Irrigation Scheduling Methods for Popcorn in the Northern Great Plains

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Abstract. *Irrigation of popcorn requires knowledge of methods of applying and scheduling irrigations. A four-year field plot study of four application-scheduling methods for popcorn was undertaken on a sandy loam soil near Oakes, North Dakota (ND), using a randomized block design. The study was designed to assess the influence of the methods on grain yields, popped volumes, and total irrigation water amounts applied for "White Cloud" popcorn. The reference method used aboveground drip irrigation (AGDI) to apply water and a scheduling method based on estimates of when 40% depletion of root zone available water (40% D) would be reached. The other irrigation application-scheduling methods were: AGDI and scheduling based on plant temperature, i.e., crop water stress index (CWSI) of 0.4; subsurface drip irrigation (SDI) and scheduling based on measured soil matric potential (SMP) of 30 kPa using a feedback and control system to automate irrigation applications through an SDI system; and AGDI and CERES-Maize (CM) growth model estimates of water use. Due to difficulties in implementing the CWSI method (high relative humidity and intermittent cloudiness), irrigations were also scheduled based on tensiometer-measured SMP of 40 kPa at 0.3-m depth for the CWSI treatment. Compared to the 40% D method, all other methods achieved statistically significant (0.05 level) irrigation water savings for popcorn without significant reductions in yields or popped volumes. Four-year average irrigation water amounts were 235, 134, 142, and 156 mm for the 40% D, CWSI, SDI, and CM methods, respectively, with corresponding popcorn yields of 4.63, 4.33, 4.44, and 4.47 Mg ha^{-1} and popped volumes of 26.3, 28.0, 28.3, and 28.0 L kg^{-1}.*
Keywords. *Growth model, Plant temperature, Soil moisture, Irrigation efficiency, Trickle irrigation.*

Popcorn is an alternative crop with production, harvest, storage, and equipment requirements and practices similar to those for field or dent corn (Dhuyvetter et al., 1991; D'Croz-Mason and Waldren, 1990; Ziegler et al., 1985). These factors may make popcorn an attractive crop for current dent corn producers who wish to include alternative crop production in their overall business strategy. Moreover, the similarities between popcorn and dent corn production practices may alleviate some of the uncertainty associated with switching from dent corn to alternative crops.

Compared to dent corn, relatively little literature is currently available which specifically addresses the irrigation requirements of popcorn. Since popcorn has a shallower root zone than dent corn, D'Croz-Mason and Waldren (1990) noted that some producers delay the first irrigation to stimulate deeper root development, while Dhuyvetter et al. (1991) noted that some producers apply smaller, more frequent irrigations to popcorn than to dent corn, to accommodate the shallower root system. Ziegler et al. (1985) stated that the tasseling and silking periods are the most critical times to avoid water stresses in popcorn; otherwise, as with dent corn, yield losses may occur. D'Croz-Mason and Waldren (1990) noted that popcorn should not be irrigated during the pollen-shedding period (to avoid washing pollen away by sprinkle irrigation) and that irrigation should continue until physiological maturity, while Dhuyvetter et al. (1991) stated that popcorn in Kansas may require one less irrigation in the fall than dent corn.

Due to the lack of irrigation scheduling information for popcorn in the northern Great Plains, popcorn producers would be advised to follow irrigation scheduling recommendations for dent corn, that is, to use evapotranspiration (ET) crop curves or crop water use tables for corn (e.g., Stegman and Coe, 1984; Lundstrom and Stegman, 1988) as part of a "water balance" regimen for irrigation scheduling. Other, "improved" methods of irrigation scheduling for dent corn have been studied in the northern Great Plains (e.g., Steele et al., 1994). The improved methods have included real-time sensor feedback (tensiometers and infrared canopy temperature measurements), partial ET replacement regimes, and the use of crop growth models to schedule irrigations. The improved methods have demonstrated significant irrigation water savings without significant reductions in corn grain yields.

Sprinkler irrigation is the fastest-growing segment of irrigation systems in North Dakota (T. Scherer, 1996, personal communication), but aboveground drip irrigation has been found useful for plot-scale research on irrigation water requirements and yield responses for dent corn

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(e.g., Steele et al., 1994) due to its accuracy of water placement and measurement. Moreover, subsurface drip irrigation (SDI) has been used effectively for irrigation of corn (Lamm et al., 1995) in Kansas and specialty crops in North Dakota (Steele et al., 1996). Subsurface drip irrigation offers several advantages over other types of irrigation, including a drier canopy and/or soil surface, improved trafficability, and reduced irrigation water requirements.

Objective

The objective of this study was to compare four irrigation treatments for irrigated popcorn production in the northern Great Plains of the U.S. The treatments were based on: (1) a water balance technique (referred to herein as the "reference" regime) similar to that recommended for dent corn; (2) plant temperature, backed up by measured soil matric potential (SMP); (3) measured SMP using a feedback and control system to automate irrigation applications; and (4) a plant growth model (CERES-Maize) to predict irrigation requirements. The irrigation requirements, popcorn grain yields, and popped volumes were compared to test the hypothesis that seasonal irrigation amounts could be significantly reduced compared to the reference regime, while maintaining yield and quality. A popcorn yield goal of 4.48 Mg ha^{-1} was set (K. Ziegler, 1992, personal communication).

Methods

Field plot experiments were conducted near Oakes, North Dakota (46°04′′ N Lat, 98°06′ W Long, and 401 m M.S.L.; Enz et al., 1995), in 1992 through 1995. The climate is subhumid and the predominant soil type is Maddock sandy loam.

Individual plots were 5.5 m wide × 12.2 m long. Rows were orientated E-W with a 0.61-m row spacing, resulting in nine rows per plot. Fertilizer application rates (table 1) were based on D'Croz-Mason and Waldren's (1990) recommendation that popcorn receive 85% of the total nitrogen that would be available for an expected yield in the same field for dent corn. Herbicide and insecticide selection and application rates were based on North Dakota State University recommendations. "White Cloud" hybrid popcorn, a very tender, hull-less variety, was planted and later thinned to a plant population of 7.66 plants m^{-2}.

Each plot was trickle irrigated with thin-wall drip tape (Chapin Watermatics, Inc., Watertown, N.Y.) placed midway between alternate pairs of rows. The tape was rated at 3.10×10^{-3} L s^{-1} m^{-1} and had 50-mm emitter spacings. Irrigation water was metered to quantify the actual irrigation application. Commercial users of drip tape may prefer lower tape flow rates to obtain greater uniformity with longer runs and prefer larger spacings between emitters to increase capillary spreading of water. For the research plot setting, however, relatively short plot lengths (12.2 m) precluded concerns about uniformity. Tape with small (e.g., 50 mm), rather than large (e.g., 0.30 m or larger), emitter spacing tape was used to produce a water application pattern as close as possible to a line source of water. Larger emitter spacings would have produced more-pronounced circular wetting patterns along the tape. Circular wetting patterns make it difficult to place tensiometers and neutron probe access tubes in the same position with respect to wetting patterns, both within and between plots. Hence we chose the smallest emitter spacing available.

Table 1. Experimental agronomic data

Agronomic Item	Year 1992	1993	1994	1995
Spring soil test NO_3-N to 0.6 m (kg N ha^{-1})	41	15	57	17
Preplant N* (kg N ha^{-1})	50	62	43	53
Planting date	6 May	6 May	12 May	16 May
Variety	White Cloud	White Cloud	White Cloud	White Cloud
Plant population (plants m^{-2})	7.66	7.66	7.66	7.66
Emergence	18 May	13 May	18 May	6 June
Fertigation dates	29-30 June; 20 July	16,17,19,20 July; 8-10 Aug.	1 July; 27-28 July	5-7 July; 9 Aug.
Fertigation† (kg N ha^{-1})	58	58	60	60
Harvest Date	28-29 Sept.	23 Sept.	4 Oct.	27 Sept.

* Preplant fertilizer N was applied in urea form (46-0-0% N-P_2O_5-K_2O) or as part of a mixed fertilizer (e.g., 18-46-0 in 1995). Levels of P_2O_5 and K_2O were based on recommended amounts for grain corn (Dahnke and Fanning, 1991).

† Liquid fertilizer applied through the drip irrigation system was 28% UAN, i.e., 0.36 kg N L^{-1}.

Water Management Treatments

Four irrigation application-scheduling methods (table 2) were replicated three times in a randomized block design. The randomized block design was used to block against a north-to-south gradient in the water holding capacity of the soil (Stegman, 1992). A companion study of irrigation application and scheduling methods for potatoes (not reported here) was used in an annual rotation with the popcorn on adjacent plots. In the following we first describe the methods used to characterize the soil for water balance algorithms and then we describe each scheduling method in detail.

A single-measurement method is proposed for quick characterization of soils and is intended to promote widespread use of the scheduling methods.

Table 2. Treatment–specific irrigation method and scheduling criteria

Treatment Abbreviation	Water Application Method	Description of Scheduling Method
40% D	Aboveground drip	Estimated depletion of available soil water not allowed to exceed 40%.
CWSI	Aboveground drip	Crop water stress index = 0.40, with backup of tensiometer (40 kPa).
SDI	Subsurface drip	Subsurface drip irrigation based on tensiometer feedback (30 kPa).
CM	Aboveground drip	Ceres-Maize estimates of available water depletion not allowed to exceed 40%.

Characterization of the water holding capacity of soils for irrigation scheduling methods requires measurement of one or more physical properties of the soil, e.g., moisture content at –10 kPa (field capacity), –1500 kPa (permanent wilting point), or the complete moisture release curve. Although more detailed hydraulic characterization could have been performed for this research study, 50% of the water content at field capacity was considered available for plant use, based on prior experience at the site (Stegman, 1992; Steele et al., 1994). To put this approach in perspective, James (1988) reported typical physical properties of soils with various textures. As a percent of field capacity, the soils have the following average available water holding capacities: 53% for sandy soil, 57% for sandy loam, 55% for loam, 50% for clay loam, 50% for silty clay, and 52% for clay. Thus on average, approximately 53% of the soil water at field capacity is available for plants, i.e., is held between field capacity and the wilting point.

For this study, estimates of total soil water at field capacity were based on neutron probe measurements in each plot in the study area on 27 May 1992 after 38 mm rain during the period 21 to 26 May 1992. The average moisture contents were 70 mm water in the top 0.3 m of the soil profile, 127 mm of water in the top 0.60 m, and 212 mm of water in the top 1.22 m. These were confirmed to be reasonable field capacity estimates the next year. A rainfall of 38 mm occurred during 29 to 30 June 1993, and soil profile moisture contents on 1 July 1993 to the same depths were 72 mm, 128 mm, and 212 mm.

A “reference” method of irrigation scheduling was developed for plots in the first treatment. The reference method was designed to account for the relative lack of literature on irrigating popcorn, the lack of a local crop curve or water use table for popcorn, and the probable lack of detailed hydraulic characterization of a particular producer’s field. Irrigations were scheduled using a water balance algorithm with in-season soil moisture corrections. Plots were irrigated when estimated depletions of available soil water exceeded 40% (denoted by “40% D”). A spreadsheet version of the irrigation scheduling algorithm developed by Stegman and Coe (1984) was used. Their dent corn ET crop curve was used “as is”, since a site-specific popcorn crop curve was unavailable. The root zone management depths were 0.3, 0.6, and 1.2 m for three time periods in the season. The first period extended from planting through the end of June, the second period consisted of the month of July, and the third period extended from August through the end of the season. For the first two periods, individual irrigation amounts were sufficient to refill the soil to slightly less than field capacity, i.e., allowing an estimated 2.5 to 5.0 mm storage to accommodate rainfall events. To put these amounts in perspective, Lundstrom and Stegman (1988) presented water balance calculations with 2.5 mm precision. During the final period, individual irrigation amounts were sufficient to refill the soil to field capacity, minus 13 to 15 mm storage. This treatment was intended to be the wettest, i.e., the reference regime. Soil moisture measurements were used to correct soil moisture estimates when available.

Three “improved” methods for irrigation scheduling were compared to the 40% D method to determine whether popcorn responds like dent corn to improved irrigation management techniques. Plots in treatment two were irrigated based on 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 based on a previous study for dent corn (Steele et al., 1994):

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

in which T_c and T_a are canopy and air temperatures, respectively (°C); and the subscripts 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. Functional forms for the lower and upper limits were based on previous work for dent corn at the site (Steele et al., 1994), because site-specific CWSI functions for popcorn were not available. Plots were irrigated when CWSI values reached 0.4. Prior to full canopy development and when CWSI data were unavailable, incomplete, or noisy, a backup irrigation scheduling technique was used. The backup method consisted of initiating irrigations when tensiometer readings exceeded 40 kPa. Individual irrigation amounts were 25 mm throughout the season for the CWSI treatment.

Plots in treatment three were irrigated when tensiometer readings exceeded 30 kPa. Subsurface drip irrigation (SDI) was used for water delivery. Tensiometers in these plots were equipped with pressure transducers and monitored by a data logger (Campbell Scientific CR10, Logan, Utah). The data logger controlled and monitored the water supply pumping and routing system (groundwater well, flow meter, and solenoid-controlled valves) to automatically apply 2.5 mm of water per irrigation. The 2.5-mm increments of water were applied to each plot up to three times daily. Drip tape was buried approximately 0.20 to 0.25 m below the soil surface. In all treatments, the tape was placed parallel to and midway between alternate pairs of rows. Prior to data logger installation and operation each season, irrigations were manually applied when tensiometer readings exceeded 30 kPa. In the manual mode, daily irrigation totals were limited to 7.6 mm d^{-1}. To put these daily amounts in perspective, Lundstrom and Stegman (1988) list a maximum expected water use of 7.6 mm d^{-1} for dent corn, based on previous research in North Dakota.

Plots in treatment four were irrigated using estimates of crop water use from the CERES-Maize (CM) crop growth model (Jones and Kiniry, 1986). Genetic coefficients used previously (Steele et al., 1994) for dent corn, were used in CM, since parameters for popcorn were unavailable. The first irrigation under this treatment was delayed until one day after the estimated Jensen-Haise (1963) based soil moisture depletion, averaged across replications, reached 50 to 60%. This corresponded to a CM soil water depletion of 63% before irrigation for one CM plot in 1995, for example. The delay in the first irrigation tested the hypothesis that irrigation amounts could be reduced from the reference method without affecting yields or quality. After the first irrigation, irrigations were scheduled based on a 40% available water depletion as predicted by CM. The root zone management depth for the growth model was held constant at 1.2 m throughout the season and individual irrigation amounts were 25 mm throughout the season. Soil moisture measurements were used to correct CM estimates of soil moisture, i.e., to force the model estimates of plant extractable soil water (PESW) to match field measurements of the same. When CM overestimated ET, the model underestimated PESW, and the estimates were corrected by adding artificial irrigation amounts to the simulation input files (not to the field plots). Thus the 40% D and CM methods both used corrections to soil moisture where possible.

For the 40% D and CM methods, an irrigation schedule was developed approximately every week for each plot. That is, plots in each treatment were scheduled independently. The ET estimates for the next week were based on long-term weather records. Daily long-term weather records for the season were pooled to construct fourth-order polynomials for daily maximum and minimum temperatures and solar radiation as functions of days into the growing season at the site. Weather records for 1 May through 30 September for the years 1972 through 1991 were used to construct the polynomials. Weather data from the current season, up to the date of scheduling, were entered into the spreadsheet for the 40% D method and into CERES-Maize for the CM method. For the next week, the long-term weather data were used to estimate soil moisture depletion for that week, with the assumption that no rainfall would occur. When rainfall occurred, the irrigation schedule was redeveloped or irrigations were delayed until ET was estimated to have consumed the rainfall.

Measurements

Root zone moisture contents were measured approximately weekly using the neutron attenuation method (Troxler, model 105A, Lakewood, Colo.) of soil water measurement. Measurements were taken in all plots at depths of 0.15, 0.30, 0.46, 0.61, 0.91, and 1.22 m. Soil matric potentials were measured manually each weekday in the CWSI treatment. The tensiometers (Irrometer IRR-RSR, Riverside, Calif.) were installed at a 0.30-m depth in the crop row. In plots in which tensiometers were used, one instrument per plot was used. Crop water stress index values were based on ambient air VPD and canopy-air temperature differences. Meteorological data collection procedures at the site were described in a previous study (Steele et al., 1994).

Final grain yield determinations were made by hand harvesting three 6.1-m rows in the center of each plot. The grain yield data were standardized to 15.5% moisture content on a wet basis (w.b.) for comparison. The popcorn was air dried to approximately 13.5% w.b. before the popping test was conducted, as suggested by Ziegler et al. (1985). In 1993, the popcorn was dried to a moisture content below 13.5% w.b., but was rewetted in a humid box to 13.5% w.b. before popping. The popped volume was used as a popcorn quality parameter. Popcorn was air popped for volume testing, using a 25-g sample of unpopped kernels. Popped corn was poured into a 2-L graduated cylinder, inverted and righted once, and the volume determined.

Irrigation Efficiency

Stegman (1982) evaluated the efficiency of irrigation management schemes using the equation,

$$IE = Y/I, \qquad (2)$$

where IE is irrigation efficiency, Y is yield per unit area, and I is irrigation depth applied. Equation 2 was used to calculate IEs for each plot in this study. Note that in the subhumid climate of the study, a few, well-timed rains may have attenuated differences between IE values for the treatments in the study. Note also that this study did not have nonirrigated plots from which to compute IE values for comparison to those from irrigated plots.

Analysis of Variance

An analysis of variance (ANOVA) was performed on irrigation water amounts, grain yields, popped volumes, and IEs for each season. The ANOVA was performed using Duncan's Multiple Range test in SAS, version 6.11 (SAS, 1995) for a randomized block design (two–way classification) at the α = 0.05 level of significance to determine if significant differences existed between treatment means. In order to statistically analyze treatment parameters across the entire four years of the experiment, the data were analyzed as a two-factor factorial design (Montgomery, 1991). Unless otherwise noted in the remainder of this article, the words "significant," "significantly," etc. are used in their statistical sense, i.e., according to these statistical tests.

Results and Discussion

Weather

The weather summaries presented here correspond to 1 May through 30 September for each year. Seasonal precipitation totals were 128%, 153%, 117%, and 108% of the 1972 through 1991 average at the site for the years 1992, 1993, 1994, and 1995, respectively (table 3). Seasonal reference ETs, calculated by the Jensen-Haise (1963) method, were 90%, 85%, 102%, and 102% of long-term averages for the years 1992, 1993, 1994, and 1995, respectively (table 3). Corn growing degree units (GDU) (°C) were calculated using the equation,

Table 3. Weather summary for the experimental period

Year*	Precipitation (mm)	Jensen-Haise Reference ET† (mm)	Growing Degree Units ‡ (°C)
1992	372	627	1089
1993	445	590	1002
1994	340	706	1284
1995	314	708	1249
1992-1995 average	368	658	1156
1972-1991 average	291	694	1244

* Values are based on 1 May through 30 September weather records for the site.

† Based on the Jensen-Haise (1963) reference ET equation for the period 1 May through 30 September each year.

‡ Growing degree units are for corn and assume a lower limit of 10°C and no upper limit.

$$GDU = [\ (T_{max} + T_{min})/2\ ] - 10, \quad (3)$$

where T_{max} and T_{min} are daily maximum and minimum temperatures (°C), respectively. Equation 3 was set to zero on days for which it produced negative values and equation 3 has no upper daily limit. Seasonal GDUs were 88%, 81%, 103%, and 100% of long-term averages for the years 1992, 1993, 1994, and 1995, respectively (table 3).

Irrigation Scheduling

The 40% D method generally overpredicted popcorn ET. For example, for the plot at replication one, five soil moisture measurements were made in the 1.2-m root zone during the period 1 August to 6 September 1995. During this period, the scheduling algorithm was run for an average of 9 d before making a soil moisture correction. On average, the soil moisture measurements indicated volumetric water contents approximately three percent greater than those estimated by the scheduling algorithm for this period. Moreover, measured soil moisture was greater than estimated soil moisture for each of the measurement dates in the period.

Several factors made CWSI data difficult to apply as an irrigation scheduling criterion for popcorn at the site and necessitated the use of the backup irrigation scheduling method. Intermittent cloudiness made leaf temperatures fluctuate with respect to receipt of direct sunlight, producing noise in the leaf temperature data. High relative humidity, i.e., low VPDs, reduce the evaporative cooling effect this method is designed to detect. To put this in perspective, VPDs obtained during this study were typically smaller than 2.0 kPa, whereas Idso (1982) reported a lower baseline for dent corn developed from data in Tempe, Arizona, in which VPDs reached approximately 4.5 kPa. The relatively cool growing seasons of 1992 and 1993 produced below-normal ETs (table 3), further reducing the evaporative cooling effect the CWSI method was designed to detect. Crop water stress index values could not be obtained until full canopy cover was reached, due to soil background interference in IRT sensing. The CWSI data collection was further compounded by the smaller plant size and lower canopy density of popcorn compared to dent corn.

The CM method overestimated ET in some cases. For example, for the plot at replication one, six soil moisture corrections averaging 10 mm each were made during the 1995 season. Note that these corrections were artificial irrigation amounts added to the model to bring the model estimates of soil moisture content into agreement with field measurements. The corrections were *not* added to the plots as field irrigations and therefore the corrections reflect periods during which CM overestimated crop ET. Corrections for cases where the model underestimated ET were not made due to the lack of means to do so in the model.

Summaries for Each Year

Treatment averages and analysis of variance results for applied irrigation water amounts are presented in table 4, yields in table 5, popped volumes in table 6, and irrigation efficiencies in table 7. In the following discussion, comparisons are made in terms of percent of the respective maximums for each year. For example, in 1992, the 40% D and SDI methods had popped volumes of 24.7 and 30.7 L kg^{-1}, respectively (table 6). Therefore, we note that the 40% D method had a (1 – 24.7/30.7) or 20% reduction in popped volume from the maximum for 1992. Comparisons of irrigation totals are based on data that include values replaced using missing plot techniques (Steel and Torrie, 1980) for one SDI plot in 1994 and one SDI plot in 1995.

For the 1992 season, yields for all methods did not differ significantly from one another, while the average irrigation amount for the 40% D method was significantly

Table 4. Irrigation water amounts for four irrigation scheduling methods, 1992 to 1995

Scheduling Method	Irrigation Water Amount (mm)			
	1992	1993	1994	1995
40% D	211a*	233a	271a‡	224a§
CWSI	73b	96c	186b	183ab
SDI	114b	164b	154b	137b
CM	102b	152b	218ab	152b
CD†	56.3	47.9	72.8	67.9

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level of significance according to Duncan's multiple range test.

† Critical Difference for adjacent, ranked means using Duncan's multiple range test.

‡ Plot 30 (SDI treatment, replication number 3) received a seasonal total of 816 mm irrigation water. An application error for one irrigation resulted in approximately 686 mm being applied over a weekend. For statistical analysis, a missing plot technique (Steel and Torrie, 1980) was used to estimate a seasonal total of 180 mm.

§ Plot 27 (SDI treatment, replication number 2) received a seasonal total of 219 mm irrigation. An equipment malfunction produced a single, unscheduled irrigation of 109 mm. For statistical analysis, a missing plot technique (Steel and Torrie, 1980) was used to estimate a seasonal total of 133 mm.

Table 5. Popcorn yields for four irrigation scheduling methods, 1992 to 1995

Scheduling Method	Yield (Mg ha^{-1})			
	1992	1993	1994	1995
40% D	4.87a*	4.54a	5.09a	4.02a
CWSI	4.26a	4.15a	4.92a	4.00a
SDI	4.50a	4.41a	5.29a	3.56ab
CM	4.78a	4.81a	5.20a	3.09b
CD†	0.716	1.22	0.81	0.65

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level of significance according to Duncan's multiple range test.

† Critical Difference for adjacent, ranked means using Duncan's multiple range test.

Table 6. Popped volumes for four irrigation scheduling methods, 1992 to 1995

Scheduling Method	Popped Volume (L kg^{-1})			
	1992	1993	1994	1995
40% D	24.7b*	28.3a	24.0a	28.4a
CWSI	29.0ab	30.3a	24.0a	28.6a
SDI	30.7a	28.0a	26.0a	28.8a
CM	29.3ab	29.0a	25.0a	28.6a
CD†	4.57	2.96	3.00	1.53

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level of significance according to Duncan's multiple range test.

† Critical Difference for adjacent, ranked means using Duncan's multiple range test.

Table 7. Irrigation efficiencies for four irrigation scheduling methods, 1992 to 1995

Scheduling Method	Irrigation Efficiency (kg ha^{-1} mm^{-1})			
	1992	1993	1994	1995
40% D	23.2b*	19.8b	18.8c	18.3a
CWSI	69.1a	48.3a	29.0ab	22.1a
SDI	39.3ab	27.1b	35.2a	26.5a
CM	51.3ab	32.0b	23.9bc	21.2a
CD†	39.7	14.1	9.8	10.1

* Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level of significance according to Duncan's multiple range test.

† Critical Difference for adjacent, ranked means using Duncan's multiple range test.

larger than for the other methods. The popped volumes did not differ significantly from each other, except for the 40% D method. The 40% D treatment had the highest irrigation application and the highest yield, but suffered a 20% reduction in popped volume compared to the maximum. Compared to the 40% D method, a 65% reduction in irrigation amount was achieved for the CWSI treatment, a 46% reduction for the SDI treatment, and a 52% reduction for the CM treatment. Compared to the 40% D method, the IE value was significantly larger (by 198%) for the CWSI method.

For the 1993 season, yields and popped volumes for all methods did not differ significantly from one another, while the average irrigation amount for the 40% D method was significantly larger than for the other methods. The 40% D treatment had the highest irrigation application, while 59% less irrigation was applied for the CWSI treatment, 30% less for the SDI treatment, and 34% less for the CM method. The CM treatment had the highest yield, while the CWSI treatment had a significantly higher IE value than all the other treatments.

For the 1994 season, yields and popped volumes for all methods did not differ significantly from one another, while the average irrigation amount for the 40% D method was significantly larger than for the CWSI and SDI methods. The 40% D treatment had the highest irrigation application, with 31% savings in the seasonal irrigation amount for the CWSI treatment, a 43% savings for the SDI treatment, and a nonsignificant, 20% savings in irrigation amount for the CM treatment. The SDI treatment produced maximums for yield, popped volume, and IE.

For the 1995 season, yields were markedly smaller than in the other years. The highest yield in 1995 was smaller than all yields from all other years. The low yields in 1995 may have been due to late emergence (table 1) and slow growth early in the season. Although the GDU for 1995 were essentially equal to the long-term average (table 3), there were only 77°C GDU in May 1995, compared to the long-term average for May of 145°C (data not shown).

In 1995, only the CM method suffered a significant yield reduction, while popped volumes and IE values did not differ significantly between methods. The irrigation amount for the 40% D method was significantly larger than for the SDI and CM methods. The 40% D treatment had the highest irrigation application and the maximum yield. Compared to the 40% D method, the CWSI treatment exhibited a nonsignificant, 18% reduction in irrigation amount and maximum popped volume. The SDI treatment exhibited a 39% reduction in irrigation amount and maximum popped volume. The CM treatment exhibited a 32% reduction in irrigation amount and a 23% reduction in yield.

Summaries for the Four-year Experiment

For the four-year period, all of the methods saved significant amounts of irrigation water compared to the reference treatment (table 8). No significant differences were found for yield or popped volume. The CWSI method exhibited the highest IE value, while the 40% D method was in the lowest statistical grouping for IE.

The 40% D treatment had the highest average yield, 4.63 Mg ha^{-1} mm^{-1} and highest average irrigation amount, 232 mm. Compared to the 40% D treatment, the CWSI method had a 44% reduction in seasonal irrigation total, the SDI method had a 39% reduction, and the CM method had a 34% reduction. The SDI method had the highest average popped volume, 28.3 L kg^{-1}.

The 40% D treatment, although not significantly higher in yield than the other methods, was the only treatment to exceed the yield goal of 4.48 Mg ha^{-1} over the four-year period of the study (table 8). Thus it appears that the simplified, single-measurement method for soil characterization is *sufficient* for purposes of scheduling irrigations for popcorn at this site, in terms of yield. However, the single-measurement method is not *optimal*, in terms of seasonal irrigation requirements. Improved methods of irrigation scheduling, including soil and/or plant monitoring and water application through SDI, produced better irrigation scheduling, i.e., they produced the same yields with reduced water inputs.

Summary

A four-year field plot study was conducted to determine whether popcorn responds to improved irrigation scheduling methods like dent corn. The study was conducted on a Maddock sandy loam soil in southeastern North Dakota. Four irrigation application-scheduling methods were compared on the basis of seasonal irrigation water requirements, yields, and popped volumes. The methods consisted of a reference method and three "improved" methods. The reference method used a water balance approach to schedule irrigations when 40% of the available water was estimated to be depleted (40% D). The improved methods were: (1) irrigation scheduling based on crop water stress index (CWSI); (2) water applied through a subsurface drip irrigation (SDI) system in response to tensiometer measurements; and (3) irrigation scheduling

Table 8. Four-year statistical summary for four irrigation scheduling methods, 1992 to 1995

Treatment	Irrigation (mm)	Yield (Mg ha^{-1})	Popped Volume (L kg^{-1})	Irrigation Efficiency* (kg ha^{-1} mm^{-1})
40% D	235a†	4.63a	26.3a	20.0b
CWSI	134b	4.33a	28.0a	42.1a
SDI	142b	4.44a	28.3a	32.0ab
CM	156b	4.47a	28.0a	32.0ab

* Each irrigation efficiency average is the average of 3 replications × 4 years = 12 values, not the overall average yield divided by the overall average irrigation amount.

† Amounts in each column with the same letter are not significantly different at the $\alpha = 0.05$ level of significance according to Duncan's multiple range test.

based on CERES-Maize (CM) estimates of plant-extractible soil water. The study indicates that in the northern Great Plains of the U.S., statistically significant irrigation water savings (compared to the reference method) can be achieved for popcorn without significant yield or popped volume reductions. Compared to the 40% D method, an irrigation water savings of 43% was achieved with the CWSI treatment, 40% with the SDI treatment, and 34% with the CM treatment, over the four years of this study. The 40% D method produced the highest yields and met the yield goal of 4.48 Mg ha^{-1} (4,000 lb ac^{-1}). The SDI method had the highest popped volume.

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