0 m SWC, as indicated by the RMSD evaluation statistic. Simulated cumulative ET was least accurate in 2006 (full E_{NS} = 0.751, limited E_{NS} = 0.759). In 2006 and 2007, the observed results were somewhat scattered, a likely result of less reliable SWC data for these years. Fully irrigated ET simulations followed the PET predictions closely, tracked very close to observed values through July, and were slightly underpredicted afterward (38 mm less by 30 September). Likewise, Dogan et al. (2006) found that CERES-Maize-simulated ET was significantly less than that found by the KanSched program, which was used to schedule irrigations in their study. Conversely, CERES-Maize had a tendency to overpredict limited irrigation cumulative ET, especially toward the end of the growing season. After 1 July, simulations for limited irrigation cumulative ET were an average of 20.1% higher than observed values. Overall, the model tracked observed values of cumulative ET well. However, as cumulative ET was underestimated for full irrigation and overestimated for limited irrigation, the differences in cumulative ET between these two treatments will likely be underestimated by the CERES-Maize model.

In 2006 and 2008, limited irrigation resulted in a significant increase in observed WUE (kg ha^{-1} mm^{-1}; fig. 6). This difference was not apparent in 2007, most likely because 2007 was the driest year of the three and saw a larger drop in yield from full irrigation to limited irrigation. Because these WUE values are based on cumulative ET (mm) values taken at different points of the growing season for each year, comparisons should only be made between treatments within a year and not between years. CERES-Maize did not predict any significant differences in WUE in any year. This is possibly due to the model's tendency to underpredict full irrigation ET and overpredict limited irrigation ET. Because these biased estimates of ET are used to determine simulated WUE, the difference between treatments is lost. Other researchers have concluded that models such as CERES-Maize are adequate for simulating yield and ET, but not their interaction. For example, Evett and Tolk (2009) suggested that crop models correctly simulate WUE under well-watered conditions but tend to poorly predict WUE under conditions of water stress.

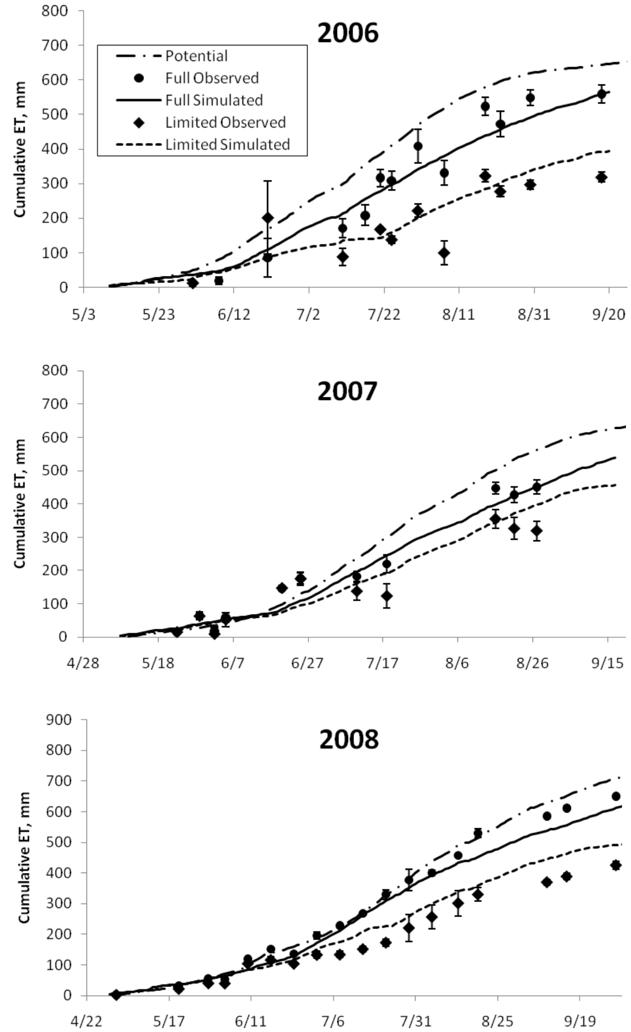

Figure 5. Cumulative evapotranspiration (ET) for 2006-2008. Error bars on observed data indicate one standard deviation from the mean.

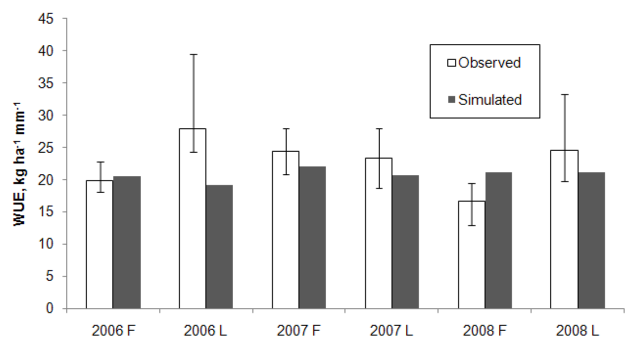

Figure 6. Water use efficiency (WUE) for all treatments and years. F indicates full irrigation, and L indicates limited irrigation. Error bars indicate maximum and minimum observed values.

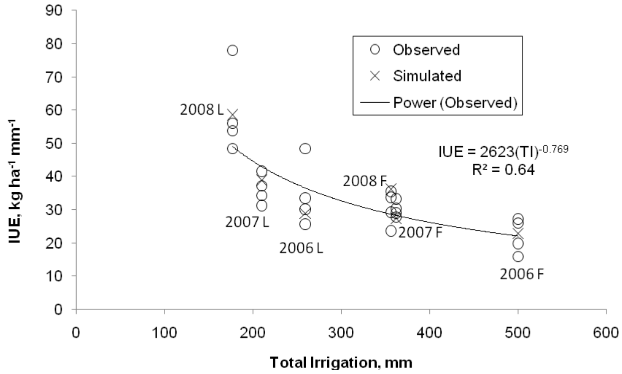

Figure 7. Irrigation use efficiency (IUE) as a function of total irrigation (TI) for all treatments and years. Regression line and formulas shown for observed values.

The other method used to compare both water use and yield among treatments is IUE (fig. 7). Figure 7 is advantageous because simultaneous comparisons can be made including treatments and years, whereas in figure 6 comparisons can only be made between treatments in the same year. A power curve was fit to the IUE (kg ha^{-1} mm^{-1}) versus total irrigation (mm) observed dataset. The CERES-Maize simulations predicted nearly the same exact trend as the observed values, with a somewhat higher R^2 of 0.72 (regression line not shown). The decaying curve in figure 7 shows that the most yield benefit from irrigation comes at smaller amounts, i.e., IUE decreases as irrigation is increased. While increased irrigation amounts certainly increase yields to a point of maximum potential (ignoring excess water stress), this is not a linear trend (fig. 7). When water is limited, net income can be maximized by decreasing the irrigation amount (English et al., 2002); therefore, it is desirable to explore yield potential with less irrigation. Saseendran et al. (2008a) compared simulated grain yield with irrigation amount over various irrigation allocations and amounts. They showed a similar increase in yield potential with irrigation, with a plateau in yields as irrigation totaled near 400 mm, while simulating N stress. While it is impossible to predict rainfall amounts and timing, figure 7 can be helpful in determining expected site-specific yields based on the available irrigation amount (assuming that the producer would follow a limited irrigation management scheme similar to that shown in this article).

Summary and Conclusion

The CERES-Maize model, calibrated using 2007 data and evaluated using 2006 and 2008 data, correctly simulated trends in treatment differences between full and limited irrigation as observed in the field experiment. Overall, the model performed better for the full irrigation treatment than for the limited irrigation treatment for nearly every statistical evaluation criterion. Simulated model grain yield, leaf area index (LAI), and leaf number generally agreed with observed values. Corn anthesis date, generally accepted as the transition between vegetative and reproductive growth stages, was predicted within four days of observed values for all years. Crop growth measurements of total leaf number and LAI had high values of accuracy, although observed LAI values in 2008 were possibly shifted in time due to a nearby tornado that occurred in the early vegetative stage. Total leaf number for limited irrigation was overestimated in the late season, due to leaf number being strictly a function of thermal time. LAI in the reproductive stage was underestimated in both treatments.

Total 1.0 m soil water content (SWC) was slightly underestimated overall, although this trend was much more prevalent in the limited irrigation treatment. Limited irrigation total 1.0 m SWC was fairly consistent in simulation error between the three years, whereas total 1.0 m SWC simulations for the full irrigation treatment improved dramatically in the last year of the experiment. While neutron moisture meter measurements are an accurate method of indirectly obtaining soil moisture content and calculating total SWC, this method is time consuming and was limited in this experiment in that measurements could not be taken within several days of irrigation without causing compaction. Experiments of similar design may benefit from alternative soil moisture monitoring methods that can log at more frequent intervals (including during and immediately following irrigation and precipitation events), especially if the accuracy of such measurement methods can be improved and made less sensitive to outside factors such as temperature and salinity.

While the weekly simulations of total 1.0 m SWC showed marginal success, the overall trends in SWC variability proved to be adequate when comparing simulated cumulative evapotranspiration (ET) with observed values found by water balance. Cumulative ET had a high correlation between simulated and observed values; however, the full irrigation treatment showed a tendency to underpredict ET (especially toward the end of the season), while the limited treatment overpredicted ET. This trend could prove problematic in using CERES-Maize to quantify treatment differences in ET, as the potential water savings as a result would be underestimated as compared to field-observed savings. Water use efficiency (WUE) showed significant treatment differences in observed values for 2006 and 2008, but no significant difference in 2007 due to this being the driest year evaluated. There were no treatment differences in simulated WUE because simulated ET was underestimated for the full irrigation treatment and overestimated for the limited irrigation treatment. Because these errors caused the overall ET difference between treatments to be underestimated, the calculation negated any treatment differences in WUE. Observed irrigation use efficiency (IUE) as a function of seasonal irrigation amount showed a decaying trend, indicating that the most benefit from irrigation occurred at low seasonal irrigation totals. CERES-Maize nearly perfectly agreed with the observed IUE trend. This relationship could be particularly interesting in the study of sensitivity and uncertainty analysis, exploring yield and ET effects of stress based on varying crop growth parameters as well as soil water and growth properties.

Overall, this study serves as an example of integrating a full and limited irrigation field experiment with agronomic modeling. Observed data indicate that limited irrigation has the potential to increase WUE; however, the inability of CERES-Maize to accurately simulate response to crop water stress hinders its capacity to consistently simulate end functions of irrigation treatments, such as WUE in stressed crops. Crop models typically are a combination of mechanistic and empirical components; while crop stresses are indicated based on mechanistic or agronomic relationships, the functions to determine degree of reduction from stress are nearly always empirical (Brisson et al., 2006). By introducing a treatment effect that is highly dependent on water stress, especially during the reproductive growth stages, the model would not be expected to perform as well as in an unstressed situation. Further modeling studies focusing on water stress functions and ET methods, such as those by Ahuja et al. (2008) and López-Cedrón et al. (2008), are needed. Improved crop models that can accurately quantify crop ET under various levels of water stress can be useful tools in maximizing net benefits from irrigation with limited water supplies.

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