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CORN IRRIGATION MACROMANAGEMENT AT THE SEASONAL BOUNDARIES –

INITIATING AND TERMINATING THE IRRIGATION SEASON

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ABSTRACT

Decisions about when to initiate and terminate the irrigation season are important irrigation macromanagement decisions that can potentially save water and increase net income when made correctly, but can have negative economic consequences when made incorrectly. A combination of nine years of pre-anthesis water stress studies and sixteen years of post-anthesis water stress studies for corn was conducted at the Kansas State University Northwest Research-Extension Center in Colby, Kansas on a productive, deep, silt loam soil. Overall, the pre-anthesis water stress studies suggest that corn grown on this soil type has great ability to handle early-season water stress, provided the water stress can be relieved during later stages. A critical factor in maximizing corn grain yields as affected by pre-anthesis water stress is maximizing the kernels/area. Maintaining a water deficit ratio (well-watered calculated corn water use / sum of irrigation and precipitation) greater than 0.7 to 0.8 or limiting available soil water depletion in the top 4 ft of soil profile to approximately 30% maximized the kernels/area. Overall, the post-anthesis water stress studies suggest that corn yield is nearly linearly related to the amount of crop water use during the post-anthesis period and that total crop water use amounts may average nearly 17 inches. Producers should plan for crop water use during the last 30 and 15 day periods that may average nearly 5 and 2 inches, respectively, to avoid yield reductions. Management allowable depletion during the post-anthesis period should be limited to 45% of the available soil water for an 8-ft profile on the deep silt loam soils of this climatic region.

INTRODUCTION

Definition of Macromanagement and Scope of the Problem

Corn (Zea mays L.) is the primary irrigated crop in the U.S. Great Plains. There are a number of efficient methods to schedule irrigation for corn on a real-time, daily, or short-term basis throughout the season. These scheduling methods essentially achieve water conservation by delaying any unnecessary irrigation event with the prospect that the irrigation season might end before the next irrigation event is required. There are larger irrigation management decisions [i.e., irrigation macromanagement (Lamm et al., 1996)] that can be considered separately from the step-by-step, periodic scheduling procedures. Two important macromanagement decisions occur at the seasonal boundaries, the initiation and termination of the irrigation season. Irrigators sometimes make these seasonal boundary determinations based on a traditional time-of-year rather than with sound rationale or science-based procedures. However, a single, inappropriate, macromanagement decision can easily have a larger effect on total irrigation water use and/or crop production than the cumulative errors that might occur due to small, systematic errors in soil-, plant-, or climatic-based scheduling procedures. This does not discount step-by-step irrigation scheduling. To the contrary, it is an implicit assumption that improved macromanagement at the seasonal boundaries can only provide the potential for increased water conservation when used in conjunction with the step-by-step, periodic scheduling procedures.

Most of the established literature on irrigation management during the early and late corn growth stages is 35-45 years old and was written at a time when irrigated corn yields were much lower (50-100 bu/acre lower) than they are today. It is quite possible that some of the numerous yield-limiting stresses (e.g., water, insects, weeds, nutrient, and soil) that were tolerable at the lower yield level are less tolerable today. On the other side of the issue, there has been much improvement in corn hybrids during the period with incorporation of traits that allow water stress tolerance and/or water stress avoidance.

Pre-Anthesis Water Stress

The corn vegetative stage is often considered the least-sensitive stage to water stress and could provide the opportunity to limit irrigation water applications without severe yield reductions. The vegetative stage begins at crop emergence and ends after tasseling, which immediately precedes the beginning of the reproductive period when the silks start to emerge. The potential number of ears/plant is established by the fifth leaf stage in corn. The potential number of kernels/ear is established during the period from about the ninth leaf stage until about one week before silking. Stresses during the 10 to 14 days after silking will reduce the potential kernels/ear to the final or actual number of kernels/ear. Therefore, in research studies designed to examine water stresses during the first one-half of the corn crop season, both ears/plant and kernels/ear might be critical factors. Additionally, there could be permanent damaging effects from the vegetative and early-reproductive period water stress that may affect grain filling (kernel weight). Often, irrigators in the Great Plains, start their corn irrigation season after early season cultural practices are completed such as herbicide or fertilizer application or crop cultivation at the lay-by growth stage (approximately 18-24 inch corn height). Crop evapotranspiration is increasing rapidly and drier weather periods are approaching, so often there is soil water storage that can be replenished by timely irrigation then for use later in the summer. However, this does not always mean that the corn crop required the irrigation at that point-in-time.

Post-Anthesis Water Stress

In contrast, the post-anthesis grain filling stage in corn is considered to be highly sensitive to water stress with only the flowering and early reproductive period being more sensitive. Plant water stress can cause kernel abortion if it occurs early enough in the post-anthesis period but is more often associated with poor grain filling and thus reduced kernel weight. Grain kernel weight is termed as a very loosely restricted yield component (Yoshida, 1972; Shaw, 1988), meaning that it can be manipulated by a number of factors. The final value is also set quite late, essentially only a few days before physiological maturity. The rate of grain filling is linear for a relatively long period of time from around blister kernel to near physiological maturity. Yield increases of over 4 bushels/acre for each day are possible during this period. Providing good management during the period can help to provide a high grain filling rate and, in some cases, may extend the grain filling period a few days thereby increasing yields. Availability of water for crop growth and health is the largest single controllable factor during this period. However, the rate of grain filling remains remarkably linear unless severe crop stress occurs (Rhoads and Bennett, 1990). This is attributed to remobilization of photosynthate from other plant parts when conditions are unfavorable for making new photosynthate. Irrigators in the Central Great Plains sometimes terminate the corn irrigation season on a traditional date such as August 31 or Labor Day (First Monday in September) based on long term experience. However, a more scientific approach might be that season termination may be determined by comparing the anticipated soil water balance at crop maturity to the management allowable depletion (MAD) of the soil water within the root zone. Some publications say the MAD at crop maturity can be as high as 0.8 (Doorenbos and Kassam, 1979). Extension publications from the Central Great Plains often suggest limiting the MAD at season end to 0.6 in the top 4 ft of the soil profile (Rogers and Sothers, 1996). These values may need to be re-evaluated and perhaps adjusted downward (smaller MAD value). Lamm et al. (1995) found subsurface drip-irrigated corn yields in northwest Kansas began to decrease rapidly when available soil water in the top 8 ft was lower than 56-60% of field capacity for extended periods in July and August. Lamm et al. (1994) permitted small daily deficits to accumulate on surface-irrigated corn after tasseling, and subsequent analysis of those data showed declining yields when available soil water levels approached 60% of field capacity for a 5-ft soil profile at physiological maturity

General Objective

This presentation will summarize the results from several long term field studies at the KSU Northwest Research-Extension Center in Colby, Kansas on a productive, deep, silt loam soil where irrigation treatments were either initiated or terminated at various points-in- time before and after anthesis, respectively.

PROCEDURES

General Procedures

The studies were conducted at the KSU Northwest Research-Extension Center at Colby, Kansas,USA on a productive, deep, well-drained Keith silt loam soil (Aridic Argiustolls) during the sixteen-year period, 1993-2008. In general, the 1990s were a much wetter period than the 2000s. The summers of 2000 through 2003 would be considered extreme droughts. The climate for the region is semi-arid with a summer pattern of precipitation with an annual average of approximately 19 inches. The average precipitation and calculated corn evapotranspiration during the 120-day corn growing period, May 15 through September 2 is 11.8 inches and 23.1 inches, respectively. The corn anthesis period typically occurs between July 15 and 20.

The corn was planted in 2.5 ft spaced rows in late April to early May, and standard cultural practices for the region were used.

Irrigation was scheduled as needed by a climate-based water budget except as modified by study protocols that will be discussed in the sections that follow. Calculated crop evapotranspiration (ET_c) was determined with a modified Penman equation for calculating reference evapotranspiration (ET_r) multiplied by empirical crop coefficients suitable for western Kansas. Precipitation and irrigation were deposits into the crop water budget and ET_c was the withdrawal.

Soil water was measured in each plot on a weekly or biweekly basis with a neutron probe to a depth of 8 ft. in 1-ft increments. These data were used to determine crop water use and to determine critical soil water depletion levels. Water use values were calculated as the sum of the change in available soil water to the specified profile depth, plus the irrigation and precipitation during the specified period. This method of calculating crop water use would also include any deep percolation or rainfall runoff that may have occurred.

Corn yield and yield components of plants/area, ears/plant, and kernel weight were measured by hand harvesting a representative 20-ft row sample. The number of kernels/ear was calculated with algebraic closure using the remaining yield components.

Specific Procedures for Pre-Anthesis Water Stress Studies

Data from two studies where the initiation date of the irrigation season was varied were combined in the analysis. The first study consisted of five years of data (1999 through 2003) with the hybrid Pioneer 3162 (full season, 118 days to maturity). The second study during the four-year period (2004 through 2007) used two corn hybrids [Pioneer 32B33 (full season, 118 days to maturity) and Pioneer 33B50 (medium season, 112 days to maturity)]. Both studies utilized the same field site that had a subsurface drip irrigation (SDI) system installed in 1990 with 5-ft dripline spacing and an emitter spacing of 12 inches. The 2.5-ft spaced corn rows were planted parallel and centered on the driplines such that each corn row would be 15 inches from the nearest dripline. The nominal dripline flowrate was 0.25 gpm/100 ft, which is equivalent to an emitter discharge of 0.15 gal/h for the 12-inch emitter spacing. The 2004-2007 study had six main irrigation treatments and the two corn hybrid split-plot treatments replicated three times in a randomized complete block (RCB) design. The 1999-2003 study used the same experimental design without the split plot. The whole plots were 8 rows wide (20 ft) and 200 ft long.

The six irrigation treatments (pre-anthesis water stress studies) were imposed by delaying the first normal irrigation either 0, 1, 2, 3, 4, or 5 weeks. This typically resulted in the first irrigation for Trt 1 being between June 5 and June 15 and the first irrigation for Trt 6 being around July 10 to July 24. In some years, excessive rainfall between two adjacent treatment initiation dates would negate the need for irrigation. In that case, the later treatments would be delayed an additional week to provide an extended data set. After the treatment initiation date occurred, SDI was scheduled to provide 0.4 inches/day until such time that the climate-based water budget fully eliminated calculated soil water deficits. It should be noted that this irrigation capacity of 0.4 inches/day is much greater than the typical irrigation capacity in this region. Additionally, the procedure of eliminating the severe irrigation deficits later in the season after the plants had been stunted may lead to excessive deep percolation. The purpose of the study was not to optimize irrigation use within the study but rather to determine what capability the corn crop had to tolerate early season water stress. Thus, the procedures were tailored to alleviate soil water deficits relatively quickly after the treatment initiation date.

Analysis of variance (AOV) of the yield and yield component data was performed for the 6 treatments for the 1999-2003 data set using a one-way AOV and using a split plot two-way AOV for the 2004-2007 data set.

Specific Procedures for Post-Anthesis Water Stress Studies

Four separate studies were conducted over the years 1993 through 2008 to examine the effects of post-anthesis water stress on corn. Prior to anthesis, all treatments in each of the studies were fully irrigated according to their need.

A two-year study (1993 through 1994) consisting of six irrigation treatments with three replications in a complete randomized block design was conducted in small level basins consisting of 6 corn rows each (15 ft) approximately 90 ft long. Surface irrigation was used to provide irrigation amounts for each event that were between 2.5 to 3 inches to help achieve higher distribution uniformity than smaller applications would have provided. The six irrigation treatments were termination of the irrigation season on either August 5, 10, 15, 20, 25 or 30. The corn hybrid was Pioneer 3183 (a full season hybrid of approximately 118 day maturity). The year 1993 was an extremely poor corn production year characterized by very cool and wet conditions while 1994 was a good year for corn production.

A four-year study (1995 through 1998) consisting of nine irrigation treatments with four replications in a complete randomized block design was conducted in small level basins consisting of 8 corn rows each (20 ft) approximately 90 ft long. Surface irrigation was used in this study with event irrigation amounts of approximately 2.5 to 3 inches. The nine irrigation treatments were termination of the irrigation season at either anthesis, anthesis plus 6, 12, 18, 24, 30, 36, 42 or 48 days. The corn hybrid was Pioneer 3183 (a full season hybrid of approximately 118 day maturity). Corn yields in 1995 were somewhat depressed due to a hail storm but were good in 1996 through 1998.

Another study was conducted from 1999 through 2001 using subsurface drip irrigation to more closely control soil water levels and distribution uniformity of irrigation water. In this study, seven irrigation treatments were replicated three times in a complete randomized block with plot size of 8 corn rows (20 ft) by approximately 280 ft. In this study irrigation during the post-anthesis period was managed for two distinct periods. Four of treatments began at anthesis with one treatment receiving no irrigation after anthesis and the other three treatments only receiving irrigation if the available soil water in the top 5 foot of profile fell below approximately 68, 48 or 27% of field capacity. Three additional treatments were no irrigation after two weeks following anthesis and soil water maintenance level treatments of either 48 or 27% of field capacity beginning also at that time. After anthesis, irrigation amounts were generally not greater than 0.5 inches for each required event and were conducted as needed to return the available soil water to the required treatment level. The year 1999 had above normal precipitation but 2000 and 2001 were extreme drought years. This study utilized an subsurface drip irrigation (SDI) system installed in 1999 with 5-ft dripline spacing and an emitter spacing of 24 inches. The 2.5-ft spaced corn rows were planted parallel and centered on the driplines such that each corn row would be 15 inches from the nearest dripline. The nominal dripline flowrate was 0.25 gpm/100 ft, which is equivalent to an emitter discharge of 0.30 gal/h for the 24-inch emitter spacing. The corn hybrid was Pioneer 3162 (a full season hybrid of approximately 118 day maturity).

The final post-anthesis water stress study (2002 through 2008) was conducted on the same SDI field site as the 1999 through 2001 study but the seven irrigation treatments were the irrigation season being terminated at one week intervals beginning one week after anthesis. This typically meant that the first irrigation treatment ceased about July 20 to 27 and the last irrigation treatment ceased about August 31 to September 7. The crop was fully irrigated until the irrigation termination date occurred and irrigation event amounts were generally not greater than 0.5 inches. The seven irrigation treatments were replicated three times in a complete randomized block design. The corn hybrid was Pioneer 3162 (a full season hybrid of approximately 118 day maturity). Post anthesis water productivity was calculated as the crop yield in bu/acre divided by the post-anthesis crop water use.

RESULTS AND DISCUSSION

Results for Pre-Anthesis Water Stress Studies

Statistical and tabular data analysis for pre-anthesis water stress studies

Delaying irrigation only statistically affected the yield components in three of the nine crop years and then only for the later irrigation dates (Tables 1 and 2). Delaying irrigation until July 10, 2001, July 17, 2003 and July 27, 2005 significantly reduced the number of kernels/ear and the grain yield. These three years had an average weather-based calculated July crop ET_c rate of 0.32 inches/day. In comparison the average July crop ET_c rate value was 0.26 inches/day for the other six years. It should be noted that the years 2000 through 2003 were extreme drought years in northwest Kansas. Delaying irrigation also significantly reduced ears/plant in 2003 and 2005. In 2003, the reduction in kernels/ear and ears/plant for Trt 6 was partially compensated for by a statistically higher kernel weight. Overall, these results suggest that corn grown on this soil type has great ability to handle vegetative and early-reproductive period water stress provided the water stress can be alleviated during the later stages.

The hybrid selection affected yield in only one of the four years, 2006, with the longer season Pioneer 32B33 providing significantly greater yields for the later irrigation initiation dates (Table 2). This is probably because of earlier pollination for the Pioneer 33B50 prior to receiving irrigation. Kernels/ear was significantly less for the shorter season Pioneer 33B50 hybrid in three of four years. Hybrid selection did not affect ears/plant in any of the four years. In 2004, kernel weight was significantly higher for Pioneer 33B50 for some irrigation treatments, probably because of the smaller number of kernels/ear for this hybrid in that year.

It should be noted that the results do not mean that irrigation can be delayed in the Western Great Plains until mid to late July. These plots generally started the season with reasonably full soil profiles. Most irrigators do not have irrigation systems with adequate capacity (gpm/acre) to quickly alleviate severely depleted soil water reserves. In addition, it is difficult to infiltrate large amounts of water into the soil quickly with sprinkler and surface irrigation systems without causing runoff problems. Rather, look at these study results as describing the corn plant’s innate ability to tolerate vegetative-period water stress.

Table 1. Summary of yield component and irrigation data from an early season water stress study for corn hybrid Pioneer 3162, KSU-NWREC, Colby, Kansas, 1999-2003.

Year and Parameter	**Trt 1**	**Trt 2**	**Trt 3**	**Trt 4**	**Trt 5**	**Trt 6**
1999 First Irrigation Date	22-Jun	29-Jun	6-Jul	13-Jul	20-Jul	27-Jul
Total Irrigation (in.)	11.2	11.2	11.2	10.0	10.0	7.6
Yield (bu/a)	253 a*	265 a	256 a	255 a	259 a	255 A
Plant Pop. (p/a)	31073 A	32234 a	31944 a	31653 a	32234 a	32234 A
Ears/Plant	0.99 A	0.99 a	0.97 a	1.00 a	0.99 a	1.01 A
Kernels/Ear	575 A	570 a	555 a	572 a	543 a	555 A
Kernel Wt. (g/100)	36.3 A	36.9 a	37.8 a	35.8 a	38.1 a	35.9 A
2000 First Irrigation Date	5-Jun	12-Jun	19-Jun	26-Jun	3-Jul	10-Jul
Total Irrigation (in.)	19.7	19.7	19.7	18.9	18.9	18.9
Yield (bu/a)	225 A	235 a	225 a	227 a	216 a	217 A
Plant Pop. (p/a)	27878 A	28169 a	26717 a	26717 a	27007 a	27297 A
Ears/Plant	1.02 A	1.04 a	0.99 a	1.03 a	1.02 a	1.01 A
Kernels/Ear	544 A	553 a	568 a	544 a	548 a	529 A
Kernel Wt. (g/100)	36.9 a	36.8 a	38.0 a	38.4 a	36.4 a	37.8 A
2001 First Irrigation Date	12-Jun	19-Jun	26-Jun	3-Jul	10-Jul	17-Jul
Total Irrigation (in.)	19.2	19.2	19.2	19.2	19.2	19.2
Yield (bu/a)	254 a	260 a	261 a	250 a	213 b	159 C
Plant Pop. (p/a)	33977 a	34993 a	35138 a	35284 a	34413 a	33831 A
Ears/Plant	0.96 a	0.98 a	0.99 a	0.99 a	0.97 a	0.99 A
Kernels/Ear	581 a	584 a	582 a	541 a	476 b	347 C
Kernel Wt. (g/100)	33.8 a	33.2 a	32.8 a	33.7 a	34.6 a	34.9 A
2002 First Irrigation Date	12-Jun	19-Jun	26-Jun	3-Jul	10-Jul	17-Jul
Total Irrigation (in.)	18.5	18.0	18.0	18.0	18.0	18.0
Yield (bu/a)	233 a	232 a	217 a	219 a	222 a	223 A
Plant Pop. (p/a)	34558 a	34848 a	34558 a	35719 a	35719 a	34558 A
Ears/Plant	0.98 a	0.97 a	0.98 a	0.99 a	1.00 a	0.99 A
Kernels/Ear	454 a	443 a	407 a	435 a	391 a	422 A
Kernel Wt. (g/100)	38.6 a	39.8 a	40.3 a	36.6 a	40.5 a	39.2 A
2003 First Irrigation Date	12-Jun	21-Jun	26-Jun	3-Jul	10-Jul	17-Jul
Total Irrigation (in.)	18.8	18.0	18.0	17.2	17.2	17.2
Yield (bu/a)	177 a	180 a	190 a	186 a	171 a	93 B
Plant Pop. (p/a)	32815 a	33396 a	34267 a	33106 a	34558 a	32815 A
Ears/Plant	0.96 a	0.92 b	0.96 a	1.00 a	0.97 a	0.82 C
Kernels/Ear	588 a	567 a	576 a	569 a	486 b	262 C
Kernel Wt. (g/100)	24.1 b	26.2 b	25.5 b	25.2 b	26.8 b	33.6 A

** Values followed by the same lower case letters are not significantly different at P=0.05.*

Table 2. Summary of corn yield component and irrigation data from an early season water stress study for hybrids Pioneer 33B50 and 32B33, KSU-NWREC, Colby, Kansas, 2004-2007.

Year and Parameter	**Hybrid**	**Trt 1**	**Trt 2**	**Trt 3**	**Trt 4**	**Trt 5**	**Trt 6**
2004 First Irrigation	**Hybrid**	8-Jun	28-Jun	13-Jul	20-Jul	27-Jul	3-Aug
Total Irrig. (in.)		12.8	11.6	10.8	10.8	10.8	10.8
Yield (bu/a)	33B50	220 aA*	213 aA	206 aA	233 aA	245 aA	210 aA
	32B33	226 aA	211 aA	209 aA	222 aA	229 aA	206 aA
Plant Pop. (p/a)	33B50	29040 aA	28169 aA	28169 aA	28169 aA	28750 aA	27878 aA
	32B33	28459 aA	29621 aA	29621 aA	28459 aA	29040 aA	28459 aA
Ears/Plant	33B50	0.85 aA	0.91 aA	0.89 aA	0.93 aA	0.88 aA	0.84 aA
	32B33	0.88 aA	0.80 aA	0.79 aA	0.90 aA	0.83 aA	0.83 aA
Kernels/Ear	33B50	595 aB	574 aB	589 aB	595 aA	648 aA	590 aB
	32B33	624 aA	616 aA	634 aA	600 aA	643 aA	612 aA
Kernel Wt. (g/100)	33B50	38.0 aA	36.8 aA	35.7 aA	38.2 aA	38.2 aA	38.6 aA
	32B33	36.8 aB	36.4 aA	36.2 aA	36.8 aB	37.6 aA	36.4 aB
2005 First Irrigation	**Hybrid**	21-Jun	28-Jun	6-Jul	12-Jul	19-Jul	26-Jul
Total Irrig. (in.)		13.2	13.2	13.2	13.2	13.2	13.2
Yield (bu/a)	33B50	254 aA	259 aA	256 aA	238 abA	227 bA	149 cA
	32B33	254 abcA	254 abcA	258 abA	264 aA	235 cA	162 dA
Plant Pop. (p/a)	33B50	28750 aA	28459 aA	28459 aA	28459 aA	29621 aA	28169 aA
	32B33	28459 aA	29040 aA	28459 aA	27848 aA	28750 aA	29621 aA
Ears/Plant	33B50	0.99 abA	1.00 aA	0.99 abA	0.98 abA	0.96 bcA	0.95 cA
	32B33	0.98 bA	0.97 bcA	1.01 aA	1.00 abA	0.96 bcdA	0.94 dA
Kernels/Ear	33B50	641 abA	653 aA	670 aA	604 bA	564 cA	422 dA
	32B33	638 bA	647 abA	644 abA	680 aA	654 abA	421 cA
Kernel Wt. (g/100)	33B50	35.4 aA	35.4 aA	34.5 aA	36.0 aA	35.9 aA	33.6 aA
	32B33	36.2 aA	35.4 aA	35.4 aA	35.5 aA	33.1 aA	35.1 aA
2006 First Irrigation	**Hybrid**	8-Jun	15-Jun	26-Jun	29-Jun	6-Jul	14-Jul
Total Irrig. (in.)		14.0	13.6	12.8	12.8	12.4	12.4
Yield (bu/a)	33B50	225 aA	230 aA	220 aB	220 aA	220 aB	206 aB
	32B33	229 aA	234 aA	246 aA	230 aA	241 aA	244 aA
Plant Pop. (p/a)	33B50	27588 aA	27007 aA	28169 aA	28169 aA	27588 aA	27297 aA
	32B33	28459 aA	27878 aA	28459 aA	27878 aA	28168 aA	28169 aA
Ears/Plant	33B50	0.98 aA	0.98 aA	0.99 aA	0.99 aA	0.99 aA	0.96 aA
	32B33	0.96 aA	0.98 aA	0.98 aA	0.97 aA	0.98 aA	0.97 aA
Kernels/Ear	33B50	561 aB	594 aAB	544 aB	547 aB	550 aB	519 aB
	32B33	597 aA	602 aA	618 aA	583 aA	585 aA	612 aA
Kernel Wt. (g/100)	33B50	37.8 aA	37.2 aA	36.8 aA	36.5 aA	37.4 aA	38.7 aA
	32B33	35.7 aA	36.2 aA	36.3 aA	37.1 aA	38.1 aA	37.2 aA
2007 First Irrigation	**Hybrid**	7-Jun	21-Jun	28-Jun	4-Jul	12-Jul	19-Jul
Total Irrig. (in.)		12.1	11.3	11.3	11.3	11.3	10.9
Yield (bu/a)	33B50	243 aA	252 aA	250 aA	245 aA	234 aA	213 aA
	32B33	259 aA	235 aA	252 aA	239 aA	255 aA	229 aA
Plant Pop. (p/a)	33B50	29040 aA	29621 aA	29331 aA	28459 aA	29040 aA	28169 aA
	32B33	29040 aA	28459 aA	28169 aA	27878 aA	28459 aA	28169 aA
Ears/Plant	33B50	0.98 aA	0.99 aA	1.00 aA	0.99 aA	0.99 aA	1.00 aA
	32B33	0.98 aA	0.95 aA	0.99 aA	0.99 aA	0.99 aA	0.97 aA
Kernels/Ear	33B50	668 aB	672 aB	693 aA	682 aA	645 aB	597 aB
	32B33	728 aA	724 aA	712 aA	712 aA	714 aA	674 aA
Kernel Wt. (g/100)	33B50	32.5 aA	32.5 aA	31.2 aA	32.4 aA	32.0 aA	32.2 aA
	32B33	31.6 aA	30.6 aA	32.3 aA	30.9 aA	32.3 aA	31.7 aA

* *Irrigation treatment values within the same row followed by the same lower case letters are not significantly different at P=0.05, and hybrid treatment values within the same column followed by the same upper case letters are not significantly different at P=0.05.*

Graphical data analysis for pre-anthesis water stress studies

The tabular data do not give a mechanistic explanation of the results. Attempts were made to relate yield component data to a large number of water factors in the broad categories of water use, evaporative demand, and critical profile soil water levels. Relative values of yield and yield components were determined by normalizing each data point to the corresponding value for the earliest irrigation treatment in that year. These relative values were used for comparisons between years. Final grain yield was largely determined by the number of sinks or kernels/area (plants/area x ears/plant x kernels/ear) indicating there was little or no effect on the grain-filling stage imposed by the vegetative and early-reproductive period water stress in these two studies (Figure 1). The individual treatment values of corn grain yield and kernels/area were values compared to the irrigation treatment that had no initial delay in irrigation (Trt 1) to give relative values. In a few cases, the Trt 1 values were not the highest value and, thus, relative values could be greater than one. Deviations below the 1 to 1 unity line in Figure 1 would indicate a permanent negative effect on corn grain yield of early-season water stress because of reduced kernels/area. Deviations above the line would indicate some grain yield compensation resulting from better grain filling of the reduced kernels/area.

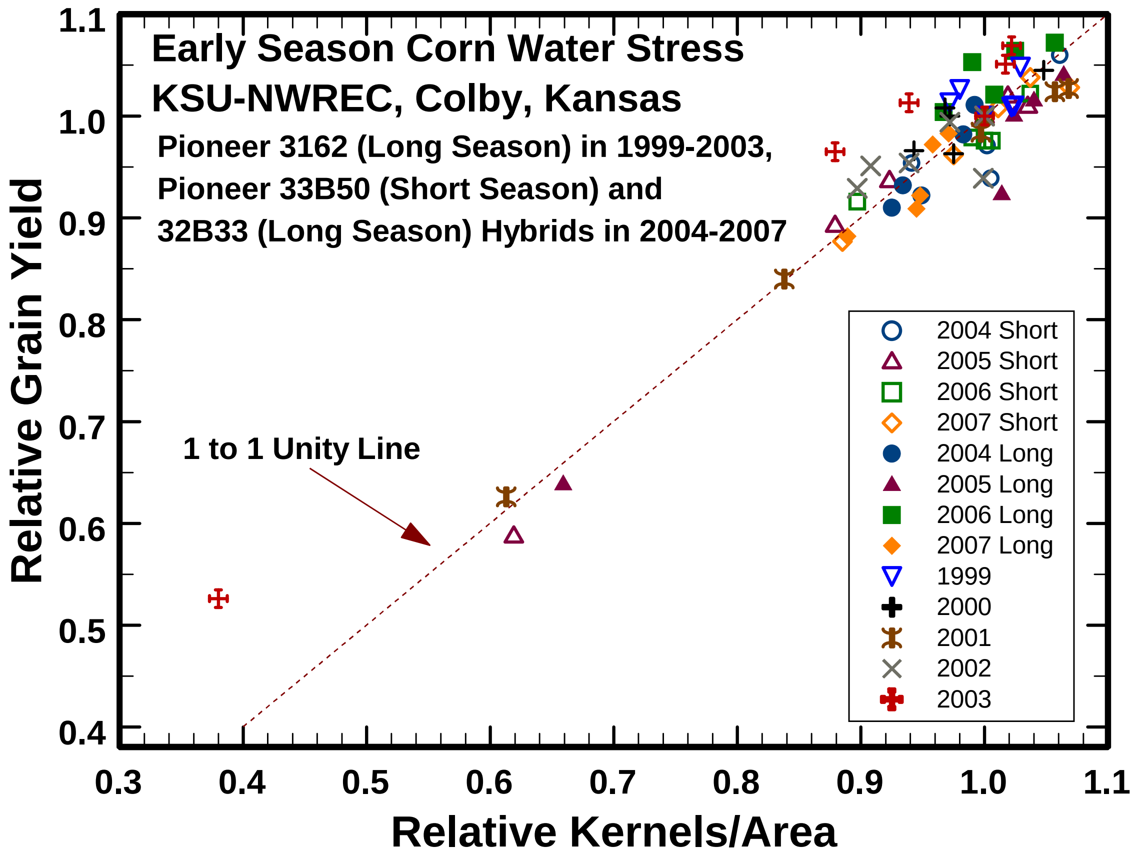

Figure 1. Relative corn grain yield as affected by relative kernels/area in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

Relative kernels/area was found to be reasonably well related to relative July water use, the minimum available soil water in the top 4 ft of the soil profile during July and to the July 1 through July 15 water deficit (Ratio of calculated well-watered corn ETc to the sum of irrigation and precipitation). Further analysis is needed to determine an improved overall relationship involving more than a single factor, but the individual factor results will be discussed here.

The 50% critical silking period for corn in this study ranged from approximately July 17 to July 22 during the study period (1999 to 2007). The short-season hybrid in the latter study would typically silk approximately one week earlier. A window of approximately two weeks on both sides around the silking period was used to compare the relative kernels/area to the relative July measured water use (sum of change in available soil water in July plus July irrigation and precipitation). Actual soil water measurements were taken on an approximately weekly basis except for equipment problems or when excessive precipitation delayed measurements, so it was not possible with the data set to always have exactly 31 days of water use. Dates used were those closest to July 1 through 31. There tended to be some reduction in relative kernels/area when relative July water use was less than 80% (Figure 2). Scatter at the lower end of relative July water use may be related to water-use differences occurring within the month or differences in evaporative demand between the years. This relationship may not result in a very good signal for procedures to determine irrigation need because the relative July water use cannot be determined until it is too late to handle the reduction in relative kernels/area.

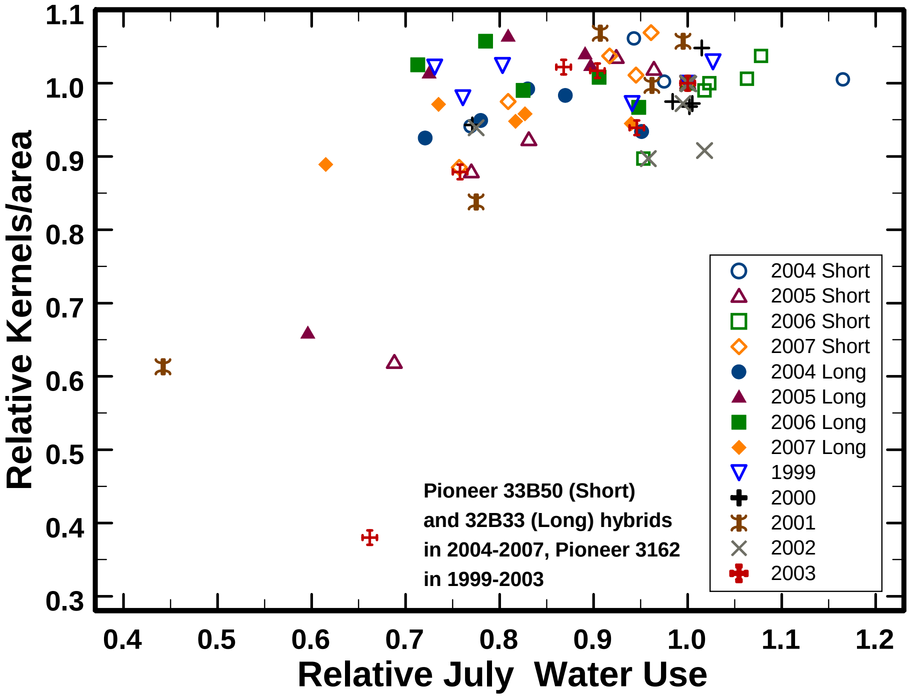

Figure 2. Relative corn grain yield as affected by relative July water use in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

The relative kernels/area tended to be reduced when July minimum available soil water in the top 4 ft (JASW) was below 0.6 (fraction) in some years (Figure 3). During years of less evaporative demand, water could be extracted from the soil profile to a further reduced level without much detriment to relative kernels/area, but severe reductions occurred for similar soil water conditions in years with large July evaporative demands. The upper and lower envelope lines of Figure 3 were manually drawn to indicate the effect of evaporative demand of the given year on relative kernels/area. These envelopes would match known theories of water stress and water flow through plants (Denmead and Shaw, 1962).

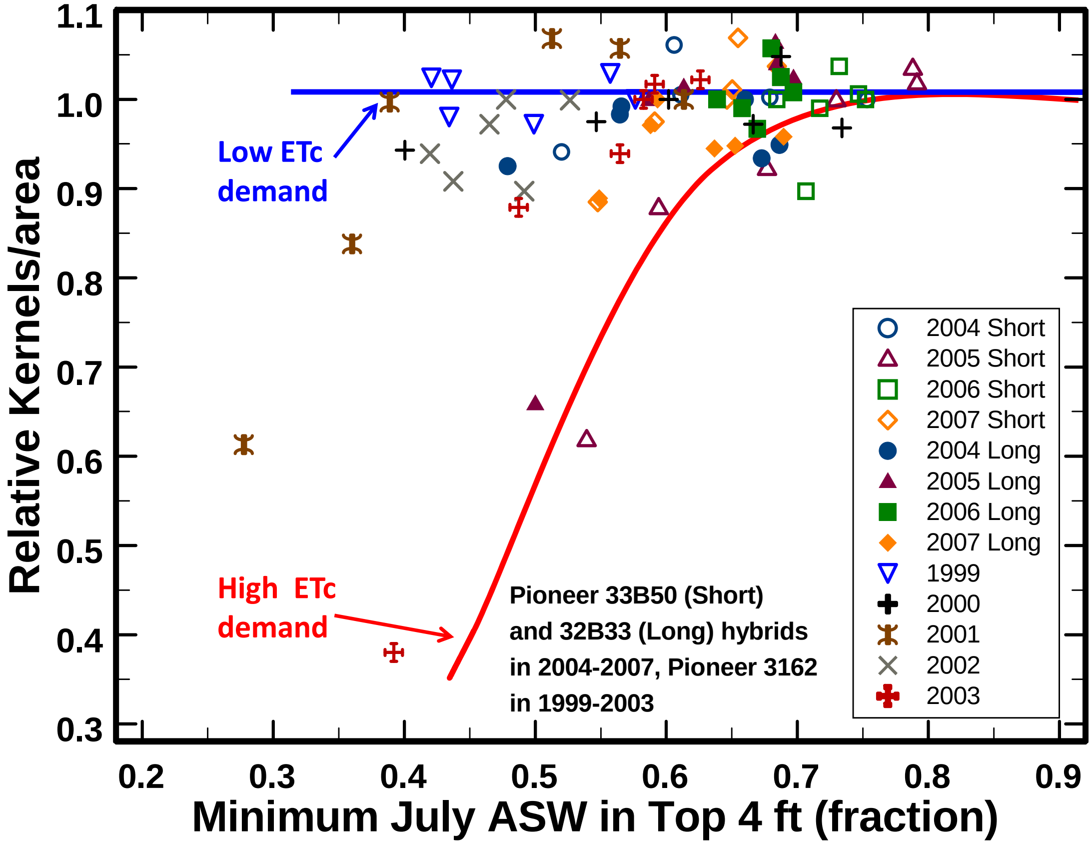

Figure 3. Relative kernels/area as affected by July minimum available soil water in the top 4 ft of soil in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007. The upper (red) and lower (blue) lines are manually drawn to illustrate years with larger and smaller July evaporative demand.

Water stress is greater both with reduced available soil water and with greater evaporative demand. The kernels/area was most sensitive to the JASW in the top 4 ft of soil as compared to both smaller and greater profile depths. This is reflecting the approximate rooting and soil water extraction depth of corn in July on this soil type. There remains considerable unexplained scatter in this graph that does not appear to be related very well to differences in evaporative demand between the years. For example, there was very little effect on relative kernels/area in 2002, although it had a moderately high evaporative demand.

The relationship of relative kernels/area to a critical level of available soil water can have some merit as a signal for determining the need for irrigation because available soil water can both be measured in real-time and the value can be projected a few days into the future.

The ratio of calculated well-watered crop ET_c to the sum of irrigation and precipitation for July 1 through 15 was also related to the relative kernels/area (Figure 4). The relative kernels/area tended to decrease when this water deficit ratio was less than 70 to 80%. Attempts were also made in varying the timeframe of the ratio (both longer and shorter and also shifting within the month of July). It appears that some of the remaining scatter in this graph is related to timing of irrigation and precipitation near the actual point of silking. For example, the isolated point from 2002 near the vertical axis may be related to a significant precipitation event that occurred near silking, but later than July 15. Further analysis should be conducted to allow the window to actually vary around the individual silking dates of each year. This might be done by computing windows based on the number of thermal units (also known as Growing Degree Days) required for silking. This relationship might also be a good signal in determining the need for irrigation because it can be determined in near real-time using the accumulated ratio to that point in time.

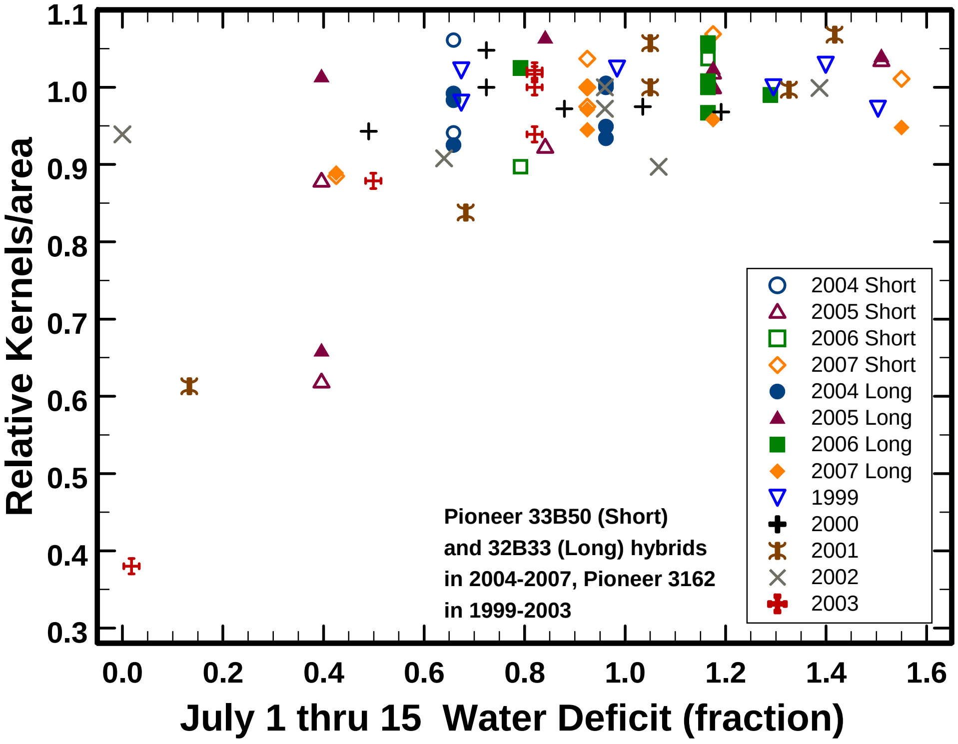

Figure 4. Relative kernels/area as affected by the July 1 through 15 water deficit (ratio of calculated well-watered crop ET_c to the sum of irrigation and precipitation) in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

Further analysis should focus on attempts to combine multiple factors (e. g., measured water use, available soil water, evaporative demand, and/or timing of irrigation and precipitation) with a focus on developing irrigation signals that can be used in near real-time to make early season irrigation decisions.

Recommendations for managing pre-anthesis corn water stress

Producers should use a good method of day-to-day irrigation scheduling during the pre-anthesis period. To a large extent the information being used to make day-to-day irrigation scheduling decisions during the pre-anthesis period can also be used as in making the macromanagement decision about when to start the irrigation season. This is because even though the corn has considerable innate ability to tolerate early season water stress, most irrigation systems in the Central Great Plains do not have the capacity (e.g, gpm/acre) or practical capability (e.g., run-off or deep percolation concerns) to replenish severely depleted soil water reserves as the season progresses to periods of greater irrigation needs (i.e., greater ET_c and less precipitation). However, there is some flexibility in timing of irrigation events within the vegetative growth period. In years of lower evaporative demand, corn grown on this soil type in this region can extract greater amounts of soil water without detriment. Timeliness of irrigation and/or precipitation near anthesis appears to be important in establishing an adequate number of kernels/area. The strong linear 1:1 relationship that existed between the relative corn yield and the relative number of kernels/area (plants/area x ears/plant x kernels/ear) indicates that optimizing kernels/area is a key in optimizing grain yields. Producers growing corn on deep silt loam soils in the Central Great Plains should attempt to maintain a water deficit ratio (well watered calculated ETc divided by sum of irrigation and precipitation) during July of approximately 0.7 to 0.8 and not allow the available soil water within a 4-ft soil profile to decrease below 70%, particularly in years of greater evaporative demand.

Results for Post-Anthesis Water Stress Studies

Tabular data analysis for post-anthesis water stress studies

Results from 16 years (1993-2008) of studies indicate that anthesis for corn in Northwest Kansas varies from July 12 to July 24 with an average date of July 19 (Table 3). Physiological maturity ranged from September 14 through October 10 with an average date of September 27. The average length of the post-anthesis period was approximately 70 days. Using the corn grain yield results from the study and the individual treatment irrigation termination dates responsible for those yields, Table 3 was created to indicate the problems with using inflexible dates for determining the irrigation season termination date. Additionally, the corn grain yield results and the treatment irrigation dates were used to estimate the date when a specified percentage of maximum grain yield would occur. Because there was not an unlimited number of irrigation treatment dates there are years when the date required for a specified percentage of maximum grain yield was the same as the date for the next higher percentage. The average estimated termination date to achieve 80, 90 and 100% of maximum corn grain yield was August 2, 13, and 28, respectively, but the earliest dates were July 17, July 17 and August 12, respectively, while the latest dates were September 14, 21, and 21, respectively. Irrigators that use average or fixed dates to terminate the corn irrigation season are not realistically considering the irrigation needs of the corn that may be greater or smaller in a particular year, and thus, often will neither optimize corn production, nor minimize water pumping costs.

Table 3. Anthesis and physiological maturity dates and estimated irrigation season termination dates* to achieve specified percentage of maximum corn grain yield from studies examining post-anthesis corn water stress, KSU Northwest Research-Extension Center, Colby, Kansas, 1993-2008. Note: This table was created to show the fallacy of using a specific date to terminate the irrigation season. Note: Because there was not an unlimited number of irrigation treatment dates, there are years when the date required for a specified percentage of maximum grain yield was the same as the date for the next higher percentage.

Year	**Date of Anthesis**	**Date of Maturity**	**Irrigation Season Termination Date For**		
			80% Max Yield	**90% Max Yield**	**MaxYield**
1993	20-Jul	30-Sep	5-Aug	5-Aug	15-Aug
1994	20-Jul	15-Sep	5-Aug	15-Aug	15-Aug
1995	20-Jul	29-Sep	5-Aug	13-Aug	18-Aug
1996	20-Jul	3-Oct	17-Jul	17-Jul	29-Aug
1997	23-Jul	1-Oct	23-Jul	23-Jul	27-Aug
1998	20-Jul	28-Sep	20-Jul	20-Jul	24-Aug
1999	23-Jul	6-Oct	24-Jul	13-Aug	20-Sep
2000	12-Jul	20-Sep	14-Sep	20-Sep	20-Sep
2001	16-Jul	29-Sep	30-Jul	22-Sep	22-Sep
2002	22-Jul	30-Sep	4-Aug	30-Aug	7-Sep
2003	22-Jul	23-Sep	3-Aug	3-Aug	18-Aug
2004	19-Jul	28-Sep	8-Aug	21-Aug	27-Aug
2005	20-Jul	28-Sep	2-Aug	9-Aug	29-Aug
2006	17-Jul	25-Sep	30-Jul	13-Aug	13-Aug
2007	18-Jul	19-Sep	14-Aug	21-Aug	28-Aug
2008	24-Jul	10-Oct	31-Jul	6-Aug	27-Aug
Average	**19-Jul**	**27-Sep**	**2-Aug**	**13-Aug**	**28-Aug**
Standard Dev.	**3 days**	**6 days**	**13 days**	**19 days**	**13 days**
Earliest	**12-Jul**	**14-Sep**	**17-Jul**	**17-Jul**	**12-Aug**
Latest	**24-Jul**	**10-Oct**	**14-Sep**	**21-Sep**	**21-Sep**

* *Estimated dates are based on the individual irrigation treatment dates from each of the different studies when the specified percentage of yield was exceeded.*

Maximum corn yields (MY) during the 16-year period in the various studies averaged 258 bu/acre with a range of 154 to 298 bu/acre (Table 4). Extremely poor growing conditions (cold and wet) greatly reduced yields in 1993 and hail suppressed yield in 1995. The post-anthesis water use that occurred for the irrigation treatment that maximized yield ($PAWU_{MY}$) averaged 16.9 inches with a range of 14.9 to 20.2 inches (Table 4). Assuming that yield formation for the corn crop started at anthesis, the average post-anthesis water productivity (i.e., $MY/PAWU_{MY}$) was 15 bu/inch and the range of water productivity over the years was 8 to 20 bu/inch (data not shown).

Table 4. Maximum corn yields and post-anthesis water use data from studies examining post-anthesis corn water stress, KSU Northwest Research-Extension Center, Colby, Kansas, 1993-2008.

Year	**Maximum Yield (bu/a)**	**$PAWU_{MY}$* (inches)**	**$PAWU_{MY}$ (inches/d)**	**$PAWU_{MY}$ during last 30 days (inches/d)**	**$PAWU_{MY}$ during last 15 days (inches/d)**
1993	154	19.23	0.287	0.288	0.178
1994	246	15.52	0.277	0.218	0.178
1995	170	18.23	0.285	0.201	0.174
1996	280	15.38	0.220	0.161	0.137
1997	245	16.13	0.230	0.162	0.150
1998	262	16.55	0.236	0.155	0.136
1999	272	18.49	0.247	0.134	0.081
2000	259	20.24	0.289	0.276	0.302
2001	268	19.44	0.259	0.161	0.160
2002	284	16.63	0.238	0.139	0.017
2003	269	15.12	0.240	0.089	0.105
2004	283	16.25	0.229	0.181	0.164
2005	295	16.31	0.233	0.088	0.036
2006	268	16.48	0.235	0.098	0.101
2007	273	16.25	0.258	0.104	0.106
2008	298	14.85	0.190	0.115	0.091
Average	**258**	**16.94**	**0.247**	**0.161**	**0.132**
Standard Dev.	**40**	**1.65**	**0.027**	**0.061**	**0.066**
Minimum	**154**	**14.85**	**0.190**	**0.088**	**0.017**
Maximum	**298**	**20.24**	**0.289**	**0.288**	**0.302**

* *$PAWU_{MY}$ is the post-anthesis water use occurring for the irrigation treatment that achieved maximum corn grain yield within the specified year.*

$PAWU_{MY}$ averaged 0.247 inches/day during the approximately 70-day period between anthesis and physiological maturity and remained at 65 and 53% of that value (0.161 and 0.132 inches/day) during the last 30 and 15 days of the season, respectively (Table 4). This emphasizes that although crop water use is tapering off during the latter part of the season, due to maturing crop canopies and also due to lower reference evapotranspiration (ET_r), therefore, it must be considered an important factor in late season crop management. Producers should also be aware that irrigation systems with marginal or insufficient capacity may have allowed considerable soil water depletion (soil water mining) during the pre-anthesis period.

Graphical data analysis for post-anthesis water stress studies

The corn grain yield results within a given year were normalized to the maximum value occurring in that particular year to give the relative yield (RY). The post-anthesis water use within a given year was then normalized with respect to the water use that occurred for the irrigation treatment that maximized corn grain yield in that particular year. This allowed treatments receiving excessive irrigation to have relative post-anthesis water use ($RPAWU_{MY}$) values greater than one.

There was a strong relationship between relative corn yield (RY) and relative post-anthesis water use ($RPAWU_{MY}$) as shown in Figure 5.

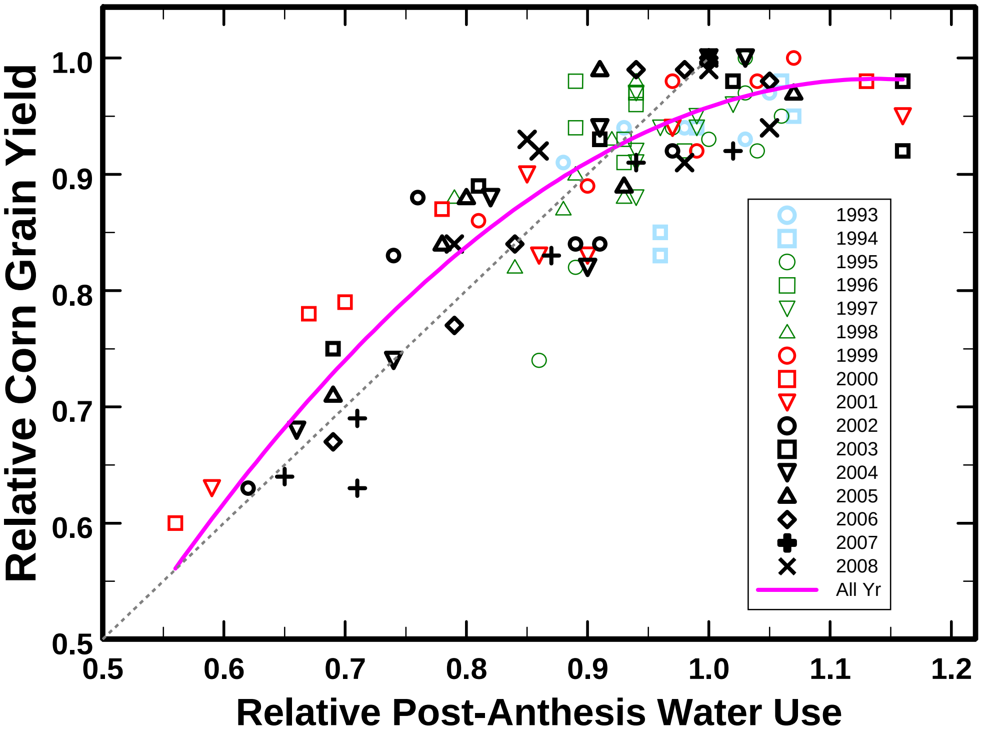

Figure 5. Relative corn grain yield (RY) as affected by relative post-anthesis water use ($RPAWU_{MY}$) for various studies examining the effect of post-anthesis water stress, KSU-NWREC, Colby, Kansas, 1993-2008. The dotted line represents a unity relationship between RY and $RPAWU_{MY}$. Note: $RPAWU_{MY}$ values can exceed one because some treatments received irrigation water in excess of the amount required to maximize corn grain yield (MY). This excessive water may have been lost in deep percolation but would have been included in the calculation procedures of post-anthesis water use.

Although there are a number of curves that can be drawn through the data (e.g., quadratic, logarithmic, etc.), there was a large portion of the data in the efficient range of $RPAWU_{MY}$ (i.e., where $RPAWU_{MY} \leq 1$) that can be adequately characterized by a one-to-one relationship between RY and $RPAWU_{MY}$. The subtle differences between assuming a curvilinear or linear relationship in the efficient range of post-anthesis water use might become important when trying to optimize corn production using water resource and economic constraints.

There was a reasonably good relationship between relative corn grain yield (RY) and the minimum post-anthesis available soil water (MPAASW, a fraction) within the 8-ft soil profile (Figure 6.) Corn yield tended to decrease for treatments having less than a minimum available soil water of approximately 55% of field capacity for any point-in- time within the post-anthesis period. Thus, the management allowable depletion (MAD) in these studies was approximately 45% as compared to the traditionally larger values often quoted in the literature (e.g., Doorenbos and Kassam, 1979; Rogers and Sothers, 1996). However, the 45% MAD value is consistent with the results of Lamm et al. (1994) and Lamm et al. (1995) from irrigated corn studies on the same soil type.

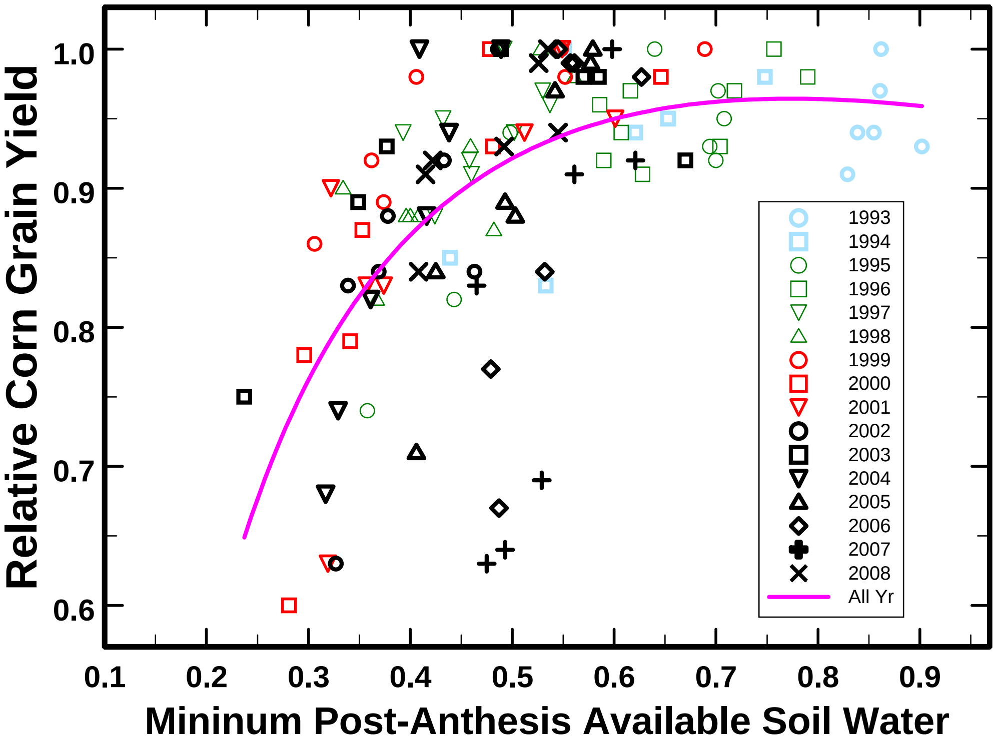

Figure 6. Relative corn grain yield (RY) as affected by the minimum value of available soil water (fraction) within the 8 ft soil profile occurring during the post-anthesis period (MPAASW). Data are from various studies examining the effect of post-anthesis corn water stress, KSU-NWREC, Colby, Kansas, 1993-2008.

There was also a relatively good relationship between $RPAWU_{MY}$ and MPAASW (Figure 7). $RPAWU_{MY}$ tended to decrease for treatments with MPAASW less than 55% of field capacity. This is to be as expected because of the strong relationship between RY and $RPAWU_{MY}$ but does provide additional evidence and rationale for a MAD value of approximately 45% for this soil type in this region as compared to the higher values in the literature.

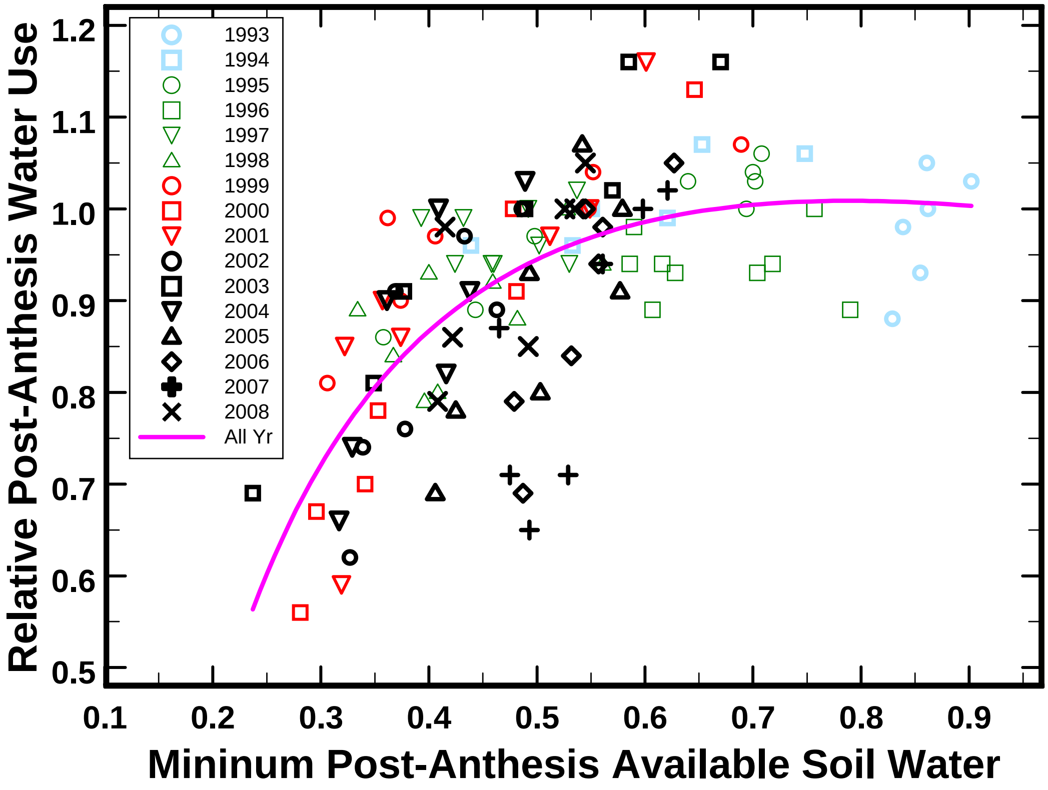

Figure 7. Relative post-anthesis water use ($RPAWU_{MY}$) as affected by the minimum value of available soil water (fraction) within the 8 ft soil profile occurring during the post-anthesis period (MPAASW). Data are from various studies examining the effect of post-anthesis corn water stress, KSU-NWREC, Colby, Kansas, 1993-2008.

Further data analysis should focus on determining the cause of increased scatter in the graph regions (Figure 6 and 7) where MPAASW is less than 0.55. Additionally, further efforts are justified in comparing the MPAASW values for different soil profile depths to see which depth has the greatest correlation and also to determine the inaccuracy associated with choosing alternative depths.

Recommendations for managing post-anthesis corn water stress

Producers should use a good method of day-to-day irrigation scheduling during the post-anthesis period. The macromanagement decision about when to terminate the irrigation season should not be based on an average or fixed date (e.g., August 31). Producers in the Central Great Plains should plan for post-anthesis water use needs of approximately 17 inches and that water use during the last 30 and 15 days of the season might average nearly 5 and 2 inches, respectively. This water use would need to come from the sum of available soil water reserves, precipitation and irrigation. When irrigation losses are minimized, a percentage decrease in post-anthesis water use will result in nearly a one-to-one percentage decrease in corn grain yield. Producers growing corn on deep silt loam soils in the Central Great Plains should attempt to limit management allowable depletion of available soil water in the top 8 ft of the soil profile to 45%.

CONCLUDING STATEMENTS

Macromanagement decisions at the seasonal boundaries should always be made in the context of having implemented appropriate day-to-day irrigation scheduling. Proper day-to-day scheduling will provide much-needed information about the crop and soil water status and evaporative demand being experienced within the given year.

Corn has greater than anticipated ability to withstand early season water stress provided that the water stress can be alleviated during the early-reproductive period. However, it should be reiterated that these results are not suggesting that irrigation can be delayed until anthesis. Most irrigation systems cannot quickly alleviate severely depleted soil water reserves as was accomplished in this pre-anthesis studies, but the results do indicate there is some flexibility in timing of irrigation events within the vegetative growth period. Timeliness of appreciable amounts of irrigation and/or precipitation near anthesis appears to be very important in maximizing yield potential.

Corn yield formation was primarily linearly related to the water use during the post-anthesis period for cases when irrigation was limited to the amount required for maximum yield. Limiting available soil water depletion to approximately 45% during the period is important in achieving maximum grain yields.

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Proper management of irrigated corn requires careful attention to crop water stress during both the pre-anthesis and post-anthesis growing periods.