ON-FARM SCHEDULING STUDIES AND CERES-MAIZE SIMULATION OF IRRIGATED CORN

E. Dogan, G. A. Clark, D. H. Rogers, V. Martin, R. L. Vanderlip

ABSTRACT. *A field study was conducted to evaluate an irrigation scheduling model (KanSched) using seven center pivot irrigated corn sites in south central Kansas from 1999 to 2001. Portions of each center pivot irrigation system were modified to apply various irrigation amounts. Site-specific irrigation, weather, and field data were used in KanSched to create comparative irrigation schedules for each test zone of each site. Those schedules were also used in the CERES-Maize corn growth simulation model.*

Irrigation treatments included deficit amounts ranging from 10 to 180 mm while excess irrigation amounts ranged from 8 to 139 mm. KanSched calculated crop evapotranspiration (ET_{ks}) ranged from 370 to 488, 356 to 426, and 386 to 566 mm, while CERES-Maize simulated crop ET ranged from 418 to 585, 398 to 699, and 409 to 712 mm for all sites in 1999, 2000, and 2001, respectively.

Analyses of measured corn grain yield versus a KanSched water balance ratio [R_w = (Net irrigation + Effective rain + Soil water depletion) / ET_{ks}] indicated that crop yield was highest at a water balance ratio of 1.0 (full irrigation). Measured yield from all treatments ranged from 9.5 to 13.1, 7.4 to 14.4, and 3.8 to 16.1 Mg ha^{-1} while CERES-Maize simulated corn yield ranged from 7.9 to 13.8, 6.9 to 17.1, and 6.6 to 13.8 Mg ha^{-1} in 1999, 2000, and 2001, respectively. In general, substantial deficit irrigation amounts reduced measured grain yield especially in drier years on south central Kansas farm sites. While the CERES-Maize model simulated average yield from all sites and years was equal to the average measured yield, the model over-predicted measured yields in the lower end of the measured yield range and under predicted yield in the upper end of the measured yield range. Thus, the CERES-Maize model may be adequate for large spatial and temporal simulations, but may not be adequate to simulate individual sites and deficit yield conditions.

Keywords. *Irrigation scheduling, water managememt, crop evapotranspiration, corn yield*

Declining aquifer levels, rising energy costs, and increased demand for water from urban areas, increases the likelihood of deficit irrigation in the central Great Plains (Stegman, 1986; Lamm et al., 1993). Deficit irrigation is generally looked upon as “the intentional under irrigation of crops with the objective of either water conservation or increased profitability over the long-term” (Martin et al., 1985).

Deficit irrigation on corn results in reduced yield (Stewart et al., 1975; Musick and Dusek, 1980; Eck, 1986; Lamm et al., 1994). In deficit irrigation studies by Lamm et al. (1993), corn grain yield was reduced by 0.14 Mg ha^{-1} for every 1-cm reduction in irrigation water below crop need. Musick and Dusek (1980) reported similar results using surface (basin) irrigation in Bushland, Texas. Field et al. (1988) reported that simulations of reduced irrigation with the SPAW-IRIG model indicated reduced corn grain yield of about 0.3 Mg ha^{-1} per cm of irrigation water applied. However, timing of deficit irrigation applications can make a substantial difference. For example, in a study at Scandia, Kansas (Gordon and Raney, 1992), a single irrigation at tassel increased corn yield from 0.2 Mg ha^{-1} dry land to 8.3 Mg ha^{-1} in 1991. The 1980-1991 average yield increase from the single tassel irrigation was 5.7 Mg ha^{-1}. Gilley and Mielke (1980) conducted a study in Nebraska where 90% of crop water need was supplied during the reproductive stage and 80% during the grain filling stage of corn and concluded that corn grain yield was not substantially reduced.

As more farms use computers and software programs in the management of their operations, irrigation scheduling using real-time evapotranspiration (ET) data is becoming more widely accepted and used. A relatively simple and easy-to-use irrigation scheduling program, KanSched, was developed and tested to schedule irrigations using daily inputs of reference evapotranspiration (grass, ETo; or alfalfa, ETr), rainfall, and irrigation to maintain and chart a field water balance (Clark et al., 2002). Henggeler (2002) reported that KanSched was easy-to-use, had nice displays, and was relatively versatile for use in states other than Kansas. Of the eight irrigation scheduling programs he evaluated, six used real-time weather data. Use of such programs becomes

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increasingly important as water resources become more limited and there is a greater need for "just-in-time" scheduling of water applications.

Accurate crop simulation models could play a role in assessing the timing and amount of water application from a limited water resource perspective. Such evaluations could be used to assess the timing and amount of water applications from a limited water resource for a variety of crop and field conditions. The CERES-Maize (Crop-Environment Resource Synthesis) simulation model (Jones and Kiniry, 1986) was designed to mimic corn grain response in a given year and location (Garrison et al., 1999). CERES-Maize yield response has been tested in Virginia (Hodges et al., 1987), Illinois (Kunkel et al., 1994), and Australia (Hargreaves and McCown, 1988). Llewelyn and Featherstone (1997) indicated that the CERES-Maize model has been widely used to assess irrigation strategies for corn. Kiniry and Brockway (1998) conducted a study using nine locations in Texas with variable weather conditions and soil types to evaluate CERES-Maize grain response to measured data. Mean simulated corn grain yield from all sites in 5 years were within 10% of measured corn grain yield. They considered the results promising enough for CERES-Maize to be used for corn grain yield simulations.

Kiniry et al. (1997) evaluated the yield response of the CERES-Maize model for nine locations in the United States and reported that CERES-Maize simulated mean grain yield was within 5% of measured grain yields for all nine locations. Hodges et al. (1987) evaluated the CERES-Maize grain yield estimations in 14 states accounting for 85% of U.S. corn production in 1982 through 1985 using information from 51 weather stations. CERES-Maize simulation results showed that yield estimates were 92%, 97%, 98%, and 101% of U.S. estimated corn grain yields averaged over all 14 states. Those results showed that the model might be used for large area corn grain yield estimations with minimal regional calibrations.

Fraisse et al. (2001) tested a version of CERES-Maize that was modified to improve the simulation of site-specific crop development and yield. The depth of claypan soil horizons was of particular interest for this application. The results indicated that the model performed well in simulating yield variability, however, simulated leaf area indices, in general, were below measured values.

Limited water resources and increasing pumping cost may cause farmers to consider deficit irrigation as an alternative to full irrigation practices. Unfortunately, existing literature documents the potential yield losses with deficit irrigation. Alternatively, farmers may consider either a reduction in planted area or to schedule irrigation events so that plants do not stress during sensitive growth stages. Additional research is needed to assess the effects of deficit irrigation practices on corn grain yield. Furthermore, while there is a need for controlled field research,valuable information can come from simple studies on commercial production fields. In addition, simulations of deficit irrigation practices using models such as CERES-Maize can be used to look at various weather years and geographic locations.

Therefore, the objectives of this study were:

- use of field-based irrigation and yield data to validate the KanSched irrigation scheduling program,
- determination of the effect of deficit irrigation practices on corn grain yield in south central Kansas (SCKS), and
- evaluation of the CERES-Maize model in simulating corn grain yield under different irrigation scenarios in south central Kansas.

MATERIALS AND METHODS

FIELD STUDIES AND WATER BALANCE MODELING

Field studies were conducted between 1999 and 2001 in south central Kansas on one experimental field (KSU Sandyland Experimental Field, SL) and six commercial corn production sites identified as GH, PS, JM, GS, SM, and TZ (table 1). The commercial corn sites had center pivot (CP) sprinkler systems while the SL site had a linear-move irrigation system. Because greater system control was available at the SL site, irrigation rates of 65%, 100%, and 135% (treatments I, II, and III) were used. The 100% rate at the SL site was scheduled using a Penman-Montieth (Allen et al., 1998) grass reference evapotranspiration (ETo) based

Table 1. Soil physical properties for all commercial and experimental sites. [a]

Sites	Soil Class	Depth from Surface (mm)	USDA Texture	Permeability ($mm\ d^{-1}$)	Available Water Capacity ($mm\ mm^{-1}$)	Location (County)
SL	Pratt-Tivoli association	0.0–178	Fine sandy loam	15.3–50.8	0.11–0.20	Stafford
		178–356		5.1–50.8	0.12–0.20	
		356–813		1.5–5.1	0.12–0.20	
GH	Pratt-Carwile association	0.0–360	Fine sandy loam	12.7–25.4	0.15	Reno
		360–1270	Light sandy clay loam	5.0–12.7	0.17	
PS	Bethany-Tabler association	0.0–410	Silt loam	5.1–12.7	0.18	McPherson
		410–1140	Silty clay loam	5.1–12.7	0.17	
JM	Blanket-Farnum association	0.0–560	Loam	15.2–50.8	0.20–0.22	Stafford
		560–1520		50.8–15.2	0.14–0.21	
GS	Crete-Ladysmith association	0.0–279	Silt loam	16.0–5.1	0.14–0.18	Harvey
		279–432	Silty clay loam	5.1–16.0	0.15–0.19	
		432–1168	Silty clay	1.5–5.1	0.14–0.18	
SM	Pratt-Carwile association	NA	Loamy fine sand	50.8–127.0	0.12	Pratt
TZ	Naron-Pratt-Carwile association	0.0–356	Fine sandy loam	16.0–50.8	0.09–0.13	Rice
		356–1016	Sandy clay loam	16.0–50.8	0.12–0.16	

[a] Data were obtained from the USDA Soil Survey books for Harvey, McPherson, Pratt, Reno, Rice, and Stafford counties.

irrigation scheduling program (KanSched, Clark et al., 2002). The commercial corn production sites were typically irrigated on "the wet side." Therefore, portions of those sprinkler irrigation systems were modified to apply about 50%, 75%, and 100% of full irrigation (treatments I, II, and III). The 100% irrigation level was the application amount scheduled by the producer. The field sites were used to evaluate the effect of reduced water applications on grain yield. The results were used in evaluating the validity of the KanSched and CERES-Maize models for individual field sites.

The linear system at the SL site had four 49-m spans. Each span had 16 low-pressure sprinklers on drop tubes that were approximately 2.4 m above the soil surface and were positioned on a 3-m horizontal spacing. Each sprinkler drop had a pressure regulator and a Low Drift Nozzle (LDN) with a grooved deflection pad (Senninger Irrigation Inc., Orlando, Fla.). Three of the four spans were modified to apply the target application rates by adjusting nozzle size and nozzle pressure. One span was used for each target application rate. Treatment areas werelocated in the middle of each span.

Commercial field site center pivot systems were modified to minimize impact to the farmer. Therefore, in order to minimize impacted area, sprinkler modifications were typically made on the second and third span out from the pivot point (table 2). Those spans were modified with the 50% and 75% design nozzle and pressure combinations. The fourth span was not modified but was used as the 100% application rate treatment zone. All of the commercial sites had rotating plate sprinklers that were approximately 2.0 to 2.4 m above the soil surface and on a spacing of 5 m. The middle five nozzles of each modified span were changed to the design treatment rates to insure adequate irrigation overlap. The JM site involved two identical systems on adjacent fields. The site used in 2000 had a limited water allocation that did not allow full irrigation for the season. However, in 2001, the study was moved to an adjacent field that had a similar center pivot system, but with a water right that allowed full irrigation. Also, because of site manager concerns regarding yield losses on the SM site in 2000, treatments I and II were adjusted to apply 70% and 85% of full irrigation.

For all study sites and years, local weather station data were obtained from a network of stations located in south central Kansas. Weather stations were generally within 15 km of each field, which was considered adequate for all data except rainfall. Weather station data included maximum

Table 2. Sprinkler irrigation system and nozzle characteristics used in 1999, 2000, and 2001.

Site	Nozzle Spacing (m)	Nozzle Pressure (kPa)	Flow Rate[a] ($L\ s^{-1}$) I	II	III	Distance to Pivot Point (m) I	II	III
SL	3.0	103	0.30	0.43	0.60	-----	-----	-----
GH	4.8	172	0.14	0.34	0.31*	92	154	116
PS	5.6	172	0.20	0.22	0.49	60	88	194
JM	2.9	103	0.12	0.13	0.28	94	112	273
GS	5.2	172	0.21*	0.40*	0.47*	76	102	128
SM	5.5/4.9	172	0.21	0.43	0.54*	86	126	155
TZ	5.6	172	0.20*	0.21*	0.48*	60	88	116

[a] Discharge rates with * are manufacturer reported values, the others were measured.

and minimum air temperatures, solar radiation, and Penman-Monteith grass reference evapotranspiration (ETo). Rainfall measured at each field site was used for the water balance portion of each study site.

Irrigation amounts within each treatment were measured using three IrriGages (IG10) (Clark et al., 2004) at a 62-cm height. One IG10 collector was also located outside of the irrigated area of all commercial sites to measure rainfall amounts. The IrriGages are a non-evaporating collection device that could be measured on a weekly basis. Sites were visited with minimal disturbance once or twice each week during the corn growing season to record irrigation depths and rainfall amounts. Those data were later used in KanSched to create a field soil water balance (SWB) of each site and for use as inputs in CERES-Maize simulations.

A field water balance was developed for each site using the KanSched program. That program uses soil water holding capacity, permanent wilting point, emergence date, crop root depth, crop canopy coverage at different growth stages, and end of the growth stage as inputs. To calculate available soil water, KanSched maintains a field water budget with daily inputs of ETo, rainfall, and irrigation amounts. The KanSched program uses only one soil texture for the management root depth. Therefore, soil water calculation in the program is for the entire defined active crop root depth. Most of the active roots for many of the field sites that had very sandy soils were observed to be within the top 0.6 m of the soil profile. While some crop roots may have been deeper and had access to that water, they were not considered in the main water balance. Both Excel and Visual Basic versions of KanSched are available on the Kansas State University Mobile Irrigation Lab web site (http://www.oznet.ksu.edu/mil/).

Crop coefficients (kc) used to calculate daily crop water requirements (KanSched-based crop evapotranspiration, ET_{ks}) were generated by KanSched and obtained from the USDA Soil Conservation Service/National Engineering Handbook (USDA, 1993). A basal crop coefficient (kc) was created using kc values of 0.25, 1.20, and 0.60 for the beginning, peak growth, and maturation stages of the corn crop, respectively. The KanSched program also adjusts (reduces) crop coefficients when the calculated soil water content is less than the management allowed deficit (MAD) level (50%) according to procedures outlined in chapter 2 of the National Engineering Handbook (USDA, 1993). KanSched then charts irrigation, effective precipitation, and soil water changes on a "Soil Water Chart." High rainfall amounts were truncated to the available soil water holding capacity of the root zone, which was called effective rainfall.

The KanSched program was run for all sites, treatments, and years to determine soil water balance parameters and optimal irrigation amounts. Measured irrigation inputs from each site and treatment were compared to the "optimal" irrigation amounts to determine excess and deficit irrigation values. Additionally, the program was run to determine non-stressed crop evapotranspiration (ET_{ks}) for comparison with the CERES-Maize program output. At the beginning of all runs, the initial soil water status of the soil profile was assumed to be at field capacity. This assumption was based on the conditions that the south central region of Kansas typically receives 0.5 to 0.6 m of annual precipitation and that a substantial portion of that occurs during the winter and spring. Thus, it is very common for fields to be at field capacity at the start of each production season.

Soils in all field sites ranged from coarse textured sand (81% sand) to fine textured silt loam (57% silt) with available water (AW) varying from 11% to 18% and permanent wilting point (PWP) ranging from 10% to 22% (table 1). Those values were used in the KanSched program. The fractions of sand, silt, and clay were also used as inputs for CERES-Maize.

In all three years, 6.1-m long sections of three corn rows from all sites and treatments were hand harvested at physiological maturity. Additionally, corn ear numbers at harvest were recorded. Corn ears were later sun dried, shelled, and weighed. Moisture content of the kernels was measured with a moisture meter (Dickey John GAC II, Auburn, Ill.). Measured corn yields were corrected to 15.5% moisture content. Since each harvested corn row was not a true replication but rather a sub-sample, yield data were analyzed graphically.

CERES-Maize Simulations

The CERES-Maize model was run with field data collected from 1999 through 2001 that included site-based irrigation and rainfall amounts. Additionally, the CERES-Maize model was run to find the crop evapotranspiration (ET_{cm}) under no water stress conditions.

At the beginning of the CERES-Maize simulations, soil water status was set to field capacity as in KanSched simulations. Planting dates, corn hybrids, seeding rates, and irrigation event and rainfall dates for all sites and years were determined by consulting with the individual site managers and with measured site data.

Morphological and physiological coefficients for the corn hybrids used on all commercial sites were not available. However, coefficients for Pioneer Seed Co. Hybrid 3162 (Johnston, Iowa) were available in the CERES-Maize model and were used for the commercial site simulations. That hybrid was widely (60% to 70%) used by the farmers in the area (Martin, 2001). The Pioneer 3162 hybrid has a 119-day maturity, which is common for the area (Belz, 1998). For the SL simulations, actual hybrid (NC+5445) coefficients were used.

General inputs in CERES-Maize included planting date, plant population (seed ha^{-1}), row spacing (m), planting depth (mm), and in-season irrigation amounts. Corn harvest occurred at grain maturity. Since collected irrigation depths were net application amounts, sprinkler irrigation system efficiency in the CERES-Maize simulations was set to be 100%. Also, because simulated yields were reported as dry matter, values were adjusted to 15.5% dry-basis moisture content.

Table 3. Treatment irrigation application rate percentages (design and measured) with measured net irrigation (Net Irrig.), excess or deficit irrigation amounts, and KanSched simulated crop ETc (ET_{ks}) values for all sites in 1999.

Sites	Trt	Irrig. Applic. Rate (%) Design (%)	Measured (%)	Net Irrig. (mm)	Excess + or Deficit − Irrig. (mm)	ET_{ks} (mm)
1999						
SL	I	65	66	165	−64	370
	II	100	100	250	+21	430
	III	135	138	344	+115	439
GS	I	41	44	71	−81	416
	II	74	73	117	−35	444
	III	100	100	160	+8	457
SM	I	54	54	219	−48	436
	II	74	73	297	+30	475
	III	100	100	406	+139	488
TZ	I	56	55	142	−87	406
	II	75	72	185	−44	423
	III	100	100	257	+28	445

Table 4. Treatment irrigation application rate percentages (design and measured) with measured net irrigation (Net Irrig.), excess or deficit irrigation amounts, and KanSched simulated crop ETc (ET_{ks}) values for all sites in 2000.

Sites	Trt	Irrig. Applic. Rate (%) Design (%)	Measured (%)	Net Irrig. (mm)	Excess + or Deficit − Irrig. (mm)	ET_{ks} (mm)
2000						
SL	I	65	64	165	−114	369
	II	100	100	256	−23	474
	III	138	131	335	+56	498
GH	I	49	61	164	−115	371
	II	71	78	209	−70	391
	III	100	100	269	−10	393
PS	I	56	58	158	−45	421
	II	73	77	209	+6	426
	III	100	100	271	+68	426
JM	I	58	61	100	−141	356
	II	70	68	112	−129	362
	III	100	100	165	−76	392
SM	I	70	71	194	−111	357
	II	85	84	228	−77	379
	III	100	100	272	−33	385
TZ	I	56	67	201	−90	378
	II	75	83	164	−53	390
	III	100	100	243	−11	406

Results and Discussion

Field Yield and Water Balance Results

In 1999, designed and measured treatment irrigation application percentages for all sites were within ±5% (table 3). In 2000 and 2001, designed and measured values were also similar (tables 4 and 5) and were within 10% except on the PS site in 2001. Variations in system inline pressure, pressure regulator performance, nozzle discharge rates, and distribution losses of applied water were probable causes of differences.

In 1999 and 2000, measured net irrigation depths from all sites and treatments ranged from 71 to 406 mm (table 3) and from 100 to 335 mm (table 4). In 2001, net irrigation amounts for all treatments ranged from 191 to 459 mm (table 5). In 1999, half of the treatments were deficit (-) and ranged from 35 to 87 mm below net irrigation amounts from the non-stressed KanSched runs, where excess irrigation depths

Table 5. Treatment irrigation application rate percentages (design and measured) with measured net irrigation (Net Irrig.), excess or deficit irrigation amounts, and KanSched simulated crop ETc (ET_{ks}) values for all sites in 2001.

Sites	Trt	Irrig. Applic. Rate (%) Design (%)	Measured (%)	Net Irrig. (mm)	Excess + or Deficit -Irrig. (mm)	ET_{ks} (mm)
2001						
GH	I	49	60	247	−134	416
	II	71	77	315	−66	477
	III	100	100	410	+29	546
PS	I	56	82	191	−63	389
	II	73	85	197	−57	405
	III	100	100	233	−21	414
JM	I	58	55	252	−180	406
	II	70	73	333	−99	471
	III	100	100	459	+27	566
SM	I	70	70	244	−124	386
	II	85	87	304	−64	429
	III	100	100	348	−20	459

ranged from 8 to 139 mm above net irrigation requirements (table 3). In 2000 (table 4), most of the irrigation amounts were deficit (10 to 141 mm). Only three treatment sites had excess irrigation that ranged from 6 to 68 mm. Similarly, in 2001 (table 5), most of the treatment sites were deficit irrigated (20 to 180 mm) with two excess irrigation treatments (27 and 29 mm).

In 1999, observations on all sites indicated no visual water stress on deficit irrigated corn plants. However, in 2000 and 2001, temperatures and solar radiation loads were greater and ETo values were greater (data not shown). These conditions appeared to create a visual water stress on the deficit irrigated corn plants during the middle and late periods of the corn growing season. In 1999 and 2000, ET_{ks} values ranged from 370 to 488 mm (table 3) and from 356 to 498 mm (table 4), respectively. In the drier 2001 season, ET_{ks} values ranged from 386 to 566 mm (table 5).

In 1999, measured corn grain yield ranged from 8.3 to 13.1 Mg ha^{-1} (table 6). Weather conditions were mild, so treatment I resulted in yield reductions for only two sites (SL and TZ). In 2000 and 2001, maximum temperatures and evaporative demand were greater and corn yield ranged from 7.4 to 14.4 Mg ha^{-1} and from 3.8 to 16.1 Mg ha^{-1}, respectively. In those two years, rainfall was less (254 and 233 mm) than 1999 (355 mm) and deficit irrigation practices reduced corn yield (table 6) on five of the six sites in 2000 and on all sites in 2001.

Measured yield is plotted with simulated corn evapotranspiration (KanSched-based, ET_{ks}) for all sites and years in figure 1. Measured grain yield was more variable at lower ET_{ks} values (350 to 430 mm) than at greater values (> 430 mm). Furthermore, with such variability the linear relationship between those two parameters was not significant ($R^2 = 0.05$; $p = 0.14$). However, because the data in this study are from commercial field sites, greater variability is expected. The slope of the linear relationship shows that the apparent water use efficiency is 0.013 Mg ha^{-1} of grain for each mm change in water use. This value is close to, but lower than the 0.018 Mg ha^{-1}-mm reported by Lamm et al. (1994) for a controlled study site in northwest Kansas. Figure 1 also

Table 6. Measured and simulated corn grain yield for the three irrigation application levels (I, II, and III) for all field sites in 1999, 2000, and 2001.

Site	Measured Yield (Mg ha^{-1}) I	II	III	Simulated Yield (Mg ha^{-1}) I	II	III
1999						
SL	12.0	13.1	12.5	12.5	12.8	12.8
GS	10.6	9.5	10.7	13.8	13.8	13.8
SM	11.5	11.0	10.7	10.1	12.4	13.3
TZ	8.3	9.1	10.1	7.9	8.4	8.9
2000						
SL	7.4	11.0	10.9	9.7	12.5	17.1
GH	12.0	14.4	14.1	10.9	11.8	12.8
PS	12.7	11.0	12.1	14.0	14.0	14.0
JM	9.3	10.6	12.3	6.9	6.9	8.3
SM	8.8	11.5	11.6	9.2	9.9	11.0
TZ	9.7	11.9	12.5	11.4	13.2	13.4
2001						
GH	5.3	16.1	13.2	12.0	12.8	13.8
PS	13.4	15.6	14.1	9.9	10.0	10.8
JM	4.3	13.2	12.3	6.6	8.7	12.1
SM	3.8	8.8	12.6	7.2	9.6	10.1

indicates that there was no substantial yield increase for ET_{ks} values greater than 500 mm and that with lower water inputs high yields might be possible for that geographic region.

Measured yield plotted with relative net irrigation (R_I = Net applied irrigation amount/Net required irrigation amount) shows an increase in yield with R_I up to a R_I value of 1.0 (fig. 2). Yield increases are not evident with R_I values that exceed 0.7. Therefore, these data indicate that farmers in that geographic region can manage their irrigation systems with R_I values slightly below 1.0 (full irrigation) with potentially no yield loss. The highest yield reductions occur when R_I values fall below 0.7. Therefore, deficit irrigations with less than 70% of the full irrigation requirement will substantially reduce corn yield in that area. These results (fig. 2) indicate that as long as the KanSched program soil water status is maintained at or above the management allowed deficit (MAD) level (0.50 used in these studies), water stress should not occur. Any additional water will result in excess use of water and energy with no yield benefit.

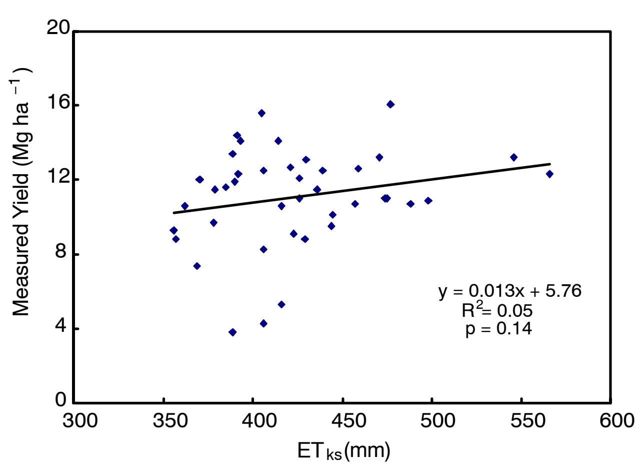

Figure 1. Measured corn yield vs. ET_{ks} for field sites in south central Kansas in 1999, 2000, and 2001.

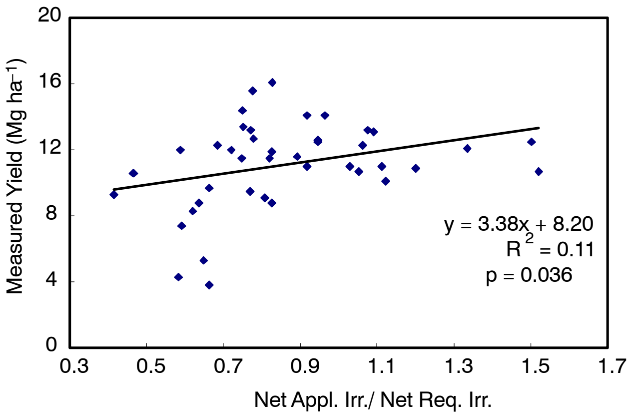

Figure 2. Measured yield and relative net irrigation (R_I = Net Appl. Irrig. / Net Req. Irrig.) from all field sites (SL and commercial) and treatments in 1999, 2000, and 2001.

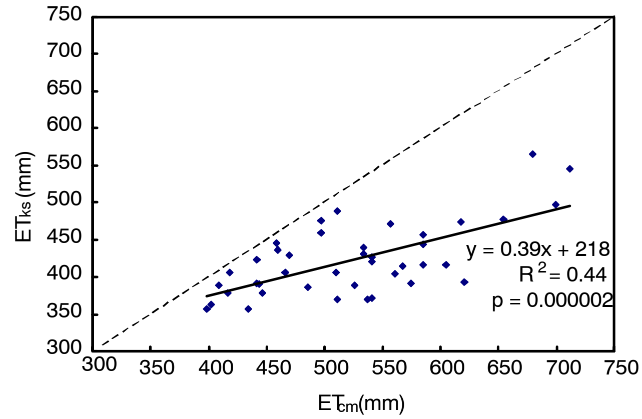

Figure 4. Comparison between estimated crop water use from the KanSched (ET_{ks}) and CERES-Maize (ET_{cm}) models between 1999 and 2001 for field sites in south central Kansas.

For most commercial sites, full irrigation depths were within the targeted range except on two sites. One site was under-irrigated (76 mm, JM, 2000), because of a limited water right. The other site (SM) was over-irrigated (139 mm) in the wetter year (1999) of the study (fig. 3). The field scheduled treatment results from the SL site (solid dots) were very close to required amounts. Most of the commercial farm sites had applied net irrigation amounts to their standard irrigation zones that were very close to required values as indicated by the KanSched water balance.

CERES-Maize Simulation Results

KanSched ET_{ks} values were consistently lower than CERES-Maize ET_{cm} values (fig. 4). Data were variable, resulting in an R^2 value of 0.44. Probable reasons for the differences may include: (1) the KanSched crop ET values do not account for the first few weeks after planting which represent up to 25-30 mm; (2) uncertainty in the field water balance data; (3) KanSched uses a different crop coefficient algorithm; (4) ET_{ks} and ET_{cm} are each calculated using different ET models (Penman-Montieth and Priestly-Taylor (Priestly and Taylor, 1972), respectively); and (5) CERES-Maize calculates evaporation from wet surfaces, but the KanSched program does not.

Simulated corn grain yield, from all treatments and sites ranged from 7.9 to 13.8, 6.9 to 17.1, and 6.6 to 13.8 Mg ha^{-1} in 1999, 2000, and 2001, respectively (table 6). Simulated yields increased linearly with crop ET (R^2 = 0.44; p = 0.000002) (fig. 5) and had a stronger relationship than the measured data (fig. 1). Furthermore, the slope of that relationship shows an apparent water use efficiency of 0.020 Mg ha^{-1}-mm, which is very close to the 0.018 Mg ha^{-1}-mm reported by Lamm et al. (1994).

Simulated yields for individual sites did not visually correlate well with measured yields (fig. 6) on a site-by-site basis. In a paired t-test analysis, measured yields were

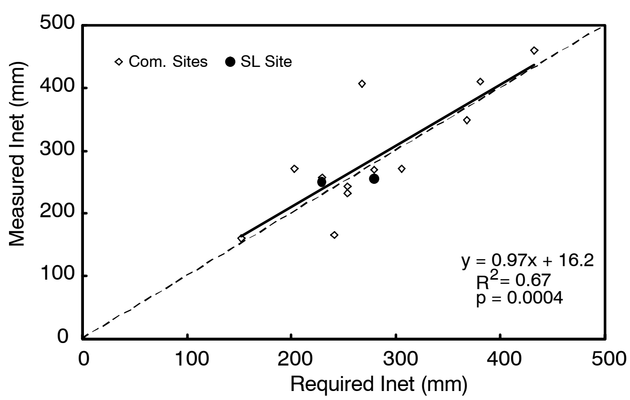

Figure 3. Measured net applied irrigation (Measured Inet) amounts for treatment III from commercial sites (Com.) and treatment II from the SL site and KanSched-based net required irrigation (Required Inet) amounts for the same treatments and sites. The diagonal line is 1:1.

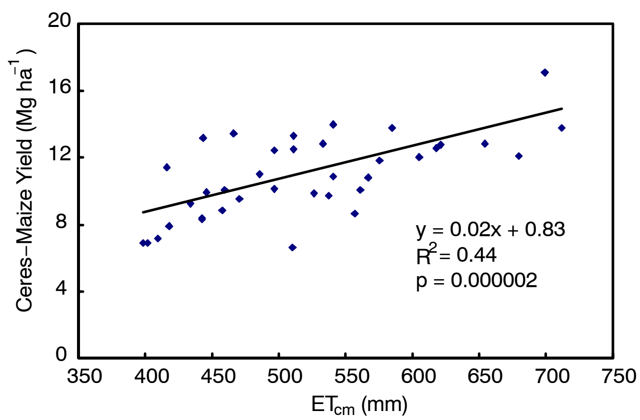

Figure 5. CERES-Maize simulated yield and CERES-Maize seasonal water use (ET_{cm}) for the various irrigation treatment levels on the field sites in south central Kansas in 1999, 2000, and 2001.

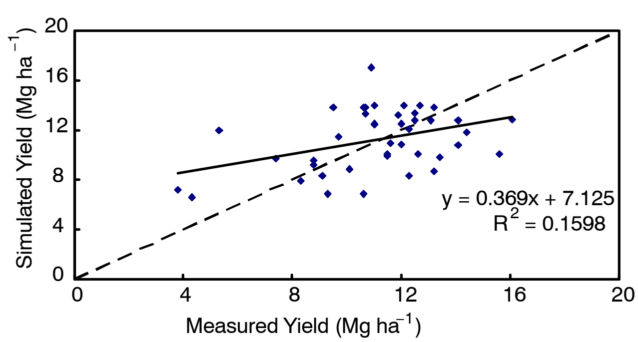

Figure 6. Simulated corn yield vs. measured values for the various irrigation treatment levels on the field sites in south central Kansas in 1999, 2000, and 2001. The diagonal line is 1:1.

Table 7. Statistical comparison between annual measured and simulated corn yields for 1999, 2000, and 2001.

Year/Range	Measured Yield (Mg ha^{-1})	Simulated Yield (Mg ha^{-1})	Significance[a] (T-Test p-values)
1999	10.8	11.7	0.058
2000	11.3	11.5	0.387
2001	11.1	10.3	0.244
1999-2000	11.1	11.2	0.381
Lower range	9.0	10.8	0.004
Upper range	12.9	11.6	0.004

[a] T-Test, paired sample p-values are shown for each grouping of yield results.

slightly lower ($p = 0.058$) than simulated yields in 1999 (table 7). However, yield differences were not significant in 2000, 2001, or for the three years (table 7). Simulated yields were typically greater than measured yields on the low end of the measured yield scale and were less than measured yields on the greater end of the scale. In a paired t-test analysis of sorted data (sorted based on measured yield) the lower range of measured yields (<11.0 Mg ha^{-1}) was significantly lower at 9.0 Mg ha^{-1} (table 7) than simulated yields at 10.8 Mg ha^{-1} ($p = 0.004$). In addition, the upper range (>11.5 Mg ha^{-1}) of the sorted measured yield data was significantly greater at 12.9 Mg ha^{-1} (table 7) than the simulated yield data at 11.6 Mg ha^{-1} ($p = 0.004$).

Summary and Conclusions

A field study involving seven field sites was conducted to evaluate the effect of sprinkler irrigation applications on corn grain yield in south central Kansas in 1999 through 2001. Irrigation systems used in this study included one linear move and six commercial center pivot sprinkler irrigation systems. Sprinklers on those systems were nozzled to provide irrigation application rates ranging from 50% to 135% of full irrigation. The KanSched irrigation scheduling program was used to create comparative irrigation schedules for each test zone of each site. Those schedules were also used in CERES-Maize model simulations as inputs. Additionally, corn growth simulation model (CERES-Maize v.3.5) yield response to deficit irrigation practices was also evaluated in this study. The CERES-Maize model was run with the data collected in 1999 through 2001 including irrigation and precipitation amounts.

Deficit irrigation amounts for all three years ranged from 10 to 180 mm while excess irrigation amounts ranged from 8 to 139 mm. Measured irrigation amounts for all sites and treatments ranged from 71 to 406, 100 to 269, and 191 to 559 mm in 1999, 2000, and 2001, respectively. The KanSched-based crop ET (ET_{ks}) ranged from 370 to 488, 356 to 426, and 386 to 566 mm while CERES-Maize simulated crop ET values were greater and ranged from 418 to 585, 398 to 699, and 409 to 712 mm for all sites in 1999, 2000, and 2001, respectively. Measured corn grain yield from all treatments ranged from 9.5 to 13.1, 7.4 to 14.4, and 3.8 to 16.1 Mg ha^{-1} while CERES-Maize corn yield simulations for all treatment zones ranged from 7.9 to 13.8, 6.9 to 17.1, and 6.6 to 13.8 Mg ha^{-1} in 1999, 2000, and 2001, respectively. The average measured yield from all sites and years of 11.1 Mg ha^{-1} was not significantly different from the average CERES-Maize simulated yield of 11.2 Mg ha^{-1} for all sites and years. However, CERES-Maize under predicted measured yield in the upper half of the measured range and over predicted measured yield in the lower half of the measured yield range.

The KanSched program results indicated that the soil water status was on target and that the greatest yield occurred at a relative net irrigation (R_I = Net applied irrigation amount/Net required irrigation amount) value of 1.0 (full irrigation). Furthermore, field data indicated that maintaining a relative net irrigation ratio between 0.85 and 1.00 resulted in no yield loss, and that relative net irrigation ratios that exceeded 1.0 did not have any yield advantage. However, yields declined when the relative net irrigation ratio dropped to 0.70 or less. Thus, these studies demonstrate that the KanSched program can be successfully used as a scheduling tool for corn in south central Kansas and that optimum yield can be expected as long as net irrigation applications remain within 85% of the net irrigation recommendation by the program.

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