

MODELING EVAPOTRANSPIRATION AND CROP GROWTH OF IRRIGATED AND NON-IRRIGATED CORN IN THE TEXAS HIGH PLAINS USING RZWQM



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ABSTRACT. Accurate quantification and management of crop evapotranspiration (ET) are critical to optimizing crop water productivity for both dryland and irrigated agriculture, especially in the semiarid regions of the world. In this study, four weighing lysimeters in Bushland, Texas, were planted to maize in 1994 with two fully irrigated and two non-irrigated for measuring crop ET. The Root Zone Water Quality Model (RZWQM2) was used to evaluate soil water balance and crop production with potential evapotranspiration (PET) estimated from either the Shuttleworth-Wallace method (PT_{SW}) or the ASCE standardized alfalfa reference ET multiplied by crop coefficients (PT_{ASCE}). As a result, two water stress factors were defined from actual transpiration (AT) and were tested in the model against the lysimeter data, i.e., AT/PT_{SW} and AT/PT_{ASCE} . For both water stress factors, the simulated daily ET values were reasonably close to the measured values, with underestimated ET during mid-growing stage in both non-irrigated lysimeters. Root mean squared deviations (RMSDs) and relative RMSDs (RMSD/observed mean) values for leaf area index, biomass, soil water content, and daily ET were within simulation errors reported earlier in the literature. For example, the RMSDs of simulated daily ET were less than 1.52 mm for all irrigated and non-irrigated lysimeters. Overall, ET was simulated within 3% of the measured data for both fully irrigated lysimeters and undersimulated by less than 11% using both stress factors for the non-irrigated lysimeters. Our results suggest that both methods are promising for simulating crop production and ET under irrigated conditions, but the methods need to be improved for dryland and non-irrigated conditions.

Keywords. ET, RZWQM modeling, Stress factor, Weighing lysimeter.

Fertile semi-arid regions of the world, like those of the western U.S., are crucial agricultural areas for providing food and fiber for a growing human population, as well as a healthy environment for many other human enterprises. Limited water resources are already major problems in many of these areas, due to prolonged droughts in recent decades (Kahil et al., 2014). Water scar-

city in these regions is expected to increase as a result of upward trending temperatures, the projected greater frequency of severe droughts, and altered precipitation patterns (Field et al., 2014). In this emerging scenario, there is widespread concern that crop productivity could decline in the coming years as demand for crop production increases. It is critical to developing water management practices to improve water use efficiency. In this context, state-of-the-science agricultural system models have been widely accepted for developing water management information to increase water productivity in agriculture (McNider et al., 2015; Saseendran et al., 2015a, 2015b; Okada et al., 2015).

Crop modeling studies have been conducted to evaluate crop responses to non-water-stressed, limited irrigation management and dryland conditions against precisely measured data, such as lysimeters. Comparison with observed data from an irrigated lysimeter field showed improved model performance of the Soil and Water Assessment Tool (SWAT) for simulations of irrigation amount and frequency and actual evapotranspiration (Chen et al., 2018). Marek et al. (2016) showed that ET values simulated by SWAT approximated lysimeter values for crops under full irrigation, but SWAT had poor performance for crops under dryland conditions. Marek et al. (2017) investigated the efficacy of the DSSAT (Decision Support System for Agrotechnology Transfer)-CERES-Maize model to simulate leaf area index (LAI), crop ET, and yield response to full and limited irriga-

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tion treatments of different corn varieties. The Root Zone Water Quality Model (RZWQM2) was developed to simulate agricultural management effects on crop production and environmental quality. RZWQM2 has been applied to field research conducted in the Great Plains, and the results have been extended to different soils and climates for managing dryland and irrigation cropping systems (Ma et al., 2003; Saseendran et al., 2005a, 2008, 2009). RZWQM2 has been incorporated with the DSSAT-CERES-Crop System Model (CSM). Saseendran et al. (2009) evaluated the response of summer crops (spring triticale, proso millet, and foxtail millet) to initial soil water content in Colorado and Nebraska from 2004 to 2005. RZWQM with CERES-CSM was adapted to the three crops and was able to simulate their response to initial soil water content, which was significant for farmers to make decisions on whether or not to plant a summer crop. Although RZWQM2 has been extensively used to simulate crop production (Ahuja et al., 2014; Islam et al., 2012; Ma et al., 2012; Nielsen et al., 2012; Saseendran et al., 2010, 2014a, 2014b), details of the ET-related modules need to be improved and tested against precisely measured data, such as lysimeters, Bowen ratio systems, eddy covariance towers, etc. (Qi et al., 2016). Anapalli et al. (2016) evaluated the accuracy of RZWQM2-simulated ET for fully irrigated corn against measured crop water use with large weighing lysimeters in the Texas High Plains. However, the response of simulation models to non-irrigated dryland management has not been thoroughly evaluated with weighing lysimeter measurements.

In RZWQM2, root water uptake in each soil layer is simulated by the Nimah-Hanks approach (Nimah and Hanks, 1973), a macroscopic approach, and is a sink term in the Richards equation solution. The uptake rate is directly proportional to the water potential gradient between soil water and root water, multiplied by the soil water hydraulic conductivity, and divided by the root resistance to water flow. The actual soil evaporation (AE) is simulated as an upward surface flux in the Richards equation. Saseendran et al. (2014a) compared the default DSSAT root water uptake and Nimah-Hanks approach and reported that the Nimah-Hanks approach performed better in both rainfed and irrigated experiments at Akron, Colorado. Therefore, in this study, we used the Nimah-Hanks approach to calculate the plant water stress factor, as described by Saseendran et al. (2014a).

In RZWQM2, crop potential evapotranspiration (PET) demand can be calculated from the extended Shuttleworth-Wallace equations (Shuttleworth and Wallace, 1985) or by using the crop coefficient (K_c) and reference ET (ET_r) (Allen et al., 1998). The ET_r is computed from weather data by assigning fixed resistances for the reference crop surface in the Penman-Monteith equation (Monteith, 1965). Reference surfaces can be fully irrigated short grass (0.12 m) or alfalfa (0.50 m) with full canopy coverage. The ASCE Environmental and Water Resources Institute (ASCE-EWRI, 2005) presented an ET_r computation method and K_c values for a variety of plants and conditions. The tall alfalfa reference better describes the mid-season ET_c of many annual field crops and is commonly used in the U.S. Great Plains (Trout and DeJonge, 2017). Anapalli et al. (2016) found better performance in simulation of crop ET and K_c using the tall alfalfa

reference than the short grass reference at the same study site. DeJonge and Thorp (2017) implemented the ASCE standardized reference ET and crop coefficient approach in the DSSAT model and reported better performance than using its default method, including spikes in the soil evaporation coefficient (K_e) due to irrigation and rainfall events and basal crop coefficient response as associated with simulated crop growth. Therefore, in this study, we calculated PET using these two methods: the extended Shuttleworth-Wallace equations and ASCE standardized alfalfa reference ET with crop coefficient.

The objective of this study was to compare simulated maize production and crop ET using two water stress factors in RZWQM2, as explained below, against daily ET measurements from irrigated and non-irrigated weighing lysimeters. Experimental data were collected using two fully irrigated lysimeters and two non-irrigated lysimeters in Bushland, Texas, in 1994, which was the only year with such an experimental design at the study site.

MATERIALS AND METHODS

LYSIMETER DESCRIPTION AND ET MEASUREMENTS

The lysimeter ET data for the fully irrigated and non-irrigated corn grown in 1994 were obtained from the large weighing lysimeter facility at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35° 11' N, 102° 6' W, 1170 m above MSL) (Evelt et al., 2015). The experiments were conducted in four large (3 × 3 × 2.4 m deep), high-precision, weighing lysimeters, each representative of the surrounding field. Two of the lysimeters and associated fields were planted to corn and managed as fully irrigated, each having a different corn variety. The other two lysimeters and fields were planted to the same two varieties but managed as non-irrigated (dryland) fields. The lysimeters contain undisturbed monoliths of Pullman silty clay loam soil (fine, mixed, superactive, thermic Torrertic Paleustoll). In the top 0.30 m of soil, the mean clay content is 0.33 g g⁻¹, the mean bulk density is 1.39 g cm⁻³, and the mean organic matter content is 0.018 g g⁻¹. A calcareous layer is located below a depth of approximately 1.4 m. The wavy boundary between this calcic horizon (Btka) and the overlying clayey (50%) horizon (Bt2) presents a capillary barrier to water flux because the Btka has significantly larger soil pores than the overlying Bt2. In years when precipitation plus irrigation (if any) is insufficient to saturate the overlying Bt horizon, there is limited deep flux into the Btka, and rooting into the Btka is therefore also limited. Each of the lysimeters is located in the center of a 4.4 ha, 210 m (E-W) by 210 m (N-S) field. The four fields are arranged in a square pattern, oriented to the cardinal points and contiguous and are designated NE (northeast), SE (southeast), NW (northwest), and SW (southwest), as were the lysimeters located in each field.

Lysimeter mass was determined using a data logger (model CR7, Campbell Scientific, Inc., Logan, Utah) to measure the lysimeter load cell signal at 6 s intervals, with recorded 5 min means and standard deviations. The load cell signals were converted to an equivalent depth of water (mm) by first converting to mass using a calibration equation (determined on

site and traceable to NIST) and then dividing lysimeter mass by the effective area of 9.18 m² instead of the 9.00 m² inside soil area (determined by multiplying by 0.98 to adjust the lysimeter area to the midpoint between the two walls (10 mm air gap; 9.5 mm wall thickness) and averaging into 5 min outputs. The 5 min mass averages can be used to calculate ET for any period of time defined as a multiple of 5 min base output, e.g., 15 min, 30 min, 60 min, etc. The ET values are determined from decreases in lysimeter mass (evaporation and transpiration), while increases in mass can be attributed to precipitation, irrigation, or the accumulation of dew.

Daily ET values used in this study were calculated by subtracting midnight-centered, average mass values (average of 5 min period before and after midnight) from consecutive days. The lysimeter ET resolution is 0.01 mm water depth equivalent based on the density of water at standard pressure and temperature, and the calibrated accuracy is 0.04 to 0.05 mm (Evelt et al., 2012; Howell et al., 1995). A pump regulated to 10 kPa vacuum promotes drainage, and the inner and outer core drainage effluent is collected in two separate tanks, suspended from each lysimeter (their mass is part of the total lysimetric mass) and independently weighed by load cells. The lysimeters are managed as either irrigated (sometimes deficit) or non-irrigated depending on the experiment. Irrigated fields were serviced by a ten-span, lateral-move sprinkler system (Lindsay Manufacturing, Omaha, Neb.) equipped with mid-elevation spray application (MESA) nozzles. Irrigations were applied to replenish soil water in the top 1.5 m to field capacity based on weekly field-calibrated neutron probe measurements (Evelt, 2008), which maintained the soil water content always above the 50% level of management-allowed depletion. Air temperature, wind speed, relative humidity, solar radiation, precipitation, and soil water contents were measured at both an adjacent research weather station and at each lysimeter (Evelt et al., 2012).

In the 1994 study, the NE and SE lysimeter fields were fully irrigated, with a short-season corn hybrid (Pioneer 3737) on the NE field and a long-season hybrid (Pioneer 3245) on the SE field (Howell et al., 1998). The corn in all lysimeters and fields was planted on 13 through 15 April 1994, i.e., day of year (DOY) 103 through 105. Due to the short-season hybrid on the NE field, irrigation ceased after DOY 213, while four more irrigations were applied to the SE field, totaling 99 mm. Two additional irrigations were applied to the SE field early in the season to increase the soil water content to levels equivalent to those in the NE field. The NW and SW lysimeters were non-irrigated except for a 22.9 mm irrigation event on DOY 109 to ensure emergence and a full stand of the short-season corn hybrid (Pioneer 3737) that was sown on the west fields. In the previous year (summer of 1993), the NE and SE fields were planted to fully irrigated grain sorghum and were tilled and left fallow after harvest. The NW and SW fields were planted to fully irrigated winter wheat following sorghum harvest. However, while the NW field was tilled following harvest, the SW field was not tilled, leaving considerably more crop residue on the soil surface prior to the planting of wheat. In the year of this study (1994), the monthly mean daily minimum temperature varied between -0.9°C in April and 22.4°C in July.

Table 1. Precipitation (*P*, cm) and irrigation (*I*, cm) for the NE, SE, NW, and SW lysimeters at Bushland, Texas, for the period from day of year (DOY) 104 through 258 (14 Apr. to 15 Sept. 1994). Treatments were fully irrigated short-season corn hybrid, fully irrigated long-season corn hybrid, non-irrigated with residue tilled under, and non-irrigated with residue left in place. The non-irrigated treatments were planted with the short-season hybrid and received an irrigation on DOY 109 to ensure emergence.

Lysimeter	Treatment	<i>P</i> (cm)	<i>I</i> (cm)
NE	Short season, fully irrigated	36.3	47.6
SE	Long season, fully irrigated	37.0	58.9
NW	Short season, non-irrigated, tilled	35.4	2.3
SW	Short season, non-irrigated, residues	36.3	2.3

Similarly, the monthly mean daily maximum temperature varied between 7.2°C in April and 38.8°C in June. Total growing season rainfall varied by no more than 4.5% between the four lysimeters (table 1). The NE and SE lysimeters received 476 and 589 mm of irrigation during the growing season, respectively.

Quality control and assurance of lysimeter and weather data were maintained through daily graphing and visual inspection for obvious errors, missing values, and exceedance of physically possible values. When necessary, adjustments to daily ET values were performed to address gains in lysimeter mass corresponding to dew and frost accumulation, and precipitation and irrigation events using techniques detailed by Marek et al. (2014). These techniques provide reasonable daily ET values for use in modeling environments requiring continuous daily data. Field soil profile water contents were determined using a field-calibrated neutron moisture meter (Evelt, 2008) periodically during the crop growing season to 2.4 m depth, with measurements in increments of 0.2 m beginning at 0.1 m depth using a depth control stand to ensure accuracy (Evelt et al., 2003). Periodic measurements of biomass and LAI were made in the field outside the respective lysimeter using destructive sampling, with means pooled from four field subsamples. The final yield data were averages from the whole field area in which the lysimeter was located. RZWQM2 was run using data beginning on day of year (DOY) 104 (14 Apr. 1994) and continuing through DOY 258 (15 Sept. 1994).

FORMULATION OF WATER STRESS FACTORS

In the RZWQM2 soil water routine, the soil water is redistributed between rainfall or irrigation events using the Richards equation (Ahuja et al., 2000):

$$\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z} \left[K(h, z) \frac{\partial h}{\partial z} - K(h, z) \right] - S(z, t) \quad (1)$$

where θ is the volumetric soil water content (cm³ cm⁻³), t is time (h), z is the soil depth (cm, assumed positive downward), h is the soil-water pressure head (cm), K is the unsaturated hydraulic conductivity (cm h⁻¹, a function of h and z), and the sink term $S(z, t)$ includes the rates of root water uptake and the contribution to tile flow from a given soil depth. The root water uptake part of the sink term, $S_r(z, t)$ (cm h⁻¹), is computed using the Nimah-Hanks equation (Nimah and Hanks, 1973):

Table 2. Soil parameters estimated from field-measured soil water contents (table 2 in Anapalli et al., 2016).^[a]

Soil Depth (cm)	Sand (fraction)	Silt (fraction)	Bulk Density (ρ_b , g cm ⁻³)	θ_s (cm ³ cm ⁻³)	θ_{fc} (cm ³ cm ⁻³)	θ_{wp} (cm ³ cm ⁻³)	h_b (cm)	λ
0-15	0.170	0.530	1.26	0.442	0.280	0.185	1.92	0.132
16-41	0.130	0.388	1.48	0.442	0.280	0.185	1.92	0.182
42-74	0.130	0.400	1.60	0.396	0.267	0.181	0.91	0.138
75-112	0.150	0.408	1.58	0.404	0.248	0.157	1.69	0.168
112-189	0.193	0.372	1.65	0.377	0.244	0.167	1.00	0.182

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

$$S_r(z,t) = \frac{[H_r + R_r z - h(z,t) - s(z,t)] R(z) K(\theta)}{\Delta x \Delta z} \quad (2)$$

where H_r is an effective root water pressure head (cm); R_r is a root resistance term, and the product ($R_r z$) accounts for gravity and friction loss in H_r (assumed = 1.05); $s(z,t)$ is the osmotic pressure head (assumed = 0 cm); Δx is the distance from the plant roots to where $h(z,t)$ is measured (assumed = 1 cm); Δz is the soil depth increment (cm); and $R(z)$ is the proportion of the total root activity in depth increment Δz , obtained from the plant growth model.

The sum of $S_r(z,t)$ across the transient root zone gives the total potential root water uptake for any given time. The actual uptake cannot exceed the potential transpiration demand (PT) of the atmosphere; this is obtained by varying the value of H_r in equation 2 until the total uptake is equal to or less than the PT. The total potential root water uptake (TRWUP) is calculated from the summation of equation 2 with H_r set equal to -1.5 MPa as the permanent wilting point. The daily water stress factors (WSFAC) in the CERES-Maize crop module were then calculated as:

$$\text{WSFAC} = \frac{\text{TRWUP}}{\text{PT}} \quad (3)$$

The stress factor mainly affects photosynthesis and other dry matter accumulation related process and ranges from 1 for no stress to 0 for complete stress. Another water stress factor (TURFAC) is also used in CERES-Maize to simulate leaf expansion, where $\text{TURFAC} = \text{WSFAC}/1.5$.

The Shuttleworth-Wallace method (Shuttleworth and Wallace, 1985; Farahani and Ahuja, 1996) and the ASCE alfalfa reference ET_r multiplied by crop coefficient (ASCE-EWRI, 2005) were used to calculate PET, which was partitioned into potential evaporation (PE) and potential transpiration (PT) based on LAI. The basal alfalfa reference crop coefficient (K_{cb}) was taken from a study conducted by Trout and DeJonge (2017) on maize in the U.S. Great Plains. The initial K_{cb} was equal to 0.17, the mid-season K_{cb} was equal to 1.05, and during the crop development stage, with canopy ground cover (cc) between 0.2 and 0.8, K_{cb} was linearly increased from 0.17 to 1.05 using $K_{cb} = 0.17 + 1.10 \times cc$. Canopy ground cover was calculated from simulated LAI using the following equation:

$$cc = 1 - \exp(-0.594 \times \text{LAI}) \quad (4)$$

Therefore, two water stress factors, denoted as $\text{AT}/\text{PT}_{\text{SW}}$ and $\text{AT}/\text{PT}_{\text{ASCE}}$, were tested in the model against the lysimeter data in this study.

MODEL CALIBRATION AND EVALUATION

The soil horizons and the respective characteristics (texture, bulk density, field capacity, and wilting point water content) of the Pullman silty clay loam soil in the lysimeters were taken from Anapalli et al. (2016), where the data from irrigation experiments in 1990, 2006, and 2007 were used in evaluating CERES-Maize v4.0 for simulating crop responses to full irrigation in Bushland, Texas.

Initial estimates of the crop parameters were taken from the DSSAT crop parameter file for the corn hybrids that matched the crop phenology timings of the observed data, following the protocols given by Ma et al. (2011). To account for the often large spatial variability of these characteristics in a given soil type, as well as specific differences among corn hybrids, the initial estimates of the soil (FC and K_{sat}) and crop parameters were refined by calibration with the help of the parameter estimation software PEST (Ma et al., 2011, 2012), using the observed data for the NE lysimeter and the associated field for LAI, biomass, and soil water content of the profile with time during the growing season, as well as the final values of biomass and grain yield. These parameters were then used to evaluate and simulate results for the SE, NW, and SW lysimeters. Because the SE lysimeter was planted to a different corn hybrid (long season) from the NE lysimeter (short season), only the phenology parameters of a full-season corn cultivar from the database were manually changed to match the observed phenology of hybrid 3245 for predicting the SE lysimeter data. This change was not required for the NW and SW lysimeters because they had the same short-season corn hybrid as the NE lysimeter. The calibrated parameters for the soil and for corn hybrids 3737 and 3245 are given in tables 2 and 3, respectively.

Model simulation started on 14 April 1994 (DOY 104) and ran through 15 September 1994 (DOY 258). Daily precipitation and irrigation data (mm) for each lysimeter field were determined from lysimeter mass data, as described by Marek et al. (2014). Meteorological data on total daily solar irradiance (MJ m⁻²), daily mean wind speed (m s⁻¹), maximum and minimum air temperature (°C), and relative humidity (%) measured at 2 m height were from the adjacent grassed research weather station.

STATISTICS FOR MODEL CALIBRATION AND EVALUATION

We evaluated the simulation results using the root mean squared deviation (RMSD, eq. 5) between simulated and observed values, the relative RMSD (RRMSD) that varies between 0% and 100% (eq. 6), the mean deviation (MD) between measured and simulated values (eq. 7; positive MD

Table 3. Plant parameters calibrated for simulations of a short-season corn hybrid (Pioneer 3737) in the NE lysimeter experiment and phenology parameters of a long-season cultivar from the database adjusted to match the observed phenology of the long-season hybrid (Pioneer 3245) in the SE lysimeter experiment at Bushland, Texas, during 1994.

Abbreviation and Definition		Parameters for Pioneer 3737	Parameters for Pioneer 3245	PEST Initial Value (and range)
P1	Degree days (base temperature of 8°C) from seedling emergence to end of juvenile phase (thermal degree days)	203.8	320.00	380 (220, 450)
P2	Day length sensitivity coefficient, i.e., 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	0.80	0.52	0.80 (0.01, 2)
P5	Degree days (base temperature of 8°C) from silking to physiological maturity (thermal degree days)	771.70	800.00	700 (600, 1000)
G2	Potential kernel number	711.40	800.00	750 (400, 1000)
G3	Potential kernel growth rate (mg kernel ⁻¹ d ⁻¹)	8.499	8.00	9 (5, 16)
PHINT	Degree days required for a leaf tip to emerge (thermal degree days)	54.700	40.00	45 (38, 55)

indicates a positive bias in prediction, and negative MD indicates a negative bias in prediction), and the coefficient of determination (R^2 , eq. 8):

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

$$\text{RRMSD} = \frac{\text{RMSD}}{O_{\text{avg}}} \quad (6)$$

$$\text{MD} = \frac{1}{n} \sum (P_i - O_i) \quad (7)$$

$$R^2 = \frac{\left[\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P}) \right]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (P_i - \bar{P})^2} \quad (8)$$

where P_i is the i th simulated value, O_i is the i th observed value, O_{avg} is the average of the observed values, \bar{O} and \bar{P} are the mean measured and simulated values, respectively, and n is the number of data pairs.

These statistics are commonly used to evaluate the accuracy of simulated results as compared to field-measured data. The acceptable ranges of RMSD vary with the crop, variable of interest, method of measurement, and the type and spatial variabilities of soil, management, and plant genetics. Therefore, no standardized ranges of RMSD are available in the literature for any of the variables of interest. In the presentation of results, we provide references to the range of RMSD and/or RRMSD values obtained in previous studies for each variable of interest.

RESULTS AND DISCUSSION

FULLY IRRIGATED LYSIMETERS ON EAST SITES

For the NE lysimeter, with calibration, the simulated results for LAI with time during the growth season compared well with the observed data, although earlier senescence was modeled than observed (fig. 1a; table 4). Measured LAI declined after maximum LAI and then increased slightly before declining during senescence, as indicated by Marek et al. (2017) for fully irrigated corn in Bushland. The simulation of LAI using the two stress factors performed similarly com-

pared to observations, except for the early senescence simulated by the model. Given the standard deviation of LAI measurements (0.4), the simulations using the two stress factors are still reasonable. Attempts have been tried to improve LAI simulation by changing the cultivar parameters in the model, but no better results were obtained. The RMSD values were 0.302 m² m⁻² for both stress factors, which is within 13.5% of the observed mean LAI (RRMSD = 0.135). These RMSD values are lower than the values for fully irrigated corn reported by Saseendran et al. (2005b) (0.78 to 1.3 m² m⁻²), Anapalli et al. (2016) (0.33 to 0.82 m² m⁻²), and Marek et al. (2017) (0.33 m² m⁻²). The biomass simulation was close to the observed values in early stages but was slightly over-predicted at later stages after DOY 206 (fig. 2a). The RMSD value was 1193 kg ha⁻¹ and the RRMSD value was 0.19 using both stress factors. This RMSD value was within the range of values (1000 to 2100 kg ha⁻¹) reported for corn in the literature (Nouna et al., 2000; Kozak et al., 2006; Anapalli et al., 2016). The mean deviation (MD) was 684.9 kg ha⁻¹ for both stress factors. This value was similar to the 760 kg ha⁻¹ reported by Anapalli et al. (2016) for 2006 data. Taking into account the uncertainties and errors in sampling biomass in a spatially variable agricultural field, along with the performance statistics reported by other modeling studies, the model-simulated results for crop growth in the fully irrigated NE lysimeter are reasonable. The grain yield was simulated with an RMSD of 25.6 kg ha⁻¹ using both stress factors, which is within 0.23% of the observed mean.

The simulated and measured changes in total soil water in the root zone soil profile (0 to 190 cm) during the growing season are shown in figure 3. The RMSD values for the simulated profile soil water content of the NE lysimeter were 0.035 cm³ cm⁻³ using AT/PT_{SW} and 0.034 cm³ cm⁻³ using AT/PT_{ASCE}, which are within 10% of the observed mean value (table 4). Similar RMSD values for the profile soil water content have been reported earlier (Saseendran et al., 2005b, 2010, 2015a, 2015b). The RMSD of the simulated total profile water was less than 5.02 cm³ using the two stress factors, which is within 8.3% of the observed mean values. The total soil water in the root zone profile was undersimulated by about 7% using both stress factors (fig. 3a). Anapalli et al. (2016) also reported undersimulation for the same weighing lysimeter with fully irrigated corn. However, the soil water content was considerably underpredicted on DOY

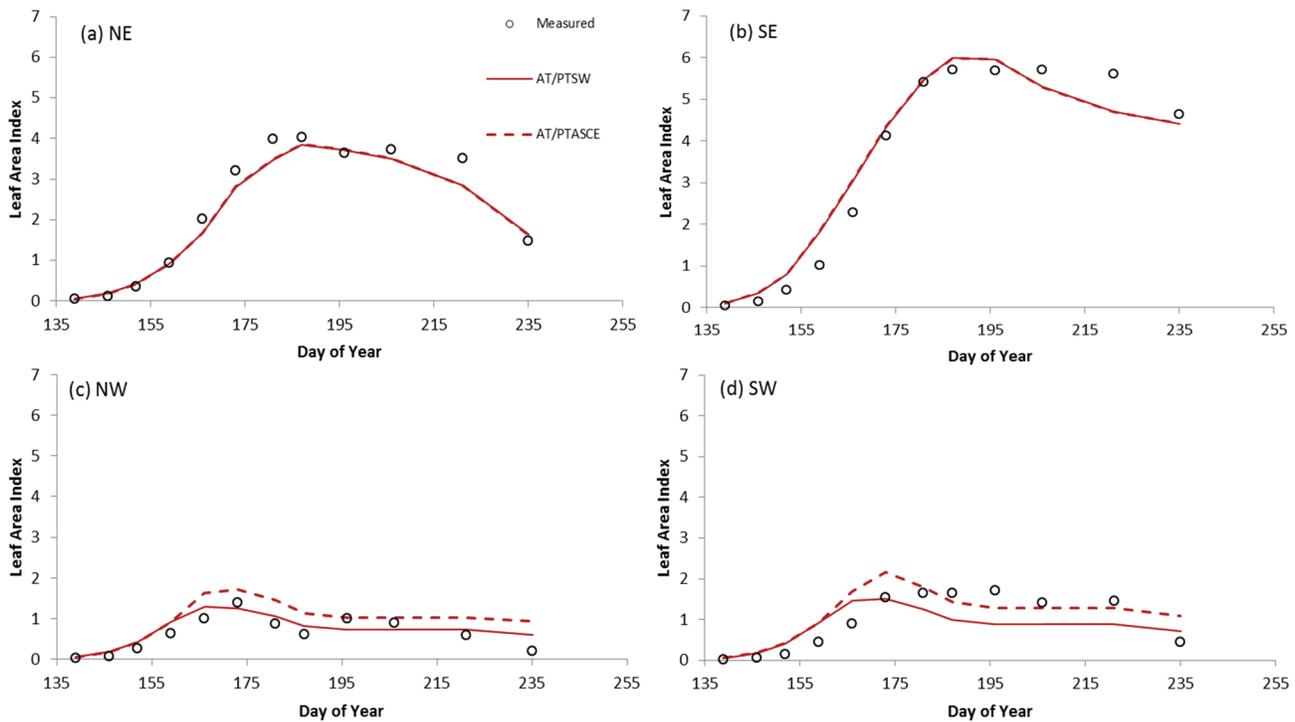


Figure 1. Measured and simulated corn leaf area index for four lysimeters using two stress factors (AT/PT_{sw} and AT/PT_{asce}).

Table 4. Summary of root mean square deviation (RMSD) values for simulations of time-dependent variables for fully irrigated (NE and SE) and non-irrigated (NW and SW) lysimeters using two stress factors (AT/PT_{sw} and AT/PT_{asce}).

Variable and Stress Factor	Lysimeter			
	NE	SE	NW	SW
Leaf area index (m ² m ⁻²)				
AT/PT _{sw}	0.302	0.478	0.223	0.46
AT/PT _{asce}	0.302	0.478	0.407	0.407
Biomass (kg ha ⁻¹)				
AT/PT _{sw}	1193	751	1159	279.6
AT/PT _{asce}	1193	751	2649	1495
Grain yield (kg ha ⁻¹)				
AT/PT _{sw}	25.6	611.4	3431.7	86.6
AT/PT _{asce}	25.6	611.4	4517.3	1120
Profile soil water content (cm ³ cm ⁻³)				
AT/PT _{sw}	0.035	0.034	0.035	0.063
AT/PT _{asce}	0.034	0.034	0.034	0.061
Total profile water (cm)				
AT/PT _{sw}	5.016	3.052	4.793	10.96
AT/PT _{asce}	4.845	3.269	4.234	10.5
ET (mm)				
AT/PT _{sw}	1.05	1.34	1.14	1.52
AT/PT _{asce}	1.0	1.19	1.05	1.47

223, which was due to high simulated ET compared to measured ET (6.5 mm vs. 5.4 mm).

The precipitation and simulated and measured daily ET values for the NE lysimeter are shown in figure 4a along with day of the year. The earlier cessation of irrigation on the NE field resulted in earlier senescence of the crop on that field and reduced seasonal (DOY 204 through 258) ET (table 5). The simulated daily ET values were close to the observed values; the RMSD was 1.05 mm for AT/PT_{sw} and 1.00 mm for AT/PT_{asce}. For both methods, the RRMSD was within 0.21, and the MD was within 0.12 mm. The simulations were better than that reported by Marek et al. (2017), where the RMSD was 2.06 mm for fully irrigated corn. We found that

a period of overestimation (DOY 234 to 237) was followed by a period of underestimation (DOY 237 to 241) in the senescence growing season using both stress factors, which was due to the lower soil water prediction shown in figure 3a. Figure 5a shows a 1:1 plot of simulated and measured ET for the NE lysimeter. Overall, ET was slightly overestimated by 2.6% with $R^2 = 0.89$ using AT/PT_{sw} and underestimated by 0.6% with $R^2 = 0.91$ using AT/PT_{asce}. Figure 4a indicates that the model also predicted soil evaporation, which is the main component of ET in the early stages of crop growth, quite well. Allen et al. (2011) provided errors in measurement of ET by the various methods used in the literature, expressed as one standard deviation from the mean. For a well-managed lysimeter with experienced personnel, the typical error in ET values is estimated at 5% to 15%. For minimally experienced management, ET measurement errors increase to 20% to 40%. In addition, errors caused by physical or equipment malfunction range from 5% to 40%. The errors associated with the next best method of measurement, the Bowen ratio method, were somewhat larger than those reported for lysimeters. For the water balance method of estimating ET, the most often used method, corresponding errors were 10% to 30% for typical error, 20% to 70% for a novice, and 10% to 40% caused by physical or equipment malfunction. For other methods, the typical errors were similar to or worse than the water balance method. Marek et al. (2014) showed that, when using lysimeters, the errors associated with measuring ET are larger on days when rainfall or irrigation occurs. However, using appropriate post-processing techniques can provide adequate data for continuous daily modeling efforts. The aforementioned error figures are for one standard deviation around the mean. In nature, the normal distribution of errors can extend to three standard deviations around the mean. The acceptable limit may be two

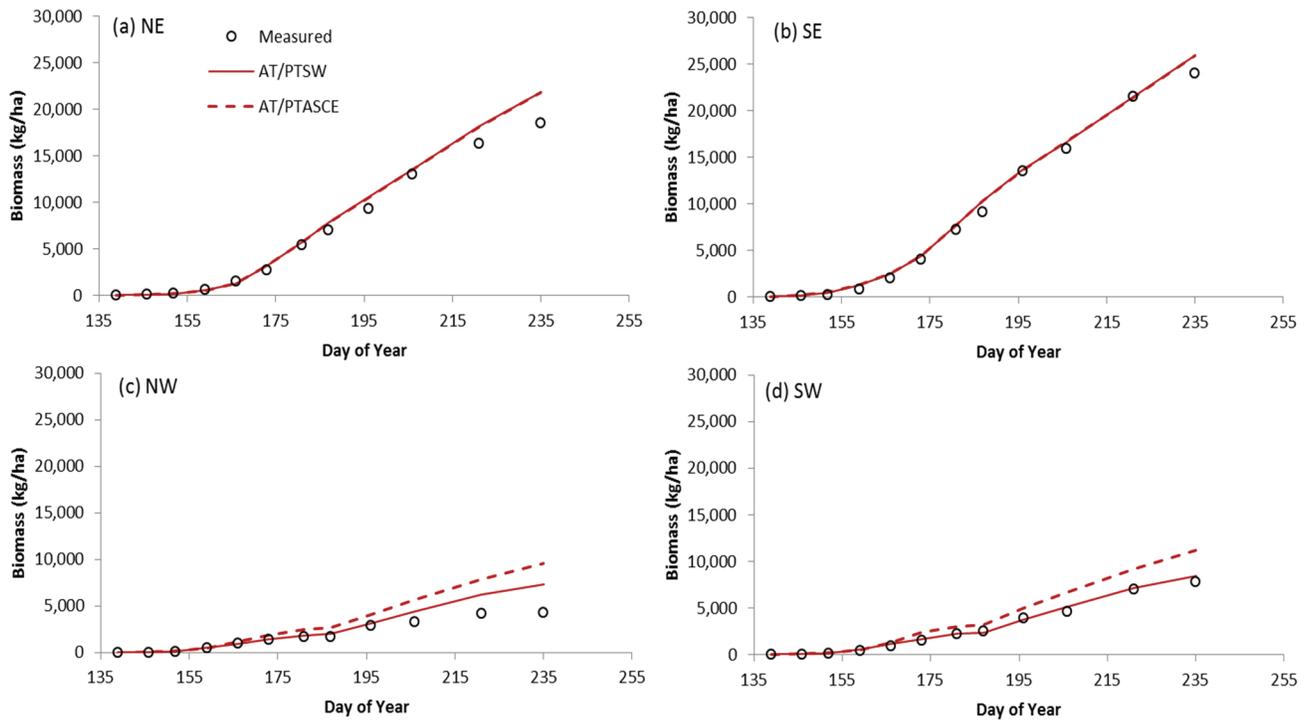


Figure 2. Measured and simulated aboveground corn biomass for four lysimeters using two stress factors (AT/PT_{SW} and AT/PT_{ASCE}).

standard deviations around the mean. Considering these error ranges, the overall error represented by the RMSD value for simulating ET in the NE lysimeter using two stress factors, i.e., about 21.4% of the mean value, was well within one standard deviation around the mean for the lysimeter, and far below the errors associated with measuring ET by the commonly used methods.

The simulations for the fully irrigated SE lysimeter compared well with the observed values and compared to the NE lysimeter (figs. 1b to 5b; table 4) had slightly larger RMSD values for LAI, ET, and grain yield, smaller RMSD values for biomass and soil water content by layer, and similar profile water content. The difference between the two stress factors in simulation of these variables was minimal. The parameters obtained from the NE lysimeter calibration were used, with manual adjustment of the cultivar parameters to obtain the observed phenology durations for the long-season corn hybrid grown in the SE lysimeter (table 3). The model slightly overestimated LAI at the crop developing stage and predicted earlier senescence than the observed values. Simulated biomass trended with the measured values very well throughout the entire season. Average soil water in the SE lysimeter was undersimulated by about 4% using both stress factors (fig. 3b). A few overestimations of ET observed in the daily ET comparison could partly account for the undersimulation of soil water content, e.g., DOY 178 and 185, and DOY after 238 (figs. 3b and 4b). The RMSD of the simulated LAI was within 14.1% of the observed mean, biomass was within 9.2%, soil water content by layer was within 12%, and yield was within 4.6% of the mean using both stress factors. The RMSD values of the simulated ET and total profile water were within 23.8% and 21.1%, respectively, of the observed mean using AT/PT_{SW} and within 5.7% and 6.2%, respectively, of the observed mean using

AT/PT_{ASCE}. From figure 5b, overall ET for the SE lysimeter was slightly underestimated by 1.1% with an $R^2 = 0.87$ and RMSE = 1.34 mm using AT/PT_{SW} and overestimated by 3% with an $R^2 = 0.89$ and RMSE = 1.19 mm using AT/PT_{ASCE}. Overall, these results for the SE lysimeter were close to those for the NE lysimeter, which indicated that the parameters calibrated using fully irrigated NE lysimeter data were applicable to the fully irrigated SE lysimeter with a different cultivar.

Table 5 presents the final biomass, grain yield, total seasonal ET values, and water use efficiency (WUE, defined as yield / (precipitation + irrigation)) for all lysimeters (irrigated and non-irrigated). Both stress factors slightly oversimulated total biomass for the two fully irrigated lysimeters (NE and SE) and produced similar simulations for grain yield, total seasonal ET, and WUE for the two lysimeters. All simulated variables using these two stress factors were comparable to each other. The results demonstrate that both stress factors produce similar simulation results when plant transpiration demands are fully met with irrigation.

Neither of the stress factors showed water stress in the two fully irrigated lysimeters. Seasonal PT using AT/PT_{SW} and AT/PT_{ASCE} was 53 and 54 cm, respectively, for the NE lysimeter and 65 and 75 cm, respectively, for the SE lysimeter. Simulated PT using AT/PT_{SW} was slightly higher than using AT/PT_{ASCE} during the early growing stage but became lower for the rest of the growing season (figs. 6a and 6b). The crop coefficient method calculated PET and then separated it into evaporation (E) and transpiration (T) components; however, it had poor responses to evaporative spikes during nearly full or full canopy growth (DeJonge and Thorp, 2017), which resulted in lower E and higher T in the E and T partitioning.

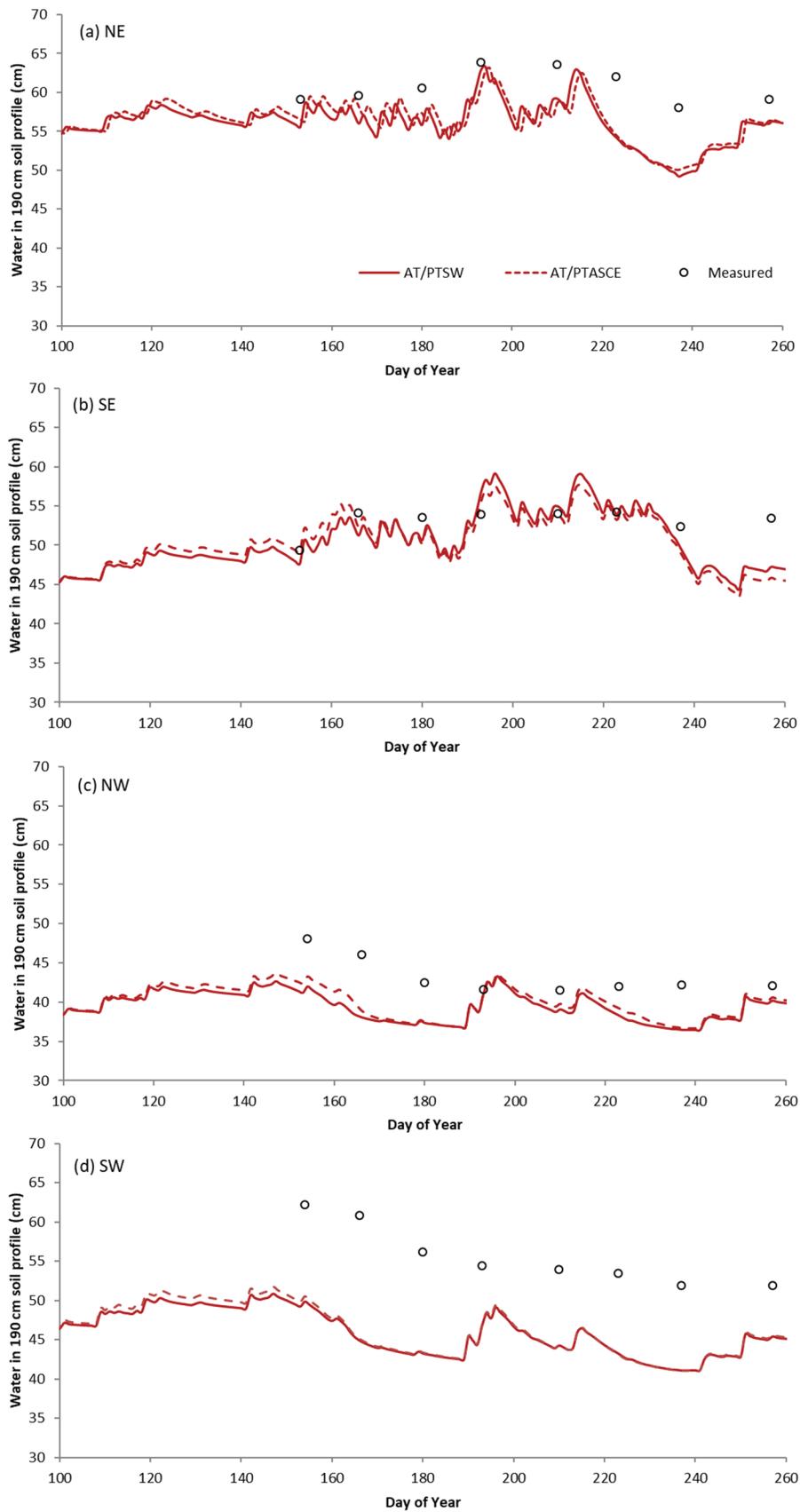


Figure 3. Measured and simulated water in the soil profile for four lysimeters using two stress factors (AT/PT_{SW} and AT/PT_{ASCE}).

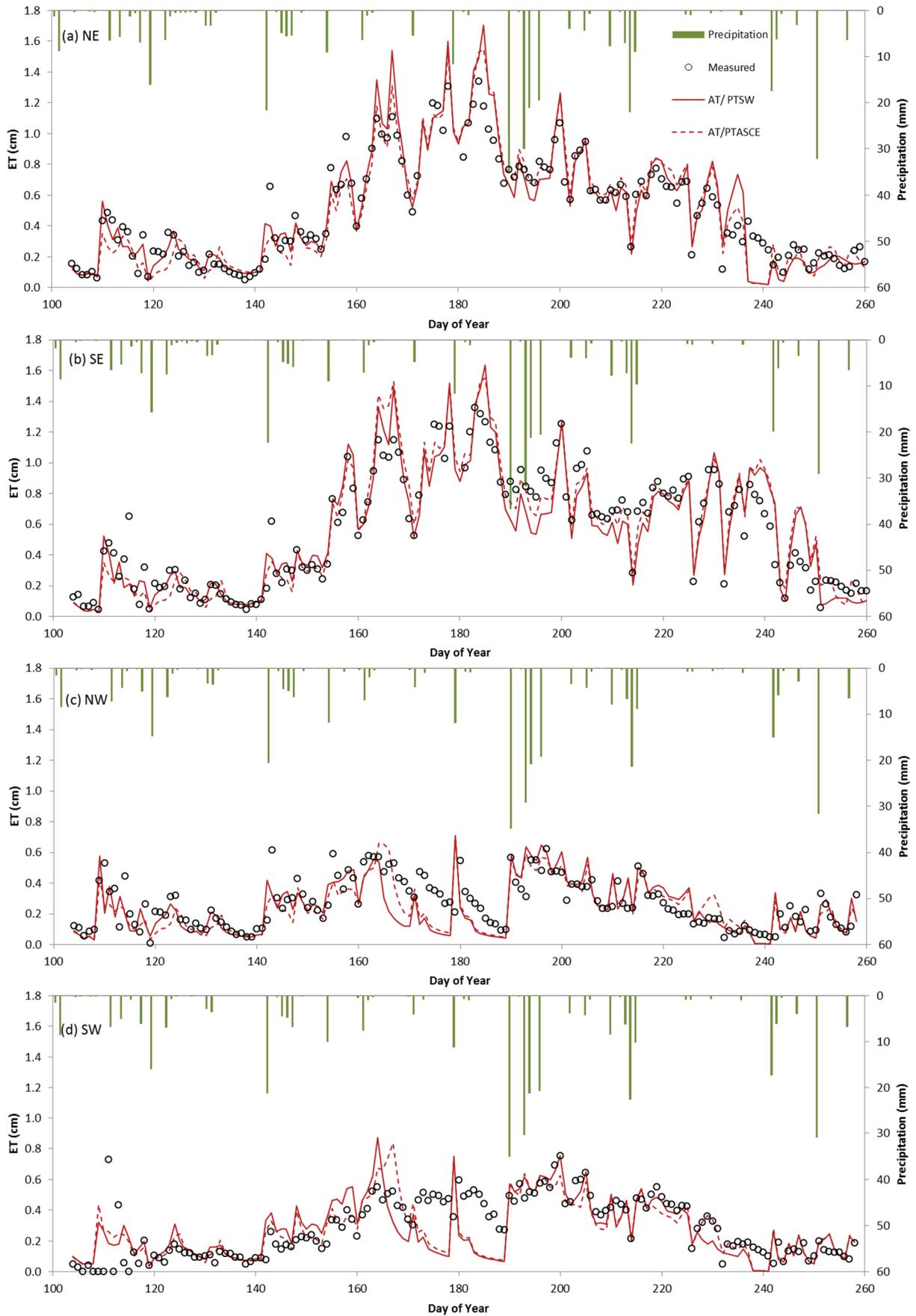


Figure 4. Precipitation and measured and simulated corn ET for four lysimeters using two stress factors (AT/PT_{SW} and AT/PT_{ASCE}).

Table 5. Final biomass, grain yield, and total ET values for fully irrigated (NE and SE) and non-irrigated (NW and SW) lysimeters using two stress factors (AT/PT_{SW} and AT/PT_{ASCE}).

Variable	Stress Factor	Lysimeter			
		NE	SE	NW	SW
Biomass (kg ha⁻¹)					
Measured	-	18501	23957	4262	7820
Simulated	AT/PT _{SW}	21816	25898	7350	8416
	AT/PT _{ASCE}	21816	25898	9627	11165
Grain yield (kg ha⁻¹)					
Measured	-	11283	13195	813	4829
Simulated	AT/PT _{SW}	11257	12584	4245	4743
	AT/PT _{ASCE}	11257	12584	5330	6029
Total ET (cm)					
Measured	-	74.01	85.03	40.79	44.10
Simulated	AT/PT _{SW}	75.91	84.08	36.60	41.47
	AT/PT _{ASCE}	74.43	87.61	36.32	41.36
Yield / (Rain + Irrigation) (WUE, kg ha⁻¹ mm⁻¹)					
Measured	-	13.45	13.76	2.16	12.51
Simulated	AT/PT _{SW}	13.42	13.12	11.26	12.29
	AT/PT _{ASCE}	13.42	13.12	14.14	15.62

NON-IRRIGATED LYSIMETERS ON WEST SITES

The simulation results for the non-irrigated, tilled NW lysimeter with the short-season corn hybrid showed differences between the two stress factors and deviated more from the observed values than the NE and SE results (table 4; figs. 1c to 5c). The simulated LAI using AT/PT_{ASCE} started to show more overprediction on DOY 165 to the end of the growing season than AT/PT_{SW} (fig. 1c). This may be attributed to the slightly lower potential transpiration simulated by AT/PT_{ASCE} than AT/PT_{SW} (fig. 6c). The lower PT using AT/PT_{ASCE} simulated less stress and higher LAI than using AT/PT_{SW}. The simulated biomass was close to the measured values for most of the growth season (fig. 2c) but was overpredicted toward the end, especially with AT/PT_{ASCE}. The trend of simulated LAI with AT/PT_{SW} was close to the result of the 75% irrigation treatment and better than the results of the 50% irrigation treatment reported by Marek et al. (2017), where RMSE ranged from 0.75 to 0.52 m² m⁻². The RMSD of total profile water and ET simulated using AT/PT_{ASCE} were less than with AT/PT_{SW} (table 4). The NW lysimeter RMSD of the simulated profile soil water content was 0.035 cm³ cm⁻³ using AT/PT_{SW} and 0.034 cm³ cm⁻³ using AT/PT_{ASCE} (table 4). The RMSD of the simulated total profile water was less than 4.79 cm using the two stress factors. Average total profile soil water was under-simulated by about 9.7% using AT/PT_{SW} and by 8.38% using AT/PT_{ASCE} (fig. 3c). Overall ET for the NW lysimeter was underestimated by about 10% with an R² = 0.46 and RMSE = 1.14 mm using AT/PT_{SW} and underestimated by 11% with an R² = 0.55 and RMSE = 1.05 mm using AT/PT_{ASCE} (fig. 5c). The under-simulated ET around DOY 180 was mainly due to the considerable underestimation of the soil water profile (fig. 3c). Overall, AT/PT_{SW} better predicted plant growth parameters and AT/PT_{ASCE} performed better for soil water and ET simulation for the non-irrigated NW lysimeter. During the plant growth to mid-growing stage (DOY 164-189) with 19 mm of rainfall, the simulated ET was less than the measured ET values (fig. 4c). During the period of DOY 220 to 240 (senescence stage) with less than 4 mm rainfall, the model started to slightly overpredict ET, especially with AT/PT_{ASCE}.

The simulations for the non-irrigated SW lysimeter with

more crop residue had larger RMSD values compared to the non-irrigated NW lysimeter, except for biomass and grain yield (table 4). For the SW lysimeter, both stress factors overpredicted LAI during the crop development stage, and AT/PT_{SW} started to underestimate LAI after DOY 175 (fig. 1d). The simulated biomass using AT/PT_{SW} trended well compared to the observed values through the entire growing season (RMSD = 279.6 kg ha⁻¹), while AT/PT_{ASCE} started to overestimate biomass from DOY 195 (RMSD = 1495 kg ha⁻¹) (fig. 2d). AT/PT_{SW} had smaller RMSD values for biomass and grain yield than AT/PT_{ASCE} and similar RMSD values for LAI, soil water content, total profile water, and ET as AT/PT_{ASCE}. The RMSD values for soil water content, total profile water, and ET with the two stress factors were larger than the NW lysimeter data. The SW lysimeter RMSD for the simulated profile soil water content was 0.063 cm³ cm⁻³ using AT/PT_{SW} and 0.061 cm³ cm⁻³ using AT/PT_{ASCE} (table 4). The RMSD for the simulated total profile water was 10.96 cm using AT/PT_{SW} and 10.5 cm using AT/PT_{ASCE}. The average total profile soil water was under-simulated by about 19% using AT/PT_{SW} and by 18.4% using AT/PT_{ASCE} (fig. 3d). The simulated ET values for the SW lysimeter were reasonably close to the measured values but much smaller at the mid-growing stage (DOY 172 to 189), as in the NW lysimeter (fig. 4d). Compared to the measured total ET, the simulated ET in the SW lysimeter was underestimated by about 5.9% with an R² = 0.43 and RMSE = 1.52 mm using AT/PT_{SW} and underestimated by 6.2% with an R² = 0.47 and RMSE = 1.47 mm using AT/PT_{ASCE} (fig. 5d). The simulated ET values for both non-irrigated (NW and SW) lysimeters were better than the 2.48 mm reported by Marek et al. (2017) for limited-irrigation lysimeters. The differences in results between the NW and SW lysimeters are likely due to crop residue remaining on the SW lysimeter; the prior wheat crop residue was tilled into the soil for the NW lysimeter, resulting in about 8% less ET for the SW lysimeter.

Both stress factors oversimulated biomass and grain yield for the non-irrigated NW and SW lysimeters (table 5). The measured grain yield in the NW lysimeter was quite low (813 kg ha⁻¹) compared with the simulated average yield using the two stress factors (4787 kg ha⁻¹). Marek et al. (2017) reported that the lowest measured yield from 50% irrigated corn was 5.24 Mg ha⁻¹ in 2013. Therefore, the low measured yield from the NW lysimeter could be due to measurement errors. WUE was oversimulated because both stress factors slightly under-simulated total ET and oversimulated grain yield for the non-irrigated NW lysimeter. For the SW lysimeter, AT/PT_{SW} oversimulated 7.6% of biomass and under-simulated 1.8% of grain yield, while AT/PT_{ASCE} oversimulated about 24.8% of biomass and 42.8% of grain yield. The result was not satisfactory, but it was better than the result reported by Marek et al. (2017), in which the simulated yield from a 50% irrigation treatment was more than twice the measured value in 2013. The WUEs using AT/PT_{ASCE} for the non-irrigated lysimeters were larger than those for the fully irrigated lysimeters. The WUEs for the NE and SE irrigated lysimeters were similar, even though they had corn hybrids of different maturity duration.

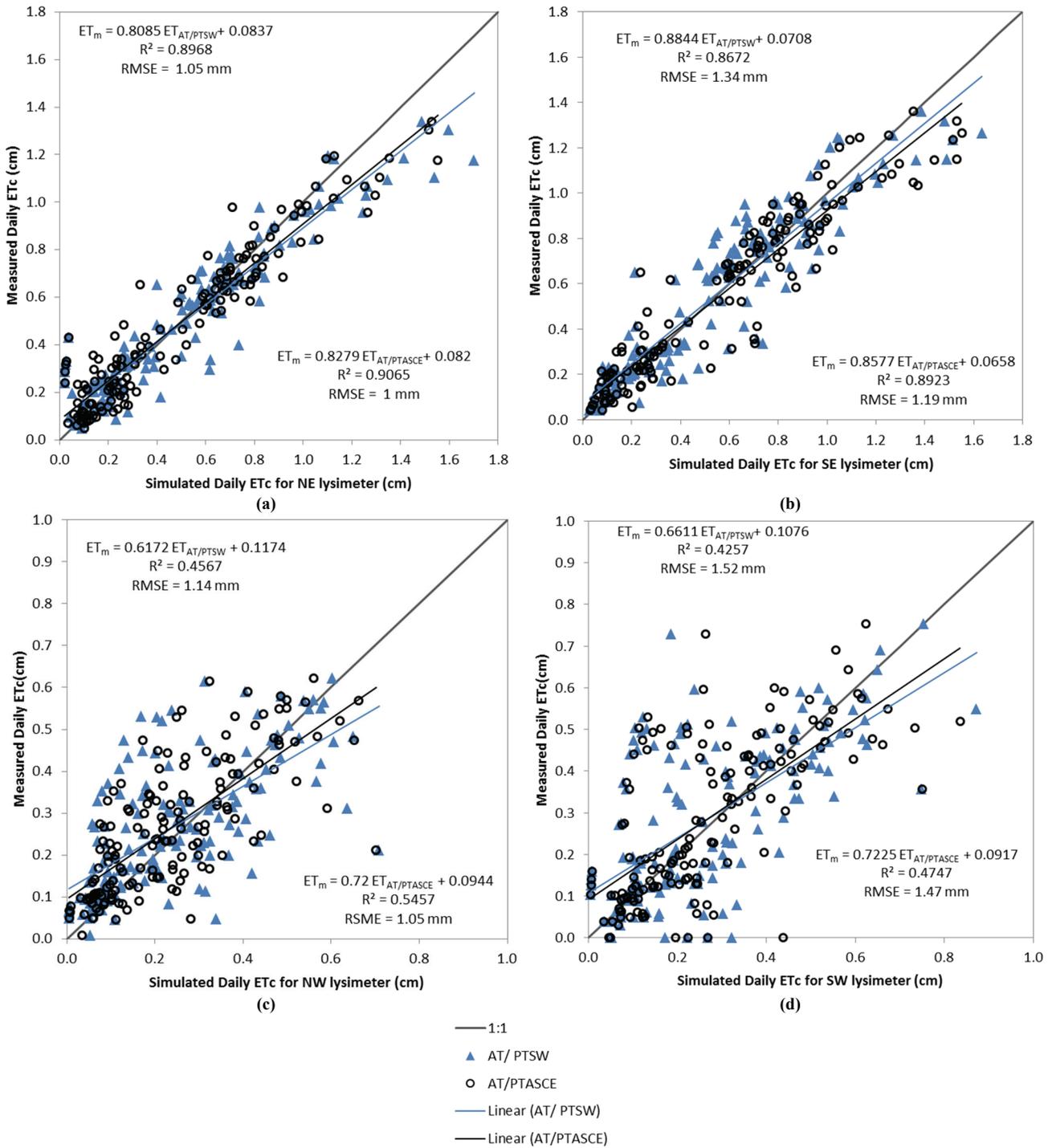


Figure 5. Plots of simulated versus measured corn evapotranspiration (ET) for four lysimeters using two stress factors (AT/PT_{SW} and AT/PT_{ASCE}). ET_m is measured ET, ET_{AT/PT_{SW}} is simulated ET using AT/PT_{SW}, and ET_{AT/PT_{ASCE}} is simulated ET using AT/PT_{ASCE}.

Seasonal PT simulated using AT/PT_{SW} and AT/PT_{ASCE} was 32.5 and 29.1 cm, respectively, for the NW lysimeter and 40.8 and 34.7 cm, respectively, for the SW lysimeter. For the SW lysimeter, simulated PT was slightly higher with AT/PT_{SW} than with AT/PT_{ASCE} throughout the growing season (fig. 6c for NW and 6d for SW). This indicated that the Shuttleworth-Wallace method could well simulate residue effects on potential T, but the ASCE crop coefficient method does not include algorithms with residue.

CONCLUSIONS

The results of this study showed that simulations of crop growth, soil water, and daily ET, using model parameters calibrated against measured data for a fully irrigated corn lysimeter, were close to the measured data for both irrigated lysimeters with short-season and long-season corn hybrids. The final simulated grain yields were also close to the measured values, except for the non-irrigated NW lysimeter. Root mean squared deviations (RMSDs) and relative RMSDs

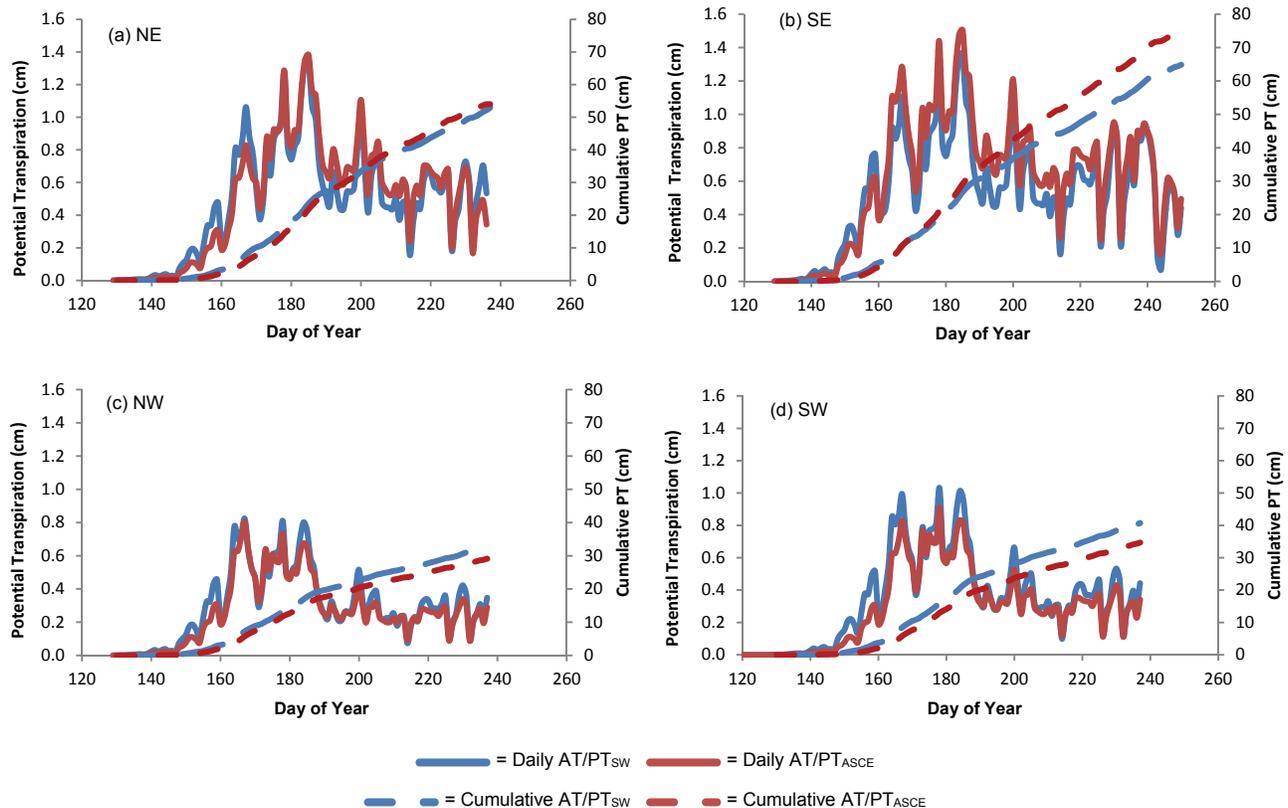


Figure 6. Simulated daily and cumulative potential transpiration (PT) for four lysimeters using two stress factors (AT/PT_{sw} and AT/PT_{asce}).

(RRMSD) values for the above variables were within the ranges reported in the literature. The parameters calibrated using data from the fully irrigated NE lysimeter were applicable to the fully irrigated SE lysimeter with a different cultivar. The two water stress factors performed comparably in the simulation of ET, crop yield and growth, and soil water profile for fully irrigated corn. For the two non-irrigated lysimeters, the simulated daily ET values were also reasonably close to the measured values but were underestimated during the mid-growing stage. Overall, ET was undersimulated by 11% using both stress factors for the NW lysimeter, and ET was undersimulated by 5.9% using AT/PT_{sw} and by 6.2% using AT/PT_{asce} for the SW lysimeter. The current model shows promise for simulating crop ET and production under fully irrigated conditions when compared to field-measured lysimeter data; however, the simulations need to be improved under dryland irrigated and non-irrigated conditions.

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