FIELD COMPARISON OF IRRIGATION SCHEDULING METHODS FOR CORN

D. D. Steele, E. C. Stegman, B. L. Gregor

ABSTRACT. *Irrigation scheduling for corn requires knowledge of methods for timing irrigation applications. A three-year field plot study of irrigation scheduling methods for corn was undertaken on a sandy loam soil near Oakes, North Dakota, using a randomized block design. The study was designed to assess the influence of the methods on grain yields and total irrigation amounts applied. The reference irrigation timing method was based on allowable root zone available water depletion (40%). The other irrigation timing methods used were: partial evapotranspiration (ET) (0.5 × ET) replacement, crop water stress index (CWSI of 0.2, 0.4, and 0.6), measured soil matric potential (30 and 50 kPa), and growth model (CERES-Maize) estimates of dry matter accumulation and water use. In terms of crop yield per unit ET, the best method was the 50-kPa treatment. The 50-kPa method resulted in the maximum average yield of 12 200 kg ha^{-1} while achieving a statistically significant average reduction of 139 mm (40%) in irrigation application compared to the reference treatment. The nonreference methods, except for CWSI = 0.6, appear to offer the potential for significant irrigation water savings without significant yield reductions. The 0.6 CWSI treatment suffered a statistically significant yield reduction of 1 600 kg ha^{-1} (13%).*

Keywords. *Growth model, Plant temperature, Soil moisture, Water use efficiency, Crop water stress index.*

Martin et al. (1990) reviewed irrigation scheduling principles. In general, methods of irrigation scheduling can be classified as plant-, soil-, or climate-based, or combinations. Phene et al. (1990) reviewed plant-based methods for irrigation scheduling. These methods have used various measurements, including infrared canopy temperature sensing (Calle et al., 1990; Jackson, 1982; Nielsen and Gardner, 1987; Stegman and Soderlund, 1992), leaf xylem pressure (Stegman, 1983), sap flow rates, leaf cell-sap concentration (Brici, 1984), stem diameter, and stomatal resistance.

Soil-based methods for irrigation scheduling typically measure or infer the water content of the soil or the matric potential of the soil water (Phene et al., 1990). Water content determinations are made either directly or indirectly through methods such as gravitational measurement, neutron attenuation, time domain reflectometry, or frequency domain reflectometry. Matric potential determinations are commonly made with soil moisture blocks, tensiometers, thermocouple psychrometers, or heat dissipation blocks.

Climate-based methods for irrigation scheduling typically use climatological parameters to estimate potential evapotranspiration (ET) for a "well-watered" crop and use site-specific crop coefficient curves to further refine crop water use estimates. Intermittent measurements frequently reference these methods to actual soil or plant water status.

Growth model applications to irrigation scheduling have been made for various crops (Hill et al., 1983; Kundu et al., 1982; and Raju et al., 1983). Specific applications include corn (Stegman and Heermann, 1990; Stockle and James, 1989), potatoes (Trooien and Heermann, 1988; Singh et al., 1989), and soybeans (Fortson et al., 1987).

Camp et al. (1988) compared three irrigation scheduling methods for corn and soybeans in South Carolina, using tensiometers, evaporation pans, and a water balance procedure. The scheduling methods showed no significant differences in yield or irrigation amount for corn. Cassel et al. (1985) compared irrigation scheduling with tensiometers and a water balance model in North Carolina and found no significant differences in corn grain yield between the scheduling methods.

Field et al. (1988) used a water balance model to evaluate three commercial scheduling services in Washington. The services used gravimetric soil sampling, neutron probe measurement of soil water, and crop curves to schedule irrigations. They also evaluated scheduling irrigations according to stress day and yield reduction indices. Their analysis indicated that careful management of deficit irrigation, using the indices, can substantially increase net economic returns for irrigation of corn.

Stegman (1986) compared corn yields under water balance irrigation scheduling approaches, strategies simulating inadequate irrigation system capacity, crop water stress index, measured and predicted leaf water potentials, and dryland conditions in a North Dakota study.

Article was submitted for publication in December 1993; reviewed and approved for publication by the Soil and Water Div. of ASAE in June 1994. Presented as ASAE Paper No. 92-2605.

Research supported by North Dakota Agricultural Experiment Station Project 1446 and by the U.S. Department of Interior, Bureau of Reclamation. Use of equipment and trade names does not constitute endorsement by North Dakota State University or the U.S. Bureau of Reclamation; names are provided for information only.

The authors are **Dean D. Steele**, *ASAE Member Engineer*, Assistant Professor, **Earl C. Stegman**, *ASAE Member Engineer*, Professor and Chair, and **Brian L. Gregor**, *ASAE Member Engineer*, Graduate Student, Agricultural Engineering Dept., North Dakota State University, Fargo.

He reported that scheduling methods could reduce irrigation applications by about 23 and 30% for coarse and medium textured soils, respectively, compared to full irrigation regimes, with yield losses of approximately 5%.

The objective of this study was to determine if irrigation timing, based on plant temperature, measured soil matric potential (SMP), growth model (CERES-Maize) predicted dry matter accumulation and irrigation requirements, and partial ET replacement, could significantly reduce seasonal irrigation application amounts compared to fully irrigated regimes, while maintaining comparable corn grain yields.

METHODS

Field plot experiments were conducted near Oakes, North Dakota (47°31′N Lat, 98°5′W Long, and 399 m elevation), in 1989, 1990, and 1991. The climate is subhumid. The predominant soil type is Maddock sandy loam. The average measured plant available water content was 114 mm for the estimated 1.2-m mature plant rooting zone depth. Plant available water holding capacity was based on field capacity measurements and measured soil water depletion levels. Field capacity was determined from measurements taken two to four days after a rainfall or irrigation event nearly saturated the soil profile. The maximum plant available soil water depletion level was determined from measurements taken during periods of severe plant water stress when no further soil water depletion was observed.

Individual plots were 6 m wide × 12 m long. Rows were orientated E-W with a 0.61-m row spacing. Fertilizer, herbicide and insecticide selection, and application rates were based on North Dakota State University Best Management Practices recommendations (table 1).

Table 1. Experimental agronomic data

Parameter	1989	1990	1991
Variety	Pioneer 3737	Pioneer 3737	Pioneer 3737
Population	7.4 plants m^{-2}	7.4 plants m^{-2}	7.4 plants m^{-2}
N Applications	kg N ha^{-1} (Date)	kg N ha^{-1} (Date)	kg N ha^{-1} (Date)
Preplant (46-0-0)	75.1 (4/17)	53.0 (4/30)	56.0 (5/8)
Top Dress (46-0-0)	56.0 (6/20,6/25)*	56.0 (7/19)	56.0 (6/13) 56.0 (7/2)
Herbicide	Rate (Date)	Rate (Date)	Rate (Date)
Cyanazine (Bladex DF)	1.55 kg ha^{-1} (5/6)	1.57 kg ha^{-1} (5/6)	No Application
Metolachlor (Dual PE)	2.34 L ha^{-1} (5/6)	2.34 L ha^{-1} (5/6)	No Application
Bromoxynil octanoate (Buctril)	1.75 L ha^{-1} (5/30)	No Application	No Application
Insecticide	Rate (Date)	Rate (Date)	Rate (Date)
Chlorpyrifos (Lorsban)	No Application	4.68 L ha^{-1} (5/3)	4.67 L ha^{-1} (5/7)
Growth Stage			
Planting	5/1	5/13	5/18
Emergence	5/14	5/17	5/18
Tasseling	7/16	7/21	7/12
Silking	7/19	7/25	7/18
Black Layer	9/5	9/6	9/15
Harvest	9/20	9/15	9/23

* No significant yield differences from split application were found.

Each field plot was trickle irrigated with thin-wall tubing placed on the soil surface between rows. Irrigation water, applied to each plot at 0.19 L/s, was metered to quantify the actual irrigation application. Maximum irrigation amounts were determined from the water balance model estimated root zone depletion levels for each event. The actual irrigation application amount was determined by decreasing the maximum irrigation amount 13 mm to provide limited storage capacity for small rainfall events.

WATER MANAGEMENT TREATMENTS

Eight irrigation timing methods were replicated three times in a randomized block design (table 2). The randomized block design was used to block against a north-to-south gradient in the soil available water holding capacity.

Plots in treatment T1 were irrigated when available soil water reached 40% depletion (40% D). Soil water content measurements were used to schedule irrigations, based on root zone available water depletion. This treatment was intended to be the wettest, i.e., the reference regime.

Plots in treatment T2 were irrigated with the experimental objective of replacing one-half of the estimated ET (0.5 × ET). A model, using ET estimates based on the Jensen-Haise (1963) equation and a corn crop curve developed for southeastern North Dakota (Stegman et al., 1977), was used to schedule irrigations. The model was updated each Monday morning throughout the growing season.

Plots in treatment T3, T4, and T6 were irrigated using crop water stress index (CWSI) criteria. The CWSI represents a normalized crop stress indicator based on the measured difference between canopy and air temperatures. The CWSI computation procedure used in this research was the same as that used by Stegman and Soderlund (1992):

$$\mathrm{CWSI} = [\,(T_c - T_a) - (T_c - T_a)_{LL}\,] \,/\, [\,(T_c - T_a)_{UL} - (T_c - T_a)_{LL}\,] \quad (1)$$

in which T_c and T_a are canopy and air temperatures, respectively (° C); and $_{LL}$ and $_{UL}$ represent lower and upper limits or baselines of crop water stress, respectively. The lower limit represents a relationship between $(T_c - T_a)$ and vapor pressure deficit (VPD, kPa) for a well-watered or nonstressed crop. The upper limit represents a relationship between $(T_c - T_a)$ and VPD for a severely stressed or nontranspiring crop. Plots in treatment T3, T4, and T6 were

Table 2. Water management criteria for attainment of selected stress levels in corn

Treatment	Description
T1	Allowable root zone depletion exceeded 40%
T2	0.5 predicted ET replacement (weekly)
T3	0.2 crop water stress index exceeded
T4	0.4 crop water stress index exceeded
T5	Soil water tension exceeded 50 kPa
T6	0.6 crop water stress index exceeded
T7	Soil water tension exceeded 30 kPa
T8	PL* to 1st irr: Delay 1st irr until predicted DM falls 15% behind that for T1. then 1st irr to BGF: 1.0 ET replacement rate then BGF to harvest: 0.6 CERES-Maize estimated available water depletion in the root zone.

* PL = planting; DM = dry matter; BGF = beginning grain fill.

irrigated when crop water stress index (CWSI) values exceeded 0.2, 0.4, and 0.6, respectively.

Plots in treatment T5 were irrigated when soil water tension at 0.3-m depth exceeded 50 kPa. Similarly, plots in treatment T7 used the irrigation timing criteria of 30 kPa. The reader should note that although treatments T5 and T7 may be similar to treatment T1, depending on the soil water characteristic, the objective of this study was to use two methods (neutron probe and tensiometers) to arrive at an irrigation decision, not to maintain similar soil moisture conditions. The former does not depend on knowledge of the soil water characteristic, while the latter does. Thus an advantage of the methods used here is that they should be more widely applicable, i.e., to situations where soil water characteristic data are not available.

Plots in treatment T8 were irrigated using the crop growth model CERES-Maize (CM) (Jones and Kiniry, 1986). The growing season was divided into three stages. The first stage lasted from planting (PL) until first irrigation. The first irrigation was applied when the predicted above-ground dry matter accumulation in the as-yet unirrigated plots fell to 85% of the value CERES-Maize predicted for the "nonstressed" treatment T1. During the second stage, lasting from the first irrigation until the beginning of grain fill (BGF), irrigations were scheduled to fully replace model-predicted ET, to meet critical water needs during reproductive stages. In the third stage, lasting from the beginning of grain fill to harvest, irrigations were scheduled to replace 60% of model-predicted ET. Third-stage irrigations were reduced to both decrease irrigation input costs and to increase off-season soil water storage capacity and thereby minimize water and chemical leaching losses.

MEASUREMENTS

Estimated root zone water depletion levels were verified weekly using the neutron attenuation method (Troxler, model 105A, Lakewood, Colo.) of soil water measurement. Measurements were taken in replications 2 and 3, for all treatments, at depths of 0.15, 0.30, 0.61, 1.2, and 1.5 m.

Soil matric potentials were measured manually each day in treatments T5, replicates 1 and 3, and treatment T7, replicates 2 and 3. The tensiometers (Irrometer IRR-RSR, Riverside, Calif.) were installed at 0.30-m depth in the crop row. In plots in which tensiometers were used, one instrument per plot was used.

The CWSI was based on ambient air VPD and canopy-air temperature differences for treatments T1, replicate 2; T3, replicate 3; T4, replicates 2 and 3; and T6, replicates 1 and 3. In this experiment, only certain replications were used for measurement because of limitations in available equipment and labor. One strategy to overcome this limitation was to move instrumentation such as infrared temperature (IRT) sensors from one rep to another. After a given CWSI plot was irrigated, the IRT sensor for that rep was not needed in that plot for a period of time and thus could be moved to another replication.

The lower CWSI baseline was derived from data taken from plots when water stress was minimal, i.e., when the soil was near field capacity. A nonstress CWSI baseline developed in 1989 had the following form:

$$T_c - T_a = 2.14 - 1.97\,\mathrm{VPD} \tag{2}$$

An upper CWSI baseline of 5° C was used.

Canopy temperatures were measured with 15° field of view, noncontacting infrared temperature sensors (Everest models 4000 and 4002, Tustin, Calif.) that detected the 8- to 14-µm band wave lengths, using an emissivity of 0.98. The canopy temperature sensors were positioned above the crop in an S-N orientation, using a 30° angle of depression. Total solar radiation intensity (Licor LI-200S Pyranometer, Lincoln, Nebr.) and net radiation (Thornthwaite Net Radiometer) were measured over the crop canopy. Relative humidity and ambient air temperature were measured at a 2-m height over the crop (Campbell Scientific Inc., Logan, Utah).

Vapor pressure deficit was estimated from the measured relative humidity and the saturation vapor pressure calculated from air temperature data (Lowe, 1977). Instantaneous values for net radiation, total solar radiation, relative humidity, ambient air temperature, canopy temperature, and estimated VPD were collected at 20-s intervals and averaged over a 5-min period with a datalogger (Campbell Scientific, Inc. 21X). Accumulated data were transferred by telephone modem to an office-based computer each day. Each morning, the data were analyzed, using microcomputer software to determine the CWSI, and appropriate irrigation instructions were telephoned to an on-site technician.

Meteorological data, used for modeling, were obtained from a weather station (Campbell Scientific, Inc. CR21) permanently located at the experimental site. Average hourly measurements and daily minimum/maximum values were recorded for ambient air temperature, relative humidity, wind speed (Met One Instruments 014 Wind Speed Sensor, from Campbell Scientific, Inc.), wind direction (Met One Instruments 024 Wind Direction Sensor), and solar radiation (Licor LI-200 Pyranometer). Daily totalized values were recorded for solar radiation, precipitation (Campbell Scientific, Inc. TE525 Tipping Bucket Rain Gage), and wind run (computed). Accumulated data were transferred automatically to an office-based microcomputer, via telephone modem, and summaries were printed out each day.

Phenological development was estimated visually, based on the Hanway (1966) corn growth scale. Stover and grain dry matter were measured weekly for treatments T1, T2, T5, and T8. Final corn grain yield determinations were made by hand harvesting two 9-m rows per plot. The yield data were standardized to 15.5% wet basis moisture content for comparison.

Analysis of variance (ANOVA) was performed on corn grain yields for each season. The Least Significant Difference (LSD) test used was the Waller-Duncan K-ratio t test, with an $\alpha = 0.05$ level of significance. Unless otherwise noted in the remainder of this article, use of the word "significant" and its derivatives is in their statistical sense, according to this t test.

RESULTS AND DISCUSSION

WEATHER

Precipitation totals were 9 mm above normal for 1989, 63 mm below normal for 1990, and 5 mm above normal for 1991 (table 3). Average ambient air temperatures for May through September were 4, 1, and 6° C above normal in

Table 3. Summary of precipitation for the 1989-1991 growing seasons

Month	30-yr Avg. (mm)	1989 Amount (mm)	1989 Dev.* (mm)	1990 Amount (mm)	1990 Dev. (mm)	1991 Amount (mm)	1991 Dev. (mm)
May	68	35	–33	6	–62	91	+23
June	90	34	–56	98	+9	134	+45
July	60	105	+45	36	–24	54	–6
Aug.	62	117	+55	61	–1	22	–40
Sept.	49	47	–2	65	+16	33	–16
Total	329	338	+9	267	–63*	335†	+5

* Deviation.

† Monthly values reported to nearest integer; totals computed before rounding.

Table 4. Summary of average air temperatures for the 1989-1991 growing seasons

Month	30-yr Avg. (° C)	1989 Avg. (° C)	1989 Dev.* (° C)	1990 Avg. (° C)	1990 Dev. (° C)	1991 Avg. (° C)	1991 Dev. (° C)
May	13	14	+1	13	0	16	+3
June	18	18	0	19	+ 1	20	+2
July	22	24	+2	21	–1	21	–1
Aug.	21	21	0	21	0	22	+1
Sept.	14	15	+1	15	+1	15	+1

* Deviation.

1989, 1990, and 1991, respectively (table 4). The normal precipitation and ambient air temperatures represent long-term monthly average values for the 1951-1980 period (USDC, 1982).

Crop and Soil Responses

The experimental objective of having the 40% depletion treatment as the wettest was attained for each year of the study. The CWSI values could not be obtained until full canopy cover was reached (e.g., V9 growth stage in 1989), due to soil background interference in IRT sensing. The soil profile water contents at this site are generally at or near field capacity at the beginning of the growing season from off-season precipitation, regardless of irrigation management the previous year.

Yield Responses

Treatment averages for applied irrigation amounts, seasonal ET estimates, and corn grain yields for each year are summarized in table 5.

For the 1989 season, yields for all treatments except T2 did not differ significantly from one another. The 40% depletion treatment had the highest applied irrigation amount, estimated ET, and grain yield for 1989. The 0.5 × ET replacement treatment had a 7% yield reduction and a 52% irrigation application reduction. The 0.2-, 0.4-, and 0.6-CWSI treatments had yield reductions of 3, 4, and 4%, respectively, compared to the maximum yield, and irrigation application reductions of 35, 50, and 56% compared to the maximum. The 50- and 30-kPa SMP treatments had yield reductions of 2 and 4%, respectively, relative to the maximum, and irrigation application reductions of 51 and 40%, compared to the maximum. The CERES-Maize growth model treatment had a yield reduction of 2% from the maximum yield and an irrigation reduction of 39%.

The grain yields in the 1990 season varied more than in 1989. The 40% depletion treatment had the highest applied irrigation amount and estimated ET for 1990, with a 2% yield reduction compared to the 1990 maximum yield. The 0.5 × ET replacement treatment had a 13% yield reduction and a 44% irrigation application reduction. The 0.2-CWSI treatment had the yield maximum, with a 31% reduction in irrigation application. The 0.4- and 0.6-CWSI treatments had yield reductions of 7 and 12%, respectively, and irrigation application reductions of 43 and 46%, respectively. The 30-kPa SMP treatment had a yield reduction of 5% and an irrigation application reduction of 14%. The 50-kPa treatment had the yield maximum, yet it had a 26% irrigation application reduction. The yield for the 50-kPa treatment was not significantly greater than those for the following treatments: 0.2 CWSI, 40% depletion, 30 kPa, and CERES-Maize. The CERES-Maize growth model treatment had a yield reduction of 5% and an irrigation reduction of 23%.

As in 1990, the grain yields in the 1991 season varied more than in 1989. The 40% depletion treatment had the highest applied irrigation amount and estimated ET for 1991, but suffered an 11% yield reduction compared to the 1991 maximum yield. The 0.5 × ET replacement treatment had a 5% yield reduction and a 43% irrigation application reduction. The 0.2-, 0.4-, and 0.6-CWSI treatments had yield reductions of 4, 15 and 25%, respectively, and irrigation application reductions of 15, 33, and 62%, respectively. The 30-kPa treatment had a yield reduction of 2% and an irrigation application reduction of 30%. The 50-kPa treatment had the yield maximum, with a 39%

Table 5. Summary of irrigation amounts, ET estimates, and grain corn yields by irrigation treatment for individual years

Treatment	1989 Irr. (mm)	1989 Est. ET (mm)	1989 Grain Yield* ($kg\ ha^{-1}$)	1990 Irr. (mm)	1990 Est. ET (mm)	1990 Grain Yield* ($kg\ ha^{-1}$)	1991 Irr. (mm)	1991 Est. ET (mm)	1991 Grain Yield* ($kg\ ha^{-1}$)
T1 40% D	432	514	13 500 a	311	448	10 800 ab	292	470	11 000 bc
T2 0.5 × ET	206	474	12 600 b	173	420	9 540 d	165	434	11 800 abc
T3 0.2 CWSI	279	494	13 100 ab	216	443	11 000 a	248	465	11 900 abc
T4 0.4 CWSI	216	482	12 900 ab	178	423	10 200 bc	197	437	10 600 cd
T5 50 kPa	210	471	13 200 ab	229	438	11 000 a	178	434	12 400 a
T6 0.6 CWSI	191	486	12 900 ab	169	411	9 640 cd	110	397	9 340 d
T7 30 kPa	260	493	13 000 ab	267	442	10 500 abc	203	452	12 200 ab
T8 C-M	262	479	13 200 ab	239	434	10 500 abc	191	445	11 300 abc

* Yields for treatments with the same letter in the same year do not differ significantly at the $\alpha = 0.05$ level. The yield LSD values were 610 kg/ha, 778 kg/ha, and 1330 kg/ha for 1989, 1990, and 1991, respectively.

irrigation application reduction. The CERES-Maize growth model treatment had a yield reduction of 9% and an irrigation reduction of 35%.

The 50-kPa treatment yields exceeded the 30-kPa treatment yields every year of the experiment, the opposite of what would be expected, since a greater level of water stress was imposed on the 50-kPa treatment than on the 30-kPa treatment. However, the yield differences were not significant in any year.

The CWSI treatment yields in 1989 did not differ significantly from one another. In 1990 and 1991, the CWSI treatment yields were inversely related to the stress level imposed. Moreover, in both 1990 and 1991, the 0.4- and 0.6-CWSI treatments yielded significantly less than the 0.2-CWSI treatment, but the differences in yields between the 0.4-CWSI and 0.6-CWSI treatments were not significant.

The 40% depletion treatment was given significantly higher applications of irrigation than all other treatments for the three-year period (table 6). No significant yield reduction occurred under any irrigation treatment, except for the 0.6-CWSI method. The CWSI treatments were given less water as the CWSI level increased, as would be expected. The 0.4- and 0.6-CWSI treatments were given significantly smaller irrigation amounts than the 0.2-CWSI treatment, but the difference between the irrigation applications for the 0.4- and 0.6-CWSI treatments was not significant. The 30-kPa SMP treatment was given more irrigation than the 50-kPa SMP treatment, again an expected result. The 30- and 50-kPa treatments did not differ statistically from one another in irrigation application amount, ET estimate, or yield. The 0.5 × ET replacement treatment was in the lowest irrigation amount and ET estimate groupings, yet did not suffer significant yield reductions compared to the reference irrigation regime. The CERES-Maize treatment resulted in significant reductions in irrigation amount compared to the reference regime, yet significantly less water was applied to the 0.5 × ET and 0.6-CWSI treatments than the CERES-Maize treatment. The yield for plots treated with the CERES-Maize scheduling method did not differ significantly from the reference treatment.

Table 6. Summary of average irrigation amounts, ET estimates, and grain yields for the three-year period

Treatment		Irrigation		Estimated ET		Grain Yield	
		Amount* (mm)	Relative†	Amount (mm)	Relative	Amount (kg/ha)	Relative
T1	40% D	345 a	1.00^1	477 a	1.00^1	11 700 a	0.96^3
T2	0.5 × ET	181 d	0.52^7	443 de	0.93^7	11 300 ab	0.93^4
T3	0 2 CWSI	248 b	0.72^2	467 ab	0.98^2	11 900 a	0.98^2
T4	0.4 CWSI	197 cd	0.57^6	447 cde	0.94^6	11 200 ab	0.92^5
T5	50 kPa	206 bcd	0.60^5	448 cde	0.94^5	12 200 a	1.00^1
T6	0.6 CWSI	157 d	0.46^8	431 e	0.90^8	10 600 b	0.87^6
T7	30 kPa	243 bc	0.70^3	462 abc	0.97^3	11 900 a	0.98^2
T8	C-M	231 bc	0.67^4	453 bcd	0.95^4	11 700 a	0.96^3

* Treatments with the same letter in each category do not differ significantly at the $\alpha = 0.05$ level. The applied irrigation, estimated ET, and grain yield LSD values were 49.2 mm, 18.4 mm, and 981 kg/ha, respectively.

† The maximum value is assigned a value of 1.00; other values are fractions of the maximum, e.g., applied irrigation for T2 is 181/345 = 0.52. Ranks are shown as superscripts, e.g., 1.00^1 is the top ranking relative value.

The ranking of treatment averages for estimated ET was the same as the ranking of treatments for irrigation application amounts (table 6). The irrigation application of 345 mm for the 40% depletion treatment (T1) was 113 mm greater than the average (232 mm) of the next-highest LSD grouping of irrigation application amounts for treatments T3, T5, T7, and T8. The average of the highest ET estimate LSD grouping (for T1, T3, and T7) was 469 mm, which is 27 mm higher than the average (442 mm) of the lowest ET estimate LSD grouping (for T2, T4, T5, T6).

The yield for the 40% depletion treatment for the three-year period was not significantly greater than any other treatment, except for the 0.6-CWSI treatment. The increased water inputs and general lack of yield advantage for the 40% depletion treatment combine to produce a reduction in net profit for this irrigation scheduling practice compared to the other treatments.

The yearly treatment-average grain yields were reasonably well correlated to estimated ET (fig. 1). The slope of the regression of grain yield versus ET was significantly different from zero, according to a t-test at the $\alpha = 0.01$ level (Miller and Freund, 1977). The regression produced an R^2 of 0.78 and a standard error (SE) in the yield estimates of 626 kg ha^{-1}. The ET was generally dependent on the year, as expected, since the Jensen-Haise (1963) potential ET is a function of solar radiation and temperature. The year-to-year dependence of grain yield on ET is shown by the general clustering of each year's data in figure 1. The lowest yield in 1989 exceeded the highest yields in both 1990 and 1991, while the lowest ET estimate in 1989 exceeded the highest ET estimates in both 1990 and 1991.

A physiologic water use efficiency, or ET ratio (Stanhill, 1986), defined as grain yield per unit area per unit ET, did not differ appreciably between treatments (table 7). The overall average ET ratio was 25.5 kg ha^{-1} mm^{-1}. The 50-kPa treatment had the highest average ET ratio for all three years in the study, as well as the highest ET ratio for every individual year in the study.

The average ET ratio for the 40% depletion treatment, which was designed to have no water stress and attain maximum yields, was 24.6 kg ha^{-1} mm^{-1}. A line through

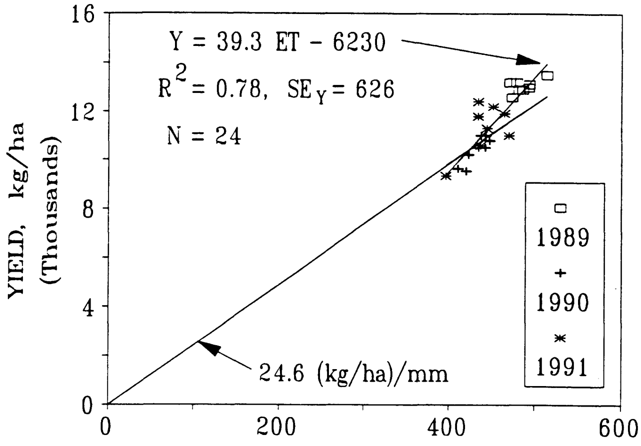

Figure 1–Grain yield response to evapotranspiration.

Table 7. Evapotranspiration ratios for 1989-1991 corn at Oakes, N.D.

Treatment	ET Ratio (Yield/ET) (kg ha^{-1} mm^{-1}) 1989	1990	1991	Average
T1 40% D	26.3	24.1	23.4	24.6
T2 0.5 × ET	26.6	22.7	27.2	25.5
T3 0.2 CWSI	26.5	24.8	25.6	25.6
T4 0.4 CWSI	26.8	24.1	24.3	25.0
T5 50 kPa	28.0	25.1	28.6	27.2
T6 0.6 CWSI	26.5	23.5	23.5	24.5
T7 30 kPa	26.4	23.8	27.0	25.7
T8 C-M	27.6	24.2	25.4	25.7

the origin and with slope 24.6 kg ha^{-1} mm^{-1} is plotted in figure 1; data points above the line represent higher ET ratios and points below the line represent lower ET ratios (Eck, 1986). Comparable ET ratios in the literature for nonwater-stressed corn were reported by Musick and Dusek (1980) as follows: 15.6 kg ha^{-1} mm^{-1} at Prossr, Washington, in 1952; 17.0 kg ha^{-1} mm^{-1} at Davis, California, in 1972; and 22.2 and 17.2 kg ha^{-1} mm^{-1} in the northern Negev of Israel in 1969 and 1970, respectively.

A brief review of research from the Great Plains reveals ET ratios ranging from 8.4 to 24.1 kg ha^{-1} mm^{-1}, with a general increase in ET ratio as one moves northward (table 8). Lower seasonal ET for our study may be attributed to method of irrigation, soil type, and climate. The surface irrigation methods on the relatively slow infiltration rate soils in Texas permit higher evaporative losses than would be expected under a drip irrigation system on the higher infiltration-rate soil at our site.

Corn grain yields appear to be somewhat less sensitive to ET reductions in the Northern Great Plains than in the Southern Great Plains. In a three-year study in Texas, Musick and Dusek (1980) reported a linear yield (kg ha^{-1}) versus ET (mm) relationship of Y = 24.1 ET – 8332, with R^2 = 0.68. With their maximum ET of 789 mm, the maximum grain yield would be estimated as 10 680 kg ha^{-1}. Five and 10% reductions from maximum ET would result in 9 and 18% yield reductions, respectively. Based on the Y versus ET regression relationship presented in fig. 1, 5 and 10% reductions from the maximum ET of 514 mm would result in 7 and 15% yield reductions, respectively. In an earlier ND study, Stegman (1982) presented the equation Y = 28 ET – 3760, with R^2 = 0.71. Using this equation, 5 and 10% reductions from the maximum ET of 549 mm would result in 7 and 13% yield reductions, respectively.

Table 8. Evapotranspiration ratios for irrigated corn on the Great Plains

Citation (Location) (Notes)	Non-Water-Stressed Treatment Yield (kg ha^{-1})	Seas. ET (mm)	ET Ratio (kg ha^{-1} mm^{-1})	Irrigation Method	Study Years
Eck, 1986 (Tex.)	9110	912	8.4-14.3	Graded and Level Border	1976-1979
Musick & Dusek, 1980 (Tex.)	9520-10 850	677-789	12.5-14.6	Level Border	1975-1977
Hattendorf et al., 1988 (Kans.)	7550	565	13.4	Basin	1981-1982
Stegman, 1986 (Oakes, N.D.)	10 800	503	21.5	Sprinkle and Trickle	1981-1983
Stegman, 1986 (Carrington, N.D.)	9020	450	20.0	Trickle	1981-1983
Hatilitgil et al., 1984 (Nebr.) (Irr. Rate Study)	13 600	563	24.1	Diked Basins	1978-1979
Hatilitgil et al., 1984 (Nebr.) (Irr. Timing Study)	12 600	551	22.9	Diked Basins	1978-1979
Steele et al., 1994 (Oakes, N.D. — this study)	11 700	477	24.6	Trickle	1989-1991

A hydrologic water use efficiency (HWUE), defined as the fraction of water applied which was beneficially used by the crop [ET/(irrigation + rain)], was smaller for the 40% depletion treatment than for the other treatments (table 9). The three-year average HWUE (0.73) for the 40% depletion treatment was virtually identical to the HWUE (0.74) of a reference treatment of 30 to 40% depletion used by Stegman (1986) in a 1981-1983 study of corn at the Oakes, North Dakota site, indicating that the reference treatment was reliably reproduced. At the Oakes site, average May through September rainfall was 273 and 313 mm for the 1981-1983 and 1989-1991 periods, respectively. Rainfall supplied 54 and 65% of the ET for the reference treatments in the 1981-1983 and 1989-1991 periods, respectively. These data indicate that relatively greater irrigation water savings without yield losses could be achieved in the 1989-1991 period than could be achieved in the 1981-1983 period. With the 50-kPa treatment, no yield reduction occurred with a 40% irrigation reduction in the present study (1989-1991), while Stegman (1986) obtained 5% yield reduction with a 23% irrigation reduction in the 1981-1983 period.

As the HWUE increases, less water is lost to deep percolation during the season, thereby reducing the potential for chemical leaching to the groundwater. On this basis, we expect the greatest potential for chemical leaching to groundwater to occur with the 40% depletion treatment. Prunty and Montgomery (1991), in a nonweighing lysimeter study at the Oakes site, reported that increased irrigation applications led to higher nitrogen fluxes below the soil profile, but not to higher corn grain yields. Over the three-year period, the 0.6-CWSI treatment had the highest average hydrologic water use efficiency, at the expense of a significant yield reduction.

SUMMARY

This study indicates that significant irrigation water savings can be achieved without significant corn grain yield reductions in the Northern Great Plains. In terms of crop yield per unit ET, the best irrigation scheduling method was the 50-kPa treatment. The 50-kPa method resulted in the maximum average yield of 12 200 kg ha^{-1} while achieving a statistically significant average reduction of 139 mm or 40% in irrigation application compared to

Table 9. Hydrologic water use efficiencies

Treatment	Hydrologic Water Use Efficiency ET/(Rain+Irrigation) 1989	1990	1991	Average
T1 40% D	0.67	0.78	0.75	0.73
T2 0.5 × ET	0.87	0.95	0.87	0.90
T3 0.2 CWSI	0.80	0.92	0.80	0.84
T4 0.4 CWSI	0.87	0.95	0.82	0.88
T5 50 kPa	0.86	0.88	0.85	0.86
T6 0.6 CWSI	0.92	0.94	0.89	0.92
T7 30 kPa	0.82	0.83	0.84	0.83
T8 C-M	0.80	0.86	0.85	0.83

the water balance reference treatment. In terms of the fraction of water applied which was used for ET, the best irrigation scheduling method was the 0.6-CWSI treatment. However, the 0.6-CWSI treatment had a statistically significant yield reduction of 1600 kg ha^{-1} or 13% relative to the maximum yield.

ACKNOWLEDGMENT. The authors gratefully acknowledge the cooperation and assistance of W. Albus and R. Greenland, former and current managers of the Oakes Irrigation Field Trials Station, respectively; D. Coe, programmer; and W. Kuehl, technician.

REFERENCES

Brici, L. 1984. Results of field experiments using the leaf cell-sap concentration as an indicator for the timing of irrigation. Karachi, Pakistan: Saad Publications, Translations Div.

Calle, J. L., H. L. Manges and P. Barnes. 1990. Scheduling irrigations of corn with infrared thermometry. ASAE Paper No. 90-2004. St. Joseph, Mich.: ASAE.

Camp, C. R., G. D. Christenbury and C. W. Doty. 1988. Scheduling irrigation for corn and soybean in the Southeastern Coastal Plain. *Transactions of the ASAE* 31(2):513-518.

Cassel, D. K., C. K. Martin and J. R. Lambert. 1985. Corn irrigation scheduling in humid regions on sandy soils with tillage pans. *Agron. J.* 77(6):851-855.

Eck, H. V. 1986. Effects of water deficits on yield, yield components, and water use efficiency on irrigated corn. *Agron. J.* 78:1035-1040.

Field, J. G., L. G. James, D. L. Bassett and K. E. Saxton. 1988. An analysis of irrigation scheduling methods for corn. *Transactions of the ASAE* 31(2):508-512.

Fortson, R. E., R. W. McClendon and J. E. Hook. 1987. Managing irrigation with soygro crop growth model in a humid environment. ASAE Paper No. 86-4511. St. Joseph, Mich.: ASAE.

Hanway, J. J. 1966. How a corn plant develops. Iowa Cooperative Extension Service Special Report 48:3-18. Iowa State Univ., Ames.

Hatlitligil, M. B., R. A. Olson and W. A. Compton. 1984. Yield, water use, and nutrient uptake of corn hybrids under varied irrigation and nitrogen regimes. *Fert. Res.* 5:321-333.

Hattendorf, M. J., M. S. Redelfs, B. Amos, L. R. Stone and R. E. Gwin, Jr. 1988. Comparative water use characteristics of six row crops. *Agron. J.* 80:80-85.

Hill, R. W., R. J. Hanks and J. L. Wright. 1983. Crop yield models adapted to irrigation scheduling programs. ASAE Paper No. 83-2528. St. Joseph, Mich.: ASAE.

Jackson, R. D. Canopy temperature and crop water stress. In *Advances in Irrigation*, ed. D. Hillel, 1:43-85. New York: Academic Press Inc.

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

Jones, C. A. and J. R. Kiniry, eds. 1986. *CERES-Maize, A Simulation Model of Maize Growth and Development.* College Station: Texas A&M Univ. Press.

Kundu, S. S., G. V. Skogerboe and W. R. Walker. 1982. Using a crop growth simulation model for evaluating irrigation practices. *Agric. Water Management* 5(3):253-268.

Lowe, P. R. 1977. An approximating polynomial for computation of saturation vapor pressure. *J. Appl. Meteor.* 16:100-103.

Martin, D. L., E. C. Stegman and E. Fereres. 1990. Irrigation scheduling principles. In *Management of Farm Irrigation Systems*, eds. G. J. Hoffman and K. H. Solomon, 155-203. St. Joseph, Mich.: ASAE.

Miller, I. and J. E. Freund. 1977. *Probability and Statistics for Engineers*. Englewood Cliffs, N.J.: Prentice-Hall Inc.

Musick. J. T. and D. A. Dusek. 1980. Irrigated corn yield response to water. *Transactions of the ASAE* 23(1):92-98, 103.

Nielsen, D. C. and B. R. Gardner. 1987. Scheduling irrigations for corn with the Crop Water Stress Index (CWSI). *Appl. Agric. Res.* 2(5):295-300.

Phene, C. J., R. J. Reginato, B. Itier and B. R. Tanner. 1990. Sensing irrigation needs. In *Management of Farm Irrigation Systems*, eds. G. J. Hoffman, T. A. Howell and K. H. Solomon. St. Joseph, Mich.: ASAE.

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.* 20:373-380.

Raju, K. S., E. S. Lee, A. W. Biere and E. T. Kanemasu. 1983. Irrigation scheduling based on a dynamic crop response model. In *Advances in Irrigation*, ed. D. Hillel, 2:257-333. New York: Academic Press.

Singh, G., D. M. Brown, A. Barr and R. Jung. 1989. Scheduling irrigation for potatoes using a crop growth model. ASAE Paper No. 89-2686. St. Joseph, Mich.: ASAE.

Stanhill, G. 1986. Water use efficiency. In *Advances in Agronomy*, ed. N. C. Brady, 39:53-85. Orlando, Fla.: Academic Press.

Stegman, E. C. 1982. Corn grain yield as influenced by timing of evapotranspiration deficits. *Irrg. Sci.* 3:75-87.

————. 1983. Corn and sunflower yield vs. management of leaf xylem pressures. *Transactions of the ASAE* 26(5):1362-1368, 1374.

————. 1986. Efficient irrigation timing methods for corn production. *Transactions of the ASAE* 29(1):203-210.

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

Stegman, E. C. and D. F. Heermann. 1990. CERES-Maize applications to irrigation scheduling. ASAE Paper No. 90-2585. St. Joseph, Mich.: ASAE.

Stegman, E. C. and M. Soderlund. 1992. Irrigation scheduling of spring wheat using infrared thermometry. *Transactions of the ASAE* 35(1):143-152.

Stockle, C. O. and L. G. James. 1989. Analysis of deficit irrigation strategies for corn using crop growth simulation. *Irrig. Sci.* 10(2):85-98.

Trooien, T. P. and D. F. Heermann. 1988. Irrigation scheduling for potatoes using a growth model. ASAE Paper No. 88-2100. St. Joseph, Mich.: ASAE.

U. S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center. 1982. Monthly norms of temperature, precipitation and heating and cooling degree days, 1951-1980; North Dakota. In *Climatography of the U.S.*, No. 81.