New Corn Evapotranspiration Crop Curves for Southeastern North Dakota

D. D. Steele, A. H. Sajid, L. D. Prunty

Abstract. *Accurate irrigation scheduling requires knowledge of crop water use. Crop curves are one means of irrigation scheduling. Crop curves are the ratio of actual crop water use to reference crop evapotranspiration presented as a function of an independent variable such as days past planting, phenological development, fraction of season, or cumulative seasonal heat units. Crop curves are commonly based on daily data from weighing lysimeters. In nonweighing lysimeters, soil moisture measurements may be taken at weekly or other nondaily intervals. We present four mean corn evapotranspiration crop curves based on 11 years of data from four nonweighing lysimeters. The crop curves are based on Jensen-Haise (J-H) or Penman-Allen (P-A) reference evapotranspiration (ET_r) computations as functions of days past planting (DPP) or cumulative growing degree days (CGDD) since planting. The r^2 and standard errors in the K_c estimates (SE_{Kc}) were 0.68 and 0.21, respectively, for the J-H DPP method; 0.54 and 0.25 for the J-H CGDD method; 0.62 and 0.24 for the P-A DPP method; and 0.52 and 0.27 for the P-A CGDD method. We also illustrate: 1) calculation procedures for development of crop curves based on nondaily soil moisture measurements; 2) a method of referencing each water balance period to the independent variable which does not bias the resulting crop curve forward or backward in time; and 3) the repercussions of using an insufficient number of significant digits in the crop curve polynomial coefficients. Reliable and unbiased crop curves should result from use of the methods described in this article.*
Keywords. *Nonweighing lysimeters, Soil moisture, Irrigation scheduling, Water use, Numerical methods.*

Accurate predictions of crop water use are necessary for efficient use of irrigation water and are essential for environmentally sound irrigated crop production. Depending on the cost of water, they are also essential for profitable crop production. Practical irrigation scheduling algorithms can be based on a soil water balance (e.g., Stegman and Coe, 1984; Lundstrom and Stegman, 1988). To develop water use functions for use in irrigation scheduling algorithms, the water used by a crop can be measured directly through the use of weighing lysimeters. Marek et al. (1988) gave a summary of weighing lysimeter installations in the United States, most of which were designed primarily for crop evapotranspiration (ET) measurement. Typical weighing lysimeter installations weigh the crop-soil-water unit at daily or subdaily intervals. From reference crop ET (ET_r) data based on climatological data and daily ET measurements from weighing lysimeters, daily crop coefficients (K_c) can be determined from the relationship $K_c = ET/ET_r$ (e.g., Wright, 1982). Each day's K_c value can be referenced to an independent variable such as days past planting or emergence, phenological development, fraction of season, or cumulative seasonal heat units. A functional form (e.g., polynomial) of K_c versus the independent variable (commonly called a *crop curve*) can be developed for one or more seasons using regression analysis. Crop curves are appealing for use in irrigation scheduling algorithms because ET_r, and hence crop ET, can be calculated from climatic data and K_c.

For purposes of monitoring the quality and quantity of soil water leaching beyond the root zone, nonweighing lysimeters are a lower-cost alternative to weighing lysimeters (e.g., Montgomery et al., 1987; Prunty and Montgomery, 1991). Crop water use determinations can also be made with nonweighing lysimeters. In typical nonweighing lysimeter systems, soil moisture is determined by a means extrinsic to the system, such as by the neutron attenuation method. Soil moisture and drainage measurements are normally taken at intervals greater than one day. Development of accurate and unbiased crop curves based on measurements of ET_r, soil moisture, and drainage which are not all taken on the same time interval requires the application of appropriate numerical techniques. The objectives of the research reported here are to: 1) revise the Stegman et al. (1977) corn crop curve based on days past emergence and on the Jensen-Haise (1963) ET_r calculation method; 2) present three new corn crop curves; and 3) illustrate unbiased calculation procedures and precise reporting practices for crop curve calculations based on data from nonweighing lysimeters in which nondaily soil moisture measurements and daily drainage measurements are taken. The new crop curves reported here are based on the Jensen-Haise ET_r as a function of cumulative growing degree days (CGDD) since

Article was submitted for publication in October 1995; reviewed and approved for publication by the Soil and Water Div. of ASAE in December 1995.

Research supported by North Dakota Agricultural Experiment Station Projects 2560 and 1446 and by the U.S. Department of Interior, Bureau of Reclamation.

The authors are **Dean D. Steele**, ***ASAE Member Engineer,*** Assistant Professor, **Ali H. Sajid**, ***ASAE Member Engineer,*** former Graduate Assistant, Agricultural Engineering Dept., and **Lyle D. Prunty**, Professor, Soil Science Dept., North Dakota State University, Fargo. **Corresponding author:** Dean D. Steele, Agricultural Engineering Dept., North Dakota State University, Fargo, ND 58105-5626; telephone: 701-231-7268; e-mail: <steele@plains.nodak.edu>.

planting, a Penman-type ET_r function of days past planting, and a Penman-type ET_r function of CGDD since planting.

METHODS

In a one-dimensional soil system with no horizontal water movement, the soil water balance equation is:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage} \quad (1)$$

with units of mass or volume of water. Inflow includes rainfall (R) and irrigation (I). Outflow includes deep drainage (D) or percolation losses beyond the root zone, soil surface evaporation (E), and transpiration (T) by the crop. The change in storage over a period of time is the difference between final soil moisture content (SMC_f) and the initial soil moisture content (SMC_i). Equation 1 can be rewritten as:

$$R + I - D - ET = SMC_f - SMC_i \quad (2)$$

The units for each of the terms in equation 2 are water equivalent (mm). The right-hand side of equation 2 is determined by weighing in weighing lysimeters, while it is inferred from soil moisture measurements in nonweighing lysimeters. Rearrangement of equation 2 yields:

$$ET = R + I - D - SMC_f + SMC_i \quad (3)$$

which is used to calculate crop water use from nonweighing lysimetry for various periods during the growing season. Daily ET_r values and periodic ET values can be combined into K_c values, which in turn can be developed into crop curves and ultimately, irrigation scheduling algorithms.

Sajid (1993) used the water balance approach to develop crop curves from 11 years of nonweighing lysimeter data under continuous corn. Field measurements of R, I, D, and SMC were obtained at the Oakes Irrigation Field Trials Site (46°04′N Lat, 98°06′W Long, and 396 m M.S.L.; Enz et al., 1993) located in southeastern North Dakota. Four tile-drained, nonweighing lysimeters (2.4 × 2.4 m and 2.3 m deep) were constructed in the fall of 1980. The lysimeters are discussed in detail by Prunty and Montgomery (1991). A buffer area around the lysimeters was cropped with corn. Daily values of tile drainage from each lysimeter from May through September were used to develop crop curves. A description of vacuum trough extractors in the lysimeters was presented by Montgomery et al. (1987). The vacuum troughs account for 5% of the surface area in the lysimeters and were not included in these water balance calculations. Soil moisture measurements by the neutron attenuation method were taken at approximately weekly intervals and, when possible, just prior to irrigations and two to four days after irrigations. Soil moisture contents were measured to a depth of 2.0 m, which is within 0.3 m of the lysimeter bottom. Daily measurements at the site included maximum and minimum air temperatures (T_{max} and T_{min}, respectively), net solar radiation (R_s), wind run, relative humidity, and precipitation (rainfall, R).

The crop curves reported here are *mean* curves, in contrast to *basal* crop curves, such as those reported by Wright et al. (1982). That is, the basal curves reported by Wright et al. represent time periods with a dry soil surface, when evaporation from the soil surface was minimal, yet when soil moisture in the root zone was not depleted enough to produce stress on the crop. In this study, the crop curves include all time periods and therefore include periods with a wet soil surface. No separate calculations were made in this study to account for wet soil surface conditions. The irrigation regimes imposed on the crop during the study period did not produce water stresses sufficient to cause statistically significant yield reductions (e.g., Prunty and Montgomery, 1991).

Reference crop evapotranspiration values were computed by two methods. The first was the unmodified Jensen and Haise (1963) equation used by Stegman (1988) for crop curve comparisons:

$$ET_{r(J-H)} = 0.0102\,(T_m + 3.36)\,R_s \quad (4)$$

where

$_{r(J-H)}$ = reference ET method of Jensen and Haise (1963)

T_m = average daily temperature (°C), and is given by $T_m = (T_{min} + T_{max})/2$

R_s = daily solar radiation (MJ m^{-2})

The second was the Penman equation as modified by Allen (1986), here denoted as Penman-Allen, i.e.:

$$ET_{r(P-A)} = [\Delta/(\Delta + \gamma)]\,(R_n - G) + [\gamma/(\Delta + \gamma)]E_a \quad (5)$$

where

$_{r(P-A)}$ = Penman-Allen reference ET method

Δ = slope of the saturation vapor pressure-temperature curve calculated at mean air temperature (mb/°K)

γ = psychrometric constant (mb/°K)

R_n = net long-wave and short-wave radiation (mm/day water equivalent)

G = heat flux into the soil (mm/day water equivalent)

E_a = aerodynamic vapor transport term (mm/day)

Refer to Allen (1986) and Sajid (1993) for computational details for the $ET_{r(P-A)}$ method.

Following is an example calculation using equation 3. Though straightforward and reported previously in the literature (e.g., Wright, 1982; Stegman et al., 1977), it is included here to facilitate later discussion of variations in the method. For the period 8 through 15 June 1988, table 1 shows totals of R = 25.9 mm, I = 19.1 mm, D = 5.74 mm, SMC_f = 232 mm, and SMC_i = 237 mm. Substituting these values in equation 3 gives an ET value of 44.3 mm for lysimeter 1. Lysimeters 2, 3, and 4 had ET values of 29.2, 49.5, and 25.7 mm, respectively, for the same period, resulting in an average ET of 37.2 mm. The $ET_{r(J-H)}$ for this period was 41.18 mm, which gives K_c = 0.90. Each K_c value was referenced to the middle of the time period Δt to reflect the average time since planting for each period. In this example, 12 June 1988 was used. Alternatively, the K_c values could have been referenced to 8 or 15 June 1988. We discuss the implications of these choices below. The date 12 June 1988 corresponds to 45 days past planting (DPP). This produces one (DPP, K_c) data point, namely, (45, 0.90). Additional data points were developed in the

Table 1. Climatic data and lysimeter number one soil water balance for 8 to 15 June 1988

Date	DPP*	R (mm)	T_{min} (°C)	T_{max} (°C)	R_s (MJ m^{-2})	$ET_{r(J-H)}$ (mm)	SMC† (mm)	I (mm)	D (mm)
8	41	0.0‡	10.0	33.3	28.7	7.32‡	237	‡	0.59‡
9	42	0.0	9.4	26.7	30.2	6.60			0.77
10	43	0.0	10.6	31.1	29.4	7.26		19.1	0.98
11	44	0.0	19.4	33.9	27.1	8.30			0.97
12	45	7.9	16.1	27.2	14.7	3.75			0.85
13	46	0.0	15.6	27.2	27.3	6.89			0.86
14	47	18.0	11.7	20.6	12.8	2.55			0.64
15	48	0.0	8.3	26.1	27.8	5.83	232		0.67
Sums	-	25.9	-	-	-	41.18		19.1	5.74

* DPP = Days past planting; R = rainfall, T = temperature, R_s = solar radiation, SMC = soil moisture content, I = irrigation, D = drainage.

† Soil moisture contents were measured to a depth of 2.0 m.

‡ These values are not included in the totals because the water balance is computed between consecutive soil moisture measurements. That is, each soil moisture measurement is assumed to represent an end-of-day condition so it corresponds to that day's totals for R, ET_r, I, and D.

same manner for other periods of soil moisture measurement (Sajid, 1993).

If a large rainfall event during period Δt_1 produces sufficiently large drainage during the next time period Δt_2, a negative K_c value may occur for period Δt_2. The time periods used to calculate K_c values were therefore lengthened to two or more periods of soil moisture measurement, where necessary, to avoid negative K_c values.

When the K_c values were referenced to CGDD since planting, a base temperature of 10°C and no upper limit temperature was used to compute the daily growing degree days.

The crop curves were generated with fifth-order, least squares regression polynomials of K_c versus DPP and K_c versus CGDD for the general form of the polynomial equation:

$$K_c = C_1 + C_2X + C_3X^2 + C_4X^3 + C_5X^4 + C_6X^5 \quad (6)$$

where X is the time base, i.e., DPP or CGDD. The polynomials were constructed by pooling the data sets for

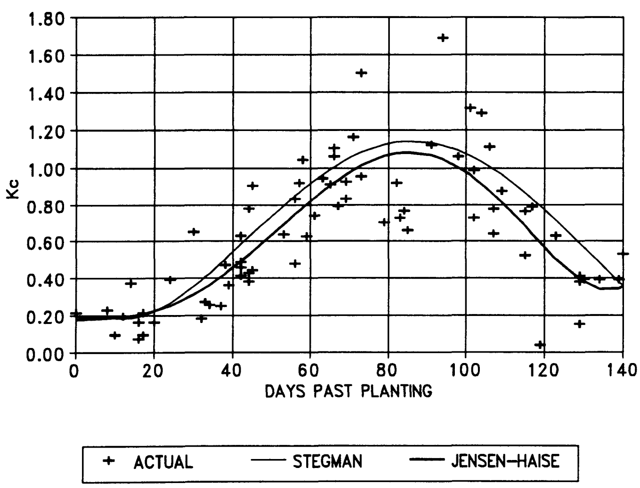

Figure 1–Comparison of crop curves obtained by using the Jensen-Haise equation and polynomial coefficients of Stegman et al. (1977).

all 11 years of the study and then performing least-squares regression. Since crop curves generally have only two or three inflection points, use of a third- or fourth-order polynomial may have been more appropriate, e.g., Stegman et al. (1977) used fourth-order polynomials for their crop curves. We selected a fifth-order polynomial for the following reason. Note the slight rise in our fitted curve for K_c at the end of the season in figure 1. When Sajid (1993) constructed a fourth-order polynomial for K_c = f[DPP, $ET_{r(J-H)}$], it produced a similar, *larger* irregularity at the beginning of the season (not shown in fig. 1), i.e., $K_c \approx 0.36$ at DPP = 0, $K_c \approx 0.19$ at DPP = 8, $K_c \approx 0.15$ at DPP = 16, and then following the seasonal trends. To avoid irregularities such as these, the fifth-order polynomial was chosen for this and the other crop curves.

Results and Discussion

Polynomial coefficients for equation 6 are presented in table 2. The data set of K_c values as a function of DPP and based on the Jensen-Haise (1963) reference ET calculation method will be denoted as K_c = f[DPP, $ET_{r(J-H)}$]. Similarly, we use the notation K_c = f[CGDD, $ET_{r(J-H)}$], K_c = f[DPP, $ET_{r(P-A)}$], and K_c = f[CGDD, $ET_{r(P-A)}$] for the remaining data sets.

The crop curve for K_c = f[DPP, $ET_{r(J-H)}$] and the actual data used to derive it are presented in figure 1. Stegman et al. (1977) developed their crop ET curve polynomials as functions of days past emergence (DPE). For comparison, figure 1 also includes the K_c = f[DPE, $ET_{r(J-H)}$] function developed by Stegman et al. (1977). Normally about 10 to 14 days are required from planting to emergence at this site (e.g., Steele et al., 1994). The curve by Stegman et al. (1977) in figure 1 was adjusted by a shift of 12 days, i.e., to DPP to compare the curves.

Figure 1 shows that our curve is close to the curve Stegman et al. (1977) obtained. Both curves have the same trend during the whole season. The maximum value of the crop coefficient at silking stage is 1.08 at about 85 days after planting compared to the value of 1.14 estimated by

Table 2. Corn crop curve polynomials (Sajid, 1993) based on a pooled data set from 11 years of field data across four nonweighing lysimeters

	Coefficient Values			
	Jensen-Haise Reference ET		Penman-Allen Reference ET	
Coef-ficient*	DPP Base†	CGDD Base	DPP Base	CGDD Base
C_1	0.17549	0.24738	0.089089	0.12083
C_2	0.0017287	–0.0014929	–0.00077211	–0.00063408
C_3	-1.7684×10^{-4}	1.6737×10^{-5}	-2.9627×10^{-5}	1.1449×10^{-5}
C_4	1.3588×10^{-5}	-3.1877×10^{-8}	9.9361×10^{-6}	-2.0619×10^{-8}
C_5	-1.7126×10^{-7}	2.2973×10^{-11}	-1.3538×10^{-7}	1.3525×10^{-11}
C_6	5.9329×10^{-10}	-5.8428×10^{-15}	4.7586×10^{-10}	-3.1228×10^{-15}
R^2	0.679	0.544	0.622	0.521
SE_{Kc}	0.21	0.25	0.24	0.27
N	73	73	68‡	68

* The parameters $C_1, C_2, \ldots C_6$ are coefficients 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.

† Time base abbreviations: DPP = Days Past Planting, CGDD = Cumulative Growing Degree Days since planting.

‡ Fewer data points were available for the Penman-Allen method than for the Jensen-Haise method due to missing wind speed data in 1982.

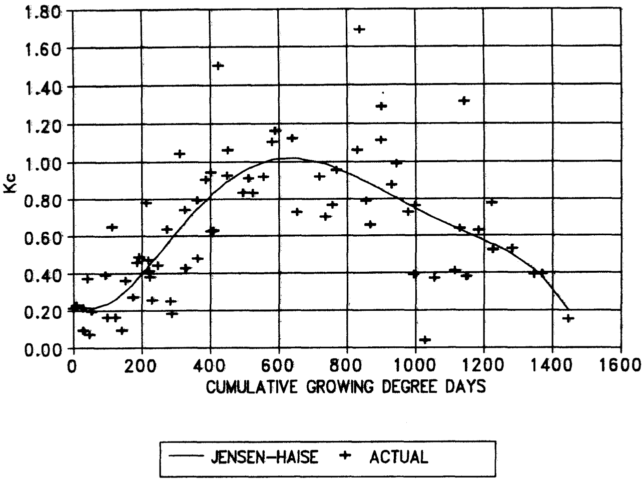

Figure 2–The CGDD crop curve for the Jensen-Haise equation.

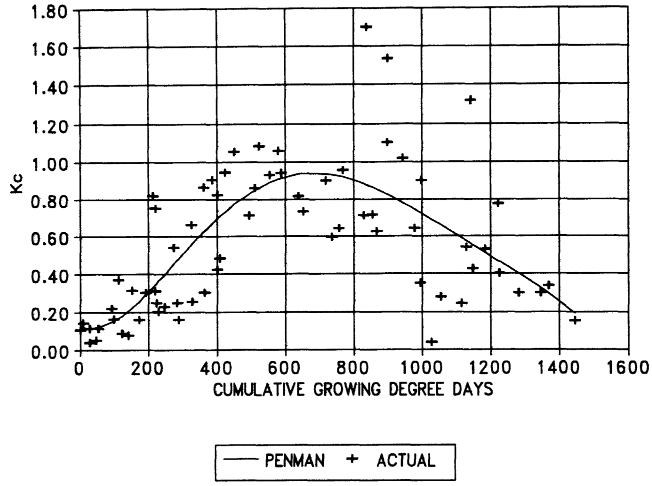

Figure 4–The CGDD crop curve for the Penman-Allen equation.

Stegman et al. (1977) using the same Jensen-Haise equation. This difference in maximum value may be because Stegman et al. (1977) used only three to five years of data to estimate the crop coefficients (for corn and other crops). Moreover, the Stegman et al. (1977) results were based on field measurements of water balances that did not measure deep percolation losses, as was done with the lysimeters; rather, they simply screened their data for suspected runoff and deep percolation losses. Hence, their measured ET values could have included small drainage amounts. The implication for irrigation scheduling is that, compared to our results, the Stegman et al. (1977) curve may overestimate crop water use, thereby resulting in higher irrigation amounts over the season. On the other hand, underestimation of K_c may be more costly than overestimation; underestimation of K_c could result in underirrigation and yield losses, which are more expensive than water costs and leaching losses produced by slightly overirrigating the crop.

Figures 2, 3, and 4 present results from this 11-year study for the K_c = f[CGDD, $ET_{r(J-H)}$], K_c = f[DPP, $ET_{r(P-A)}$], and K_c = f[CGDD, $ET_{r(P-A)}$] data sets, respectively, along with the actual K_c values on which the curves are based. Table 3 shows the seasonal (1 May through 30 September) sums for measured ET, $ET_{r(J-H)}$, and $ET_{r(P-A)}$. Seasonal sums for CGDD and the ratios $ET/ET_{r(J-H)}$ and $ET/ET_{r(P-A)}$ are also shown in table 3 for each year of the study. The ET/ET_r ratios vary substantially between years. The variability may be attributed to the fact that the reference ET methods were not locally developed. We discuss two more limitations of nonweighing lysimeters below.

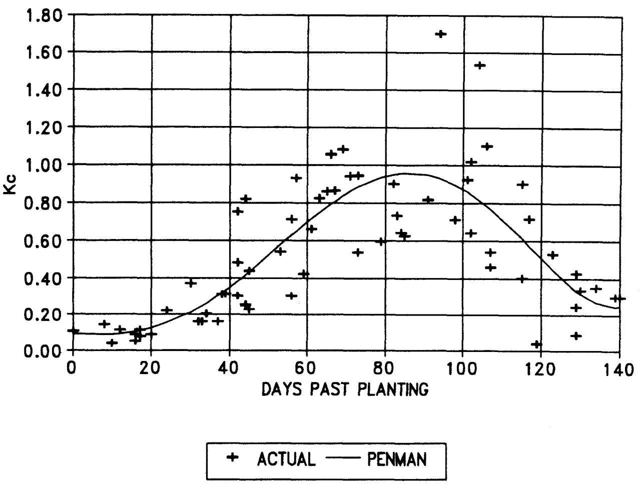

Figure 3–The DPP crop curve for the Penman-Allen equation.

The results indicate that the crop curves based on DPP are more accurate than the curves based on CGDD due to higher r^2 and lower standard errors in the K_c estimates (table 2). However, users of the results may find the CGDD-based curves more useful during unusually warm or cool seasons, when crop development is strongly affected by CGDD. The r^2 values for all four curves are not high, indicating sources of variation that are still unexplained. One source of variability is that due to use of the neutron attenuation for determining soil moisture. For

Table 3. Seasonal sums of CGDD, measured ET, and estimated ET_r for 1981 through 1991 (1 May through 30 September)

Year	Seasonal CGDD (C) (1)	Measured ET (mm) (2)	Estimated ET_r Jensen-Haise (mm) (3)	Estimated ET_r Penman-Allen (mm) (4)	ET/ET_r Jensen-Haise - (2)/(3)	ET/ET_r Penman Allen - (2)/(4)
1981	1230	487	433	280	1.13	1.74
1982	1154	469	455	*	1.03	-
1983	1303	481	479	411	1.00	1.17
1984	1183	504	433	496	1.16	1.02
1985	1072	453	404	455	1.12	1.00
1986	1134	394	416	388	0.95	1.01
1987	1424	401	500	519	0.80	0.77
1988	1546	501	532	791	0.94	0.63
1989	1326	414	485	548	0.85	0.76
1990	1241	338	424	411	0.80	0.82
1991	1396	359	456	432	0.79	0.83
Average	1274	436	456	473	0.96	0.98
S.D.	142	58	39	135	0.14	0.31
Coef of V.	11%	13%	9%	29%	15%	32%
Maximum	1546	504	532	791	1.16	1.74
Minimum	1072	338	404	280	0.79	0.63

* Not available due to missing wind speed data.

example, a 1% error in volumetric water content determination by a neutron probe, over the 2.0 m depth measured in our nonweighing lysimeters, is equivalent to 20 mm water—which is 400 times less accurate than the 0.05 mm detection capability of the weighing lysimeters described by Marek et al. (1988). Another source of variability is the 0.3-m region at the bottom of the lysimeters for which soil moisture contents were not determined.

Crop curves developed from daily water balance data and water balance-based irrigation scheduling methods commonly use daily time steps. For example, Lundstrom and Stegman's (1988) checkbook method predicts soil moisture representing an end-of-day condition. The same end-of-period referencing should not be done for longer time steps because it introduces errors in the resulting crop curves. That is, even though the K_c versus DPP and K_c versus CGDD data developed in this study represent average responses over time periods, each K_c value should be referenced to the middle, rather than the beginning or end, of its time period. Following is an example for the data developed from this study. Referencing each K_c value to the beginning or end of the time period on which it is based, rather than referencing it to the middle of its time period, changes the shape, amplitude, and position of the crop curve. For example, figure 5 shows a comparison of the results of assigning the K_c values to the ending and middle dates of each ET calculation period (e.g., 15 and 12 June 1988, respectively, in the example based on table 1). The later K_c referencing method results in a later peak in the crop curve, which corresponds to a later period of maximum crop water use within the season. The shift in the crop curve to the right (later in time) will reduce its accuracy for use in irrigation scheduling algorithms. Note that in this example, the K_c values are higher at the end of the season for the later K_c referencing method. Other factors excluded, this implies that more water than actually needed by the crop will be applied by the irrigator near the end of the season. If more water than needed is applied, production costs and the potential for leaching of nutrients and chemicals to groundwater increase. Similar problems will occur if the K_c values are referenced to the beginning of each water balance period. Although the effect of this shift may be insignificant if short time periods (e.g., weekly or shorter) are used to calculate all increments in the water balance, we recommend that K_c values be referenced to the middle of the time period over which the water balance is calculated.

Finally, we note a nontrivial detail in reporting the coefficients for crop curve polynomials. Note from table 2 that five significant digits are reported for the coefficients in equation 6, even though the input data (table 1) indicates that two digits should be the expected precision of the crop curve. Five digits are reported to ensure sufficient accuracy in the output polynomials. Since two digits are reported in the SE_{Kc} values (table 2), the polynomial results should not be assumed to be more precise than two significant digits. However, if the user is given only two significant digits for each coefficient, significant errors in the crop curve will result (fig. 6). Figure 6 shows the crop curves resulting from use of the coefficients for K_c = f[DPP, $ET_{r(J-H)}$] in table 2, with the use of two, three, or five significant digits in the coefficients $C_1, C_2, \ldots, C_6$, from equation 6.

Summary

The use of crop curves for irrigation scheduling depends on accurate estimates of crop water use. We have presented four new corn evapotranspiration crop curves based on 11 years of data from four nonweighing lysimeters. The results indicate that the crop curves based on DPP are more accurate than the curves based on CGDD due to higher r^2 and lower standard errors in the K_c estimates (table 2). However, users of the results may find the CGDD-based curves more useful during unusually warm or cool seasons, when crop development is strongly affected by CGDD. The r^2 values for all four curves are not high, indicating sources of variation that are still unexplained. One source of variability is that due to use of the neutron attenuation for determining soil moisture. Another source of variability is the 0.3-m region at the bottom of the lysimeters for which soil moisture contents were not determined. The development of reliable crop curves must be based on procedures which do not produce a bias in numerical descriptions of the underlying data and which produce sufficient numerical precision. We have illustrated calculation procedures for development of crop curves based on nondaily soil moisture measurements from nonweighing lysimeters, a method of referencing each water balance period to the independent variable which

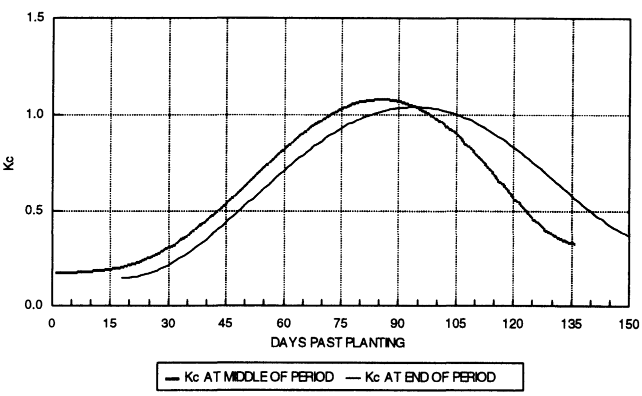

Figure 5–Comparison of methods of referencing K_c values within ET calculation intervals. Referencing K_c values to the end of the periods shifts the crop curve forward (later) in time.

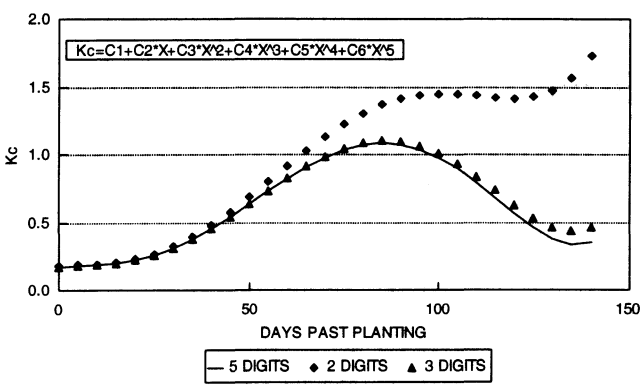

Figure 6–Dependence of crop curves on the number of significant digits in the polynomial coefficients C_1, C_2, etc. The use of three-digit precision produces better results than the use of two-digit precision.

does not bias the resulting crop curve forward or backward in time, and the repercussions of reporting an insufficient number of significant digits in the crop curve polynomial coefficients.

REFERENCES

Allen, R. G. 1986. A Penman for all seasons. *J. Irrig. Drain. Engr.* 112(4):348-368.

Enz, J., C. Brenk, R. Egeberg and D. Rice. 1993. *Weather: Software Users Guide 11*. Fargo: North Dakota Agricultural Weather Network, North Dakota State Univ. Ext. Service.

Jensen, M. E. and H. R. Haise. 1963. Estimating evapotranspiration from solar radiation. *J. Irrig. and Drain. Div. ASCE* 89(IR4):15-41.

Lundstrom, D. R. and E. C. Stegman. 1988. Irrigation scheduling by the checkbook method. Bull. AE-792 (Rev.). Fargo: North Dakota State Univ. Ext. Service.

Marek, T. H., A. D. Schneider, T. A. Howell and L. L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. *Transactions of the ASAE* 31(2):477-484.

Montgomery, B. R., L. Prunty and J. W. Bauder. 1987. Vacuum trough extractors for measuring drainage and nitrate flux through sandy soils. *Soil Sci. Soc. Am. J.* 51(2):271-276.

Prunty, L. and B. R. Montgomery. 1991. Lysimeter study of nitrogen fertilizer and irrigation rates on quality of recharge water and corn yield. *J. Environ. Qual.* 20(3):373-380.

Sajid, A. H. 1993. Corn crop curve development by nonweighing lysimeter water balance at Oakes, North Dakota. Unpub. M.S. thesis, North Dakota State Univ., Fargo.

Steele, D. D., E. C. Stegman and B. L. Gregor. 1994. Field comparison of irrigation scheduling methods for corn. *Transactions of the ASAE* 37(4):1197-1203.

Stegman, E. C., A. Bauer, J. C. Zubriski and J. Bauder. 1977. Crop curves for water balance irrigation scheduling in south eastern North Dakota. Research Report No. 66. Fargo: Agricultural Exp. Station, North Dakota State Univ.

Stegman, E. C. and D. A. Coe. 1984. Water balance irrigation scheduling based on Jensen-Haise equation: Software for Apple II, II+, and IIE Computers. Research Rep. No. 100. Fargo: North Dakota Agricultural Exp. Station, North Dakota State Univ.

Stegman, E. C. 1988. Corn crop curve comparisons for the Central and Northern Plains of the U.S. *Applied Engineering in Agriculture* 4(3):226-233.

Wright, J. L. 1982. New evapotranspiration crop coefficients. Am. Soc. Civ. Engr., *J. Irrig. Drain. Div.* 108(IR1):57-74.