Water Balance Irrigation Scheduling: Comparing Crop Curve Accuracies and Determining the Frequency of Corrections to Soil Moisture Estimates

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Abstract. *Water balance methods are commonly used to schedule irrigations and use evapotranspiration (ET) functions and crop curves to estimate crop ET (ET_c). Because the methods may over or underestimate ET_c, field-measured values of available soil moisture content (SMC) are often used to correct or adjust estimates of soil moisture during the growing season. This study was conducted to (1) compare the accuracies of four crop curves, based on the Jensen-Haise reference ET method, for corn in the northern Great Plains, and (2) determine the need for and frequency of in-season corrections to SMC estimates. The comparisons were based on differences between estimated and measured SMC for the 1990, 1991, 1992, and 1994 seasons using nonweighing lysimeters near Oakes, North Dakota. The SMC data were compared to estimates using bias and absolute errors, r^2, Friedman Rank Sums, and sign distributions. The SMC estimates were corrected to measured values at three frequencies: start of season only, approximately monthly, and approximately semi-monthly. The crop curve based on days past planting was generally the most accurate, followed by the crop curve based on cumulative growing degree days. All of the methods tended to overestimate ET_c. Selection of a correction frequency is more important than selection of a particular independent variable—days or weeks past emergence, days past planting, or cumulative growing degree days since planting—for a crop curve. For the crop curves, soil types, and climatic conditions of this study, none of the crop curves should be used without in-season SMC corrections on at least a monthly frequency, and semi-monthly corrections are preferred. The methods employed in this study can be transferred to other sites, climates, and crops.* ***Keywords.*** *Error analysis, Lysimeters, Soil moisture, Maize, Northern Great Plains.*

Water balance irrigation scheduling methods are more likely to be used when producers are confident of the methods' accuracies and when the methods are easy to use. Because water balance techniques for irrigation scheduling may over- or under-predict crop evapotranspiration (ET_c), corrections or adjustments should be used to correct or "reset" a water balance to accurately reflect field conditions during the growing season (Lundstrom and Stegman, 1988). Accurate predictions of ET_c are necessary for efficient use of irrigation water. Efficient use of irrigation water not only assists with maximized returns, but also helps to minimize losses of chemicals to ground water through excessive leaching of water through the soil.

Estimates of ET_c are commonly made available to producers. For example, Enz et al. (1995) presented computerized, on-line, real-time ET_c estimates for producers that are available through the North Dakota Agricultural Weather Network (NDAWN). Forty-eight weather stations throughout North Dakota allow users to estimate local ET_c for alfalfa, turf grass, corn, potatoes, wheat, barley, dry beans, and sugarbeets.

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Water balance algorithms use ET_c estimates to indicate when irrigations should be scheduled. Stegman and Coe (1984) presented irrigation scheduling software based on the unmodified Jensen-Haise (1963) equation:

$$ET_r = 0.0102\,(T_m + 3.36)\,R_s \qquad (1)$$

where ET_r is the reference evapotranspiration (mm d^{-1}); T_m is the average daily temperature (°C), and is given by $T_m = (T_{min} + T_{max}) / 2$; and R_s is the solar radiation (MJ m^{-2} d^{-1}). Jensen and Haise (1963) used the term "potential evapotranspiration" for their equation, although equation 1 was based on data from alfalfa, cotton, oats, and winter wheat. Here we employ the more commonly referenced "alfalfa-based ET" (ET_r) term, distinct from "grass-based ET" (ET_o) terminology. Crop ET was computed by the equation:

$$ET_c = K_c ET_r \qquad (2)$$

where K_c is a dimensionless crop coefficient given by:

$$K_c = K_{co}K_a + K_s \qquad (3)$$

In equation 3, the factor K_{co} represents the basal crop curve calibrated to the reference crop, i.e., a non-water-stressed condition with minimal evaporation from the soil surface. The factor K_a represents a reduced-ET condition when plant-available water (AW) in the root zone is limited and is given by $K_a = 1$ if AW > 50% and K_a = AW/50 if AW < 50%. The factor K_s represents conditions with incomplete crop cover ($K_{co} < 0.9$) and when the soil surface is wet, and is given by:

$$K_s = 0.8(0.9 - K_{co}) \quad (4)$$

on the day of rain or irrigation

$$K_s = 0.5(0.9 - K_{co}) \quad (5)$$

on the first day after rain or irrigation

$$K_s = 0.3(0.9 - K_{co}) \quad (6)$$

on the second day after rain or irrigation

and $K_s = 0$ for other times or when $K_{co} > 0.9$.

Crop coefficients for Stegman and Coe's (1984) publication were based on earlier work (Stegman et al., 1977) and used days past emergence (DPE) as the independent variable (table 1). In addition to the inputs required for ET_r computation, the method requires rainfall and irrigation data, crop type and emergence date, soil root zone depth, and soil water holding capacity.

Lundstrom and Stegman (1988) presented a simplified *checkbook* irrigation scheduling method that uses daily T_{max} as the only climatological input. The checkbook method contains ET_c tables derived from the earlier crop curves of Stegman et al. (1977) and long-term weather records for North Dakota. Their corn water use values are shown in table 2. The checkbook method has gained acceptance in the northern U.S., as evidenced by Wright and Bergsrud's (1991) adaptation of the checkbook method for use in Minnesota and Werner's (1996) development of similar checkbook tables for South Dakota based on climatic data.

Steele et al. (1996) presented crop curves for corn (table 1) based on days past planting and cumulative growing degree days since planting for use with Jensen-Haise (1963) ET_r computations. Their crop curve polynomials were developed for use in equation 2 and include time periods or conditions in which transpiration may have been limited, the soil surface was wet, and/or crop cover was incomplete. That is, they developed crop curves for K_c, not K_{co}, and they did not employ equations 3 through 6. In the data sets used to construct the crop curves, periods of limited transpiration did not cause yield-reducing stresses (Steele et al., 1996).

Lundstrom and Stegman (1988) recommended soil sampling and moisture determination at least every two weeks to correct, if necessary, soil moisture estimates made by their method. Whether producers routinely monitor soil moisture every two weeks is uncertain, and the consequences for less frequent corrections is unknown. If the irrigation scheduling methods over predict ET_c, producers will over-irrigate. Consequences include possible yield reductions, excessive pumping costs, and leached agricultural crop chemicals. Conversely, underprediction of ET_c will result in under-irrigation and probable yield reductions.

Comparisons between model estimates and measured values of ET_c and/or soil moisture content (SMC) are too numerous to review here. However, a few examples illustrate the variety of statistics that can be applied. Linear regression of model estimates of ET versus measured ET values has been used to evaluate the accuracy of ET models (e.g., Farahani and Bausch, 1995; Abtew and Obeysekera, 1995). Mahdian and Gallichand (1995) used mean bias error, mean absolute error, root mean square error, and a coefficient of efficiency to compare model estimates and measured values of soil moisture. Jacovides and Kontoyiannis (1995) suggested using the *t*-statistic in addition to the mean bias error and the root mean square

Table 1. Corn crop curve polynomials based on days past planting, cumulative growing degree days, and days past emergence

	Coefficient Values		
Coefficient	DPP Base*	CGDD Base*	DPE Base†
C_1	0.17549	0.24738	0.1814466119
C_2	0.0017287	–0.0014929	-1.877271×10^{-4}
C_3	-1.7684×10^{-4}	1.6737×10^{-5}	7.004694×10^{-4}
C_4	1.3588×10^{-5}	-3.1877×10^{-8}	-9.3707×10^{-6}
C_5	-1.7126×10^{-7}	2.2973×10^{-11}	3.12×10^{-8}
C_6	5.9329×10^{-10}	-5.8428×10^{-15}	-
R^2	0.679	0.544	(Not reported)
SE_{Kc}	0.21	0.25	(Not reported)
N	73	73	(Not reported)

* The coefficients $C_1, C_2, \ldots C_6$ are used in the equation $K_c = C_1 + C_2X + C_3X^2 + C_4X^3 + C_5X^4 + C_6X^5$, where K_c is the crop coefficient and X is the time base (days past planting or cumulative growing degree days since planting); SE_{Kc} is the standard error of the K_c estimates; and N is the number of data points (Steele et al., 1996). Time base abbreviations: DPP = Days Past Planting, CGDD = Cumulative Growing Degree Days since planting. The CGDD values use a 10°C base and no upper limit. The K_c values are used in the equation $ET_c = K_cET_r$, where ET_c is the crop ET and ET_r is the Jensen-Haise (1963) reference ET equation.

† The coefficients $C_1, C_2, \ldots C_5$ are used in the equation $K_{co} = C_1 + C_2DPP + C_3DPP^2 + C_4DPP^3 + C_5DPP^4$, where K_{co} is the basal crop coefficient and DPP is the time base days past emergence (Stegman and Coe, 1984).

Table 2. Corn water use table from *Irrigation Scheduling by the Checkbook Method*

Max. Temp. (°C)*	Average Corn Water Use (mm d^{-1}) Week After Emergence																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10-15	0.3	0.5	0.8	1	1.3	1.5	1.8	2	2	2	2	2	1.8	1.8	1.5	1	0.8	1.5	0.3	0
16-21	0.5	0.8	1.3	1.5	2	2.5	3	3.6	3.6	3.3	3.3	3.3	3	2.8	2.3	1.8	1.5	4.5	3.3	0
21-26	0.8	1	1.5	2.3	3	3.6	4.3	4.8	4.8	4.8	4.6	4.3	4.3	4.1	3.3	2.5	2	5.5	3.3	0
27-32	1	1.5	2	2.8	3.8	4.8	5.6	6.1	6.4	6.1	5.8	5.6	5.3	5.1	4.3	3.3	2.5	6.5	3.3	0
32-37	1.3	1.8	2.5	3.6	4.6	5.8	6.9	7.6	7.6	7.4	7.4	6.9	6.6	6.4	5.1	4.1	3	8	4	0
		3-Leaf				12-Leaf	Tassel	Silk	Pollinate		Blister Kernel			Early Dent	Dent		Black Layer			

* Overlap due to conversions from 10°F intervals.

† Lundstrom and Stegman's (1988) original table contained values for weeks 1 through 17 only. For full-season analysis, values for weeks 18 and 19 were interpolated between values at week 17 and week 20. Values for weeks 20 and 21 were set to zero.

error when evaluating ET models. None of these authors employed in-season corrections to model estimates.

The objectives of this study were to: (1) compare the accuracy of four crop curves when used in a single water balance algorithm; and (2) to determine from the comparisons whether once-per-season, monthly, or semi-monthly soil moisture corrections are appropriate.

Methods and Materials

Model estimates and measured values of SMC were compared using four ET_c crop curves reviewed above and summarized in table 3. A water balance algorithm similar to that presented by Lundstrom and Stegman (1988) was used to evaluate each of the methods using a spreadsheet. If deep percolation (D) is assumed negligible, the water balance method for irrigation scheduling can be written as:

$$SMC_f = R + I - ET_c + SMC_i \qquad (7)$$

where SMC_f is the soil moisture content at some future date, R is rainfall, I is irrigation, and SMC_i is the soil moisture content for day (i). The units for all terms in equation 7 are depth equivalents. Note that R and I are "as-measured" amounts, not "effective amounts", and no attempt was made to account for runoff or canopy losses. That is, this study followed the production practice of reading R and I from rain gauges in the field and entering those amounts in the water balances. The assumption of D = 0 was obtained by resetting the SMC value to field capacity whenever SMC is calculated to exceed field capacity. That is, excess water is assumed to drain in one day (Lundstrom and Stegman, 1988). The drainage rate varies with soil type, but the one-day drainage to field capacity is a convenient first approximation and is reasonably accurate for many irrigated soils in the northern Great Plains.

Four disturbed profile, nonweighing lysimeters described by Steele et al. (1992) were used for this study. The lysimeters are located within the irrigated area of a center-pivot-irrigated field (402-m diameter irrigated area) near Oakes, North Dakota. Predominant soils at the site are a Hecla fine sandy loam (sandy, mixed, Udic Haploborall) and a Wyndmere fine sandy loam (coarse-loamy, frigid, Aeric Calciaquoll). The lysimeters were installed in 1989 in each of four sectors or quadrants of the field and their positions are denoted by "NW" for northwest sector, "NE" for northeast, "SE" for southeast, and "SW" for the southwest. Pioneer 3737 corn was grown at the site for the 1990 through 1994 seasons. Soil moisture measurements were taken by the neutron attenuation method at depths of 0.15, 0.3, 0.6, 0.9, 1.2, and 1.5 m in each lysimeter on a weekly to biweekly frequency as other field and research operations permitted. Results for the 1993 season are not presented because of an insufficient number of soil moisture measurements during that season.

As a first approximation, field capacity estimates were based on soil moisture measurements during 11-12 July 1994. Rainfall during the period 6-8 July was 105 mm, followed by no rain on 9-10 July and 2 mm on 11 July — hence we considered the soil profiles at field capacity on 11-12 July 1994. Based on experience with similar soils, Steele et al. (1997) found that assuming plant-available water is one-half of field capacity is a reasonable approximation for irrigation scheduling purposes. The same approximation was used in this study and values for plant-available water for a 1.2-m soil profile were 137 mm for the NW lysimeter, 122 mm for the NE, 148 mm for the SE, and 107 mm for the SW. The 6-8 July rainfall appears to have been more than sufficient to refill the profile to field capacity — the soil moisture deficit on 5 July 1994 was estimated at 47 mm, using soil moisture measurements (corrections) on 27-28 June 1994 and averaging across the four lysimeters and the four crop curves. Although the stated field capacity values were used to estimate the 47 mm deficit, lower values would still have indicated that the 105-mm rainfall would refill the soil profile so that reasonable estimates of field capacity could be made using the 11-12 July measurements.

We compared estimated SMC to measured SMC for a 1.2-m depth. This depth of the control volume used to calculate the water balance was held constant for the entire season and did not depend on percent canopy cover, growth stage, or percent of seasonal growing degree days. Initial SMC values for each method were set to SMC values measured near the beginning of each season. The water balance algorithms were then run for the rest of the season, without in-season SMC corrections. Later, SMC corrections were made at approximately monthly and semi-monthly intervals. For example, figure 1 shows the DPE method in the NE quadrant for the 1990 season. Two cases are shown to illustrate the correction procedure — one with no in-season SMC corrections, the other with SMC corrections approximately every month.

To compare the methods, we computed the bias errors (BE) at each time (i) using the equation:

$$BE_i = (SMC_{est})_i - (SMC_{meas})_i \qquad (8)$$

and the mean bias errors (MBE) for each lysimeter using the equation:

$$MBE = \sum_i \left[(SMC_{est})_i - (SMC_{meas})_i\right] / n \qquad (9)$$

where $(SMC_{est})_i$ is the estimate of SMC on day (i), $(SMC_{meas})_i$ is the measured value of SMC on day (i), and n is the number of comparisons made in the season. To further quantify the accuracy of the methods, we computed the absolute errors (AE) or the deviations of SMC estimates from measured SMC values for each lysimeter using the equation:

Table 3. Notation, descriptions, references, and abbreviations for the irrigation scheduling methods used in this study

Notation	Description of Method	Reference
CGDD*	Cumulative Growing Degree Days method. Uses K_c = f(CGDD) polynomial.†	Steele et al., 1996
CKBK	Checkbook Water Use Table. Uses daily T_{max} and weeks past emergence.	Lundstrom and Stegman, 1988
DPP*	Days Past Planting method. Uses K_c = f(DPP) polynomial.	Steele et al., 1996
DPE*	Days Past Emergence method. Uses K_c = f(DPE) polynomial.	Stegman and Coe, 1984

* These methods require daily T_{max}, T_{min}, and R_s values to compute Jensen-Haise ET_r.

† Abbreviations: T_{max} is daily maximum temperature (°C), T_{min} is daily minimum temperature (°C), R_s is solar radiation (MJ m^{-2} d^{-1}), ET_r is reference ET (mm d^{-1}), ET_c is evapotranspiration (mm d^{-1}), and K_c is a crop coefficient. The notation "K_c = f(CGDD) polynomial" means that K_c is a function of a polynomial with cumulative growing degree days (CGDD) as the independent variable.

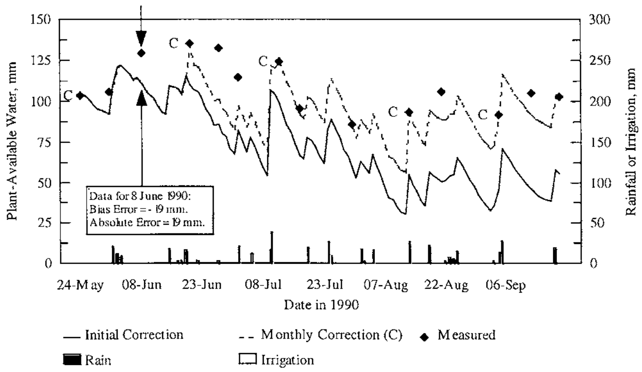

Figure 1–Improvement in water balance estimates due to in-season corrections of soil moisture content. This example is for the Stegman and Coe (1984) crop curve ("DPE" method in table 3) at the NE quadrant lysimeter. "Initial" refers to initial-only corrections of soil moisture estimates; "Monthly" refers to approximately monthly corrections of soil moisture estimates. The "C" data labels correspond to dates for which soil moisture corrections were made in the "Monthly" correction line.

$$AE_i = \left|(SMC_{est})_i - (SMC_{meas})_i\right| \qquad (10)$$

and the mean absolute errors (MAE) using the equation:

$$MAE = \sum_i \left[\left|(SMC_{est})_i - (SMC_{meas})_i\right|\right] / n \qquad (11)$$

Using the SAS software, we computed the following statistics for the 12 combinations consisting of four crop curves and three correction frequencies: means and standard deviations of BE and AE values, the coefficient of determination r^2 for estimated versus measured values of SMC, Friedman Rank Sums (Conover, 1980) for the AE values, and the distribution of positive, negative, and zero BE values. For each date on which soil moisture was measured, the procedure for the Friedman Rank Sums ranks each of the 12 methods and gives a numerical value of 12 to the most accurate method, i.e., the method with the smallest AE_i value, an 11 to the second-most accurate method, etc. The procedure is repeated for each measurement time and a cumulative sum is calculated, so that the method with the highest score can be considered the most accurate.

Note that irrigations were not rescheduled. The SMC corrections are after-the-fact analyses, and on the days for which SMC corrections were made, $BE_i = AE_i = 0$ in the water balance algorithms. The denominator (n) in equations 9 and 11 was *not* reduced by one for each SMC correction, i.e., corrected SMC values *did* enter the computation of MBE or MAE, since the in-season correction is part of the method. To condense the data reported here, values of MBE and MAE from each lysimeter or quadrant were averaged and we use the notation MBE_q and MAE_q to indicate averages from four quadrants.

Rescheduling irrigations or modifying the irrigation schedule within the growing season was not possible within the larger context of the experiment from which these data are taken. Such an experiment would produce crop curves applicable for semi-monthly or monthly periods—rather than crop curves applicable for the entire season—and thus was beyond the scope of this study.

No attempt was made to account for variations in ET_c between the methods following corrections to the water balance algorithms. Only the DPE method alters ET_c as a function of soil moisture conditions and the K_a factor in equation 3 for the DPE method dampens any over predictions of ET_c compared to the other methods.

Analysis of variance and general linear model techniques were not used because the data are not independently distributed, an assumption underlying such statistics (Steel and Torrie, 1980). That is, errors early in the season influence errors later in the season. Time series analyses were not performed because the data sets—corresponding to individual lysimeters, years, algorithms, and correction frequencies—were too small (D. Galster, 1997, personal communication).

Results and Discussion

In figure 1, note that the DPE method predicts SMCs lower than measured values, i.e., it tends to overestimate ET_c. By providing soil moisture corrections, the accuracy of the methods can be improved. In the case of the DPE method for the NE quadrant lysimeter in 1990, providing no in-season SMC corrections produced MBE = –33 mm and MAE = 33 mm. The identical magnitudes of these MBE and MAE values indicate that all of the MBE values were negative, i.e., that the DPE method overestimated ET_c for each measurement period during the 1990 season. For the NE lysimeter in 1990, monthly corrections produced MBE = –8 mm and MAE = 8 mm, and semi-monthly corrections produced MBE = –7 mm and MAE = 7 mm.

The statistical summaries for BE and AE values (table 4) indicate that the crop curve based on days past planting (the DPP method) was generally more accurate than the other crop curves at each correction frequency. That is, for each correction frequency, the DPP method produced the best results in terms of means and standard deviations of bias and absolute errors, r^2, and Friedman Rank Sums—with the single exception of the third-best mean value for bias error at the monthly correction frequency.

Similar comparisons of each of the statistics at each correction frequency (table 4) indicate that the CGDD method is the second-best crop curve. The DPE and CKBK

Table 4. Statistical summary of bias errors and absolute errors for four lysimeters and four years

		Bias Error (mm)		Absolute Error (mm)				Bias Error Sign Distribution (%)		
Method	Correc. Freq.*	Mean	Std. Dev.	Mean	Std. Dev.	r^2†	Friedman Rank Sums‡	Pos.	Neg.	Zero
DPE	1	–23.7[3]§	25.0[2]	26.2[3]	22.4[2]	0.057[3]	687[4]	11.8	78.7	9.6
DPE	2	–5.5[1]	18.4[4]	11.9[4]	15.0[4]	0.710[4]	1157[4]	23.0	43.3	33.7
DPE	3	–4.2[2]	11.1[4]	6.3[4]	10.1[3]	0.889[3,4]	1447[4]	12.9	31.5	55.6
CKBK	1	–24.4[4]	32.8[4]	28.6[4]	29.2[4]	–0.323[4]	710[3]	22.5	68.0	9.6
CKBK	2	–7.2[4]	16.9[3]	11.1[3]	14.6[3]	0.733[3]	1262[2]	20.8	46.1	33.1
CKBK	3	–4.6[3,4]	10.9[3]	6.1[2,3]	10.2[4]	0.889[3,4]	1515[2]	11.8	33.1	55.1
DPP	1	–16.8[1]	23.9[1]	20.4[1]	20.7[1]	0.328[1]	889[1]	20.2	69.1	10.7
DPP	2	–6.3[3]	16.0[1]	10.5[1]	13.5[1]	0.767[1]	1270[1]	20.2	45.5	34.3
DPP	3	–4.0[1]	10.2[1]	5.7[1]	9.3[1]	0.905[1]	1518[1]	11.2	34.8	53.9
CGDD	1	–21.5[2]	26.8[3]	24.7[2]	23.8[3]	0.067[2]	723[2]	16.9	73.6	9.6
CGDD	2	–6.2[2]	16.4[2]	10.9[2]	13.7[2]	0.757[2]	1213[3]	21.9	44.9	33.1
CGDD	3	–4.6[3,4]	10.6[2]	6.1[2,3]	9.7[2]	0.895[2]	1493[3]	9.6	35.4	55.1

* Correction frequencies: 1 = Initial soil moisture only; 2 = Initial soil moisture plus approximately monthly thereafter; 3 = Initial soil moisture plus approximately semi-monthly thereafter.
† Computed as [1 – (error sum of squares) / (corrected total sum of squares)].
‡ Computed for absolute errors. The higher the sum, the more accurate the method.
§ Superscripts indicate the relative rank (1 = best, 4 = worst) within each correction frequency for each column. Thus the DPE method had the third-best mean value for bias error at the initial-only correction frequency. Ties are indicated by two numbers.

methods are less accurate, and this order of decreasing accuracy reflects the decreasing amount of input data used to derive and operate the crop curves. The DPP and CGDD data were based on 11 years of lysimeter data (Steele et al., 1996), while data for the DPE and CKBK methods was based on three to five years of data (Stegman et al., 1977) without lysimeter measurements of drainage beyond the root zone. Hence, measured ET_c values used to derive the DPE and CKBK methods could have included small drainage amounts, which would produce higher ET_c values. The DPP, CGDD, and DPE methods use local, current-season R_s, T_{max}, and T_{min} data for operation. In contrast, the CKBK method uses local, current-season data for T_{max} in 5.6°C increments only, and long-term averages for R_s and T_{min} are built into the crop curves (D. Lundstrom, 1996, personal communication). We attribute the reduced accuracy of the CKBK method to this simplification. The reduced accuracy of the DPP method may have been due to the wet soil surface factor K_s in equation 3 causing overestimation of ET_c, but verifying this was beyond the scope of this study.

The results indicate that increasing the correction frequency increased the accuracy of the methods, regardless of the method chosen (table 4). That is, the means and standard deviations for BE and AE values, the r^2 values, and the Friedman Rank Sums indicate better results for any method at the monthly correction frequency than the best method at an initial-only correction frequency. Similarly, the same statistics indicate that any method used with semi-monthly corrections produce better results than the best method at a monthly correction frequency. We conclude that increasing the correction frequency is more important than selection of a particular independent variable—days or weeks past emergence, days past planting, or cumulative growing degree days since planting—for a crop curve.

Based on the mean BE values, most of the gains in accuracy were obtained by changing from initial-only corrections to monthly corrections, with little additional gains to be realized from semi-monthly corrections. In terms of the means of the AE values, appreciable gains in accuracy were obtained by changing from monthly to semi-monthly correction intervals, as well as by changing from initial-only to monthly correction intervals. Examination of the r^2 values shows that initial-only corrections do not produce acceptable results, while most of the gains in accuracy occur by changing from initial-only to monthly correction frequencies. Note that the r^2 values in the nonlinear models employed here are not subject to the constraint $0 \leq r^2 \leq 1$ characteristic of simple linear regression. Thus the negative r^2 for the CKBK method with initial-only corrections indicates that the mean SMC measurement is a better predictor of SMC than the estimates provided by the algorithm in the sense of a coefficient of determination. Like the r^2 values, the Friedman Rank Sums indicate that most of the gains in accuracy occur by changing from initial-only to monthly correction frequencies.

The negative signs on all BE means and the sign distribution of the BE values (table 4) indicate that the methods all tended to overestimate ET_c. The overestimation of ET_c occurred at all correction frequencies. This translates to a somewhat "conservative" approach to irrigation scheduling, such that the irrigation manager using these methods will tend to slightly over-irrigate the crop rather than under-irrigate it.

Summaries are presented for MBE_q in table 5 and MAE_q in table 6. Nearly all MBE_q values in table 5 are negative, further indicating that all methods tended to overestimate ET_c. Two anomalies are evident in tables 5 and 6. First, the MBE_q and MAE_q values with initial-only soil moisture corrections in 1991 are in some cases nearly double those in other years, indicating that the crop curves substantially overestimated ET_c that year. We attribute the overestimation of ET_c in 1991 to the application of an excessive amount of the commercial soil additive IRON-SUL that damaged the crop in the lysimeters in 1991, resulting in ET_c values lower than those predicted by the crop curves. The second anomaly is that, for some cases, monthly corrections produce MBE_q values closer to zero than do semi-monthly corrections. This happened because not all individual differences between estimated and measured SMC values were negative. For example, some positive errors were eliminated by increasing the correction frequency from monthly to semi-monthly (table 7). Elimination of the positive errors caused the MBE value for the 1990 season in the NW lysimeter to be closer to zero for the monthly correction frequency (3 mm) than for the semi-monthly correction frequency (–6 mm). Note that

Table 5. Mean bias errors for four irrigation scheduling methods using four lysimeters and three correction frequencies

	Mean Bias Error* (mm) Irrigation Scheduling Method														
	DPE Correction Frequency†			CKBK Correction Frequency			DPP Correction Frequency			CGDD Correction Frequency			Overall Average Correction Frequency		
Year	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1990	–19	–0	–3	–12	–2	–4	–2	1	–3	–2	0	–3	–9	–0	–3
1991	–37	–6	–6	–51	–11	–6	–30	–10	–5	–48	–9	–7	–41	–9	–6
1992	–23	–12	–5	–28	–15	–7	–21	–13	–5	–25	–13	–6	–24	–13	–6
1994	–12	–4	–2	–5	–1	–1	–9	–4	–3	–10	–4	–3	–9	–3	–2
Avg.‡	–23	–5	–4	–24	–7	–5	–16	–6	–4	–21	–6	–5	–21	–6	–4

* Values reported are averages of mean bias errors obtained from four lysimeters, one in each quadrant of the experimental field.

† Correction frequencies: 1 = Initial soil moisture only; 2 = Initial soil moisture plus approximately monthly thereafter; 3 = Initial soil moisture plus approximately semi-monthly thereafter.

‡ Simple averages are reported. Since no attempt was made above to weight the averages according to differences in the number of measurements during each year or in each quadrant, four-year average values reported above do not always equal the average values in table 4.

Table 6. Mean absolute errors for four irrigation scheduling methods using four lysimeters and three correction frequencies

	Mean Bias Error* (mm) Irrigation Scheduling Method														
	DPE Correction Frequency†			CKBK Correction Frequency			DPP Correction Frequency			CGDD Correction Frequency			Overall Average Correction Frequency		
Year	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1990	29	11	5	24	7	5	22	8	5	22	8	5	24	9	5
1991	37	13	7	51	13	7	31	12	6	48	13	7	42	13	7
1992	28	17	9	30	18	9	23	16	7	26	16	8	26	16	8
1994	16	7	4	18	7	4	14	7	4	15	7	5	16	7	4
Avg.‡	27	12	6	31	11	6	23	11	6	28	11	6	27	11	6

* Values reported are averages of mean absolute errors obtained from four lysimeters, one in each quadrant of the experimental field.

† Correction frequencies: 1 = Initial soil moisture only; 2 = Initial soil moisture plus approximately monthly thereafter; 3 = Initial soil moisture plus approximately semi-monthly thereafter.

‡ Simple averages are reported. Since no attempt was made above to weight the averages according to differences in the number of measurements during each year or in each quadrant, four-year average values reported above do not always equal the average values in table 4.

Table 7. Bias errors and absolute errors using the DPE method for the NW lysimeter in 1990

	Bias Error (mm) Correction Frequency*			Absolute Error (mm) Correction Frequency		
Date	1	2	3	1	2	3
24 May	0†	0	0	0	0	0
31 May	–17	–17	–17	17	17	17
8 Jun	–21	–21	0	21	21	0
20 Jun	–33	0	0	33	0	0
2 Jul	–58	–25	–25	58	25	25
12 Jul	–61	0	0	61	0	0
17 Jul	–61	–0	–0	61	0	0
30 Jul	–19	42	0	19	42	0
21 Aug	–20	41	–1	20	41	1
27 Aug	–29	31	–10	29	31	10
4 Sep	–40	0	0	40	0	0
12 Sep	–60	–20	–20	60	20	20
Sums	–417	31	–73	417	197	73
Number	12	12	12	12	12	12
Means	–35	3	–6	38	16	6

* Correction frequencies: 1 = Initial soil moisture only; 2 = Initial soil moisture plus approximately monthly thereafter; 3 = Initial soil moisture plus approximately semi-monthly thereafter.

† The method was initialized on 24 May 1990. For dates on which soil moisture corrections were made, bias errors and absolute errors were equal to zero.

the MAE values (38, 16, and 6 mm) decrease with increasing correction frequency, as expected (table 7).

Based on the overall averages for MBE_q values (table 5), the DPP method was the most accurate when initial-only corrections were made. The four-year-average MBE_q values for the other methods at the initial-only correction frequency were somewhat larger in magnitude, ranging from –21 to –24 mm. For the typical irrigation manager applying 25 mm of water per irrigation, these errors are equivalent to having nearly one extra irrigation in the soil at a given time in an average season and clearly illustrate the need for in-season measurements of soil moisture. While soil variability and measurement uncertainty may make this an acceptable margin of safety in terms of water availability for the crop, it may produce unacceptable losses of nutrients such as N and produce unacceptable impacts on ground water quality, in addition to added pumping costs. For monthly and semi-monthly correction frequencies, the four-year-average MBE_q values were similar for all methods, ranging from –4 to –7 mm.

The MAE_q values decreased as the frequency of correction was increased (table 6). All methods performed nearly equally well at the monthly correction frequency and at the semi-monthly correction frequency. When monthly corrections were made, the MAE_q values ranged from 11 to 12 mm, while semi-monthly corrections produced an MAE_q value of 6 mm for all methods. Based on the overall averages for the MAE_q values (table 6), most of the gains in accuracies are obtained between the initial-only and the monthly corrections, with some additional gain in accuracy for the semi-monthly corrections. For example, the overall average MAE_q was 27 mm for the initial-only correction, while the MAE_q was 11 mm for the monthly correction frequency and 6 mm for the semi-monthly correction frequency.

Based on the results of this study, we suggest the following refinements of Lundstrom and Stegman's (1988) recommendation that soil moisture be checked every two weeks: (1) in no case should the crop curves described here be used without in-season soil moisture measurements and corrections in the corresponding water balance algorithms; (2) at a minimum, monthly corrections should be made; and (3) semi-monthly corrections are preferred, if possible. It is important to note that these recommendations apply to the crop curves, soil types, and climatic conditions of this study.

Aside from applying these methods to other crops and using different statistical analyses, at least three areas for future study are apparent. First, we did not attempt to correlate the accuracies of the crop curves with persistent weather patterns. For example, one of the crop curves may be more accurate during periods of relatively hot, dry weather, while another may be more accurate during relatively cool, wet weather.

The second area of future study would be to correlate the accuracies of the crop curves with phenological development or fraction of growing season. For example, in figure 1, the DPE estimates appear to match measured values better for the weeks following the 12 July correction than for the weeks following the 22 June correction. Thus, further study may indicate that corrections to SMC estimates are more important during early phases of crop development than later phases. On the other hand, accuracy of SMC estimates is more critical during the reproductive stage of corn growth. Previous research by Stegman (1982) indicated that avoidance of crop water stress between the 12-leaf and blister kernel stages of growth is critical to maximizing corn yields, while water stresses during other phenological stages are less detrimental to yields.

The third area for future study would be to further improve the accuracies of the methods by better soil characterization. The "best" field capacity values for the data sets could be fit from the data at hand. That is, field capacity or plant-available water values could be adjusted to minimize BE, AE, MBE, and/or MAE values for different quadrants and years. However, this was not an objective of the present study and would not make the crop curves easier to use or understand.

Summary and Conclusions

Using nonweighing lysimeters in a corn field, measurements of SMC were compared to estimates of SMC from four ET_c crop curves for the 1990, 1991, 1992, and 1994 growing seasons. The crop curves were all based on the Jensen-Haise (1963) equation for reference ET and all tended to overestimate ET_c for the conditions and period of this study. In-season adjustments of the model estimates of SMC were made at three frequencies: (1) at the beginning of the season only; (2) at the beginning of the season and approximately monthly thereafter; and (3) at the beginning of the season and approximately semi-monthly thereafter. Several statistics were used to quantify errors or differences between algorithm estimates and measured values of SMC and to compare the accuracies of the methods.

The crop curve based on days past planting (DPP) was the most accurate, followed by the crop curve based on cumulative growing degree days (CGDD). The DPE and CKBK crop curves were the least accurate.

Increasing the frequency of SMC adjustments to the crop curves improved their accuracies. The selection of a correction frequency was found to be more important than the selection of a particular independent variable—days or weeks past emergence, days past planting, or cumulative growing degree days since planting—for a crop curve. Compared to setting only the initial SMC values for the crop curves, most of the improvements in accuracy were gained by monthly SMC corrections, with some additional gains being obtained by semi-monthly SMC corrections. This study indicates that Lundstrom and Stegman's (1988) recommendation of checking soil moisture every two weeks can be refined to the following recommendations: (1) using only a start-of-season initialization of the water balance algorithms is insufficient for all the crop curves described here; (2) corrections should be made at least monthly; and (3) semi-monthly corrections are preferred, if possible. These recommendations depend on sufficiently accurate soil moisture measurements and are limited to the crop curves, soil types, and climatic conditions of this study. More frequent field visits are recommended and often practiced by producers to assess aspects of irrigated corn production other than soil moisture status, such as insect, disease, and weed infestations. The methods presented in this study may be applied to other crops, crop curves, and water balance algorithms, and to locations outside the northern Great Plains.

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