CORN YIELD AND WATER USE CHARACTERISTICS AS AFFECTED BY TILLAGE, PLANT DENSITY, AND IRRIGATION

F. R. Lamm, R. M. Aiken, A. A. Abou Kheira

ABSTRACT. *Corn (*Zea mays *L.) was grown on a deep, well drained silt loam soil (Aridic Argiustolls) at Colby, Kansas, from 2004 to 2007 using three plant densities (66,300, 74,500, or 82,300 plants /ha) under conventional, strip, or no tillage systems for irrigation capacities that were limited to 25 mm every 4, 6, or 8 days. Corn yield increased approximately 10% (1.43 Mg/ha) from the minimum to maximum irrigation capacity in these four years of varying precipitation and crop evapotranspiration. Although strip tillage and no tillage had numerically greater grain yields than conventional tillage in all four years [approx. 8.1% and 6.4% (1.11 and 0.88 Mg/ha), respectively, for the four-year average], strip tillage was significantly greater in only two years and no tillage in only one year. Seasonal water use of the crop tended to be greater for the strip tillage and no tillage treatments as compared to conventional tillage and was significantly greater for strip tillage in two years and for no tillage in one year. The small increases in total seasonal water use (<10 mm) for strip tillage and no tillage correspond with greater grain yields for these tillage systems. Water productivity (grain yield/crop water use) also tended to be numerically greater (three of four years) for the strip tillage and no tillage treatments as compared to conventional tillage because of increased yields for the reduced tillage schemes. Increasing plant density from 66, 300 to 82,300 plants/ha generally increased grain yield and water productivity (four-year average of approximately 6% for each factor). Results suggest that strip tillage obtains the residue benefits of no tillage in reducing evaporation losses without the yield penalty that sometimes occurs with large amounts of residue. Both strip tillage and no tillage should be considered as improved alternatives to conventional tillage, particularly when irrigation capacity is limited.*

Keywords. *Corn production, Irrigation management, No tillage, Strip tillage, Water productivity, Yield components.*

Declining groundwater supplies and reduced well capacities are forcing irrigators in the Central Great Plains to look for ways to conserve and get the best utilization from their water. Residue management can conserve soil water, decrease evaporation and runoff, and increase rainfall infiltration (Pierce et al., 1992). Residue management techniques such as no tillage or conservation tillage have long been accepted to be very effective tools for dryland water conservation in the Great Plains (Greb, 1979). However, adoption of these techniques is lagging for continuous irrigated corn. There are many reasons given for this lack of adoption, but some of the major reasons expressed are: difficulty handling the increased level of residue from irrigated production; cooler and wetter seedbeds in the early spring, which may lead to delayed emergence; poor or slower development of the crop (Karlen and Sojka, 1985; Carter and Barnett, 1987; Fortin; 1993; Opoku et al., 1997, Licht and Al-Kaisi, 2005); and ultimately a corn grain yield penalty as compared to conventional tillage systems (Halvorson et al., 2006). This can be particularly true in northern climates and at increased elevations such as the western Great Plains, where soils are slower to warm in the spring. In Ontario, seed zone soil temperature was greater for conventional tillage than no tillage, and the time required for corn to reach the V6 growth stage was 5 to 7 days longer for no tillage relative to conventional tillage in a two-year study (Fortin, 1993). Karlen and Sojka (1985), in the coastal plain of South Carolina, found more rapid and uniform plant emergence and early season growth with conventional tillage than with conservation tillage. Water was conserved in conservation tillage, but a yield increase was observed only for the non-irrigated treatments in one of four years. Under high-yielding production systems, even a reduction of a few percentage points in corn yield can have a significant economic impact with today's crop prices.

Strip tillage might be a good compromise between conventional tillage and no tillage, possibly achieving most of the benefits in water conservation and soil quality management of no tillage, while providing a method of handling the increased residue and increased early growth similar to conventional tillage. The many terms and definitions related to strip tillage are discussed in detail by Morrison (2002), such as strip-till, zone-till, row-till, and band tilling. A common feature of these conservation tillage systems is that tillage is restricted to narrow strips or zones of soil (no more than 25% of the field area) where the individual rows will be planted for

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The authors are **Freddie R. Lamm, ASABE Member Engineer,** Research Irrigation Engineer, **Robert M. Aiken,** Research Crop Scientist, and **Abdrabbo A. Abou Kheira,** Research Irrigation Engineer, Kansas State University Northwest Research-Extension Center, Colby, Kansas. **Corresponding author:** Freddie R. Lamm, Kansas State University Northwest Research-Extension Center, 105 Experiment Farm Road, Colby, KS 67701; phone: 785-462-6281; fax: 785-462-2315; e-mail: flamm@ksu.edu.

the next crop. The actual methodologies and implementation of the strip tillage system depend upon the characteristics of the soil, climate, crop, and other desired cultural practices, such as in association with irrigation or fertilization (Morrison, 2002). Strip tillage systems allow for more cultural management options than a strict no-tillage regimen and also greater yields than conventional tillage in the drier years (Morrison, 2002). Strip tillage can retain surface residues and thus suppress soil evaporation and also provide subsurface tillage to help alleviate effects of restrictive soil layers on root growth and function. Strip tillage for cotton production into terminated wheat stubble in the Texas High Plains resulted in more evapotranspiration being partitioned into transpiration than into soil water evaporation and thus increased lint yield by 35% (Lascano et al., 1994). From modeling research, Lascano et al. (1994) estimated that the transpiration to soil water evaporation ratio for conventional tillage would be 0.5, while it would be improved to 0.69 for strip tillage production of cotton into wheat stubble. Chisel tillage and no-tillage systems resulted in greater near-surface (0 to 0.15 m) rooting and total profile root lengths than disked treatments on a silty clay loam soil in Nebraska (Newell and Wilhelm, 1987). Both dryland and deficit irrigation treatments were also associated with improved root proliferation in this study. The researchers concluded that better corn rooting under conservation tillage might allow irrigators to increase water productivity. Strip tillage had greater emergence than conventional tillage and no tillage in a study in Iowa (Licht and Al-Kaisi, 2005), but the resulting crop yield and water productivity were similar between tillage systems. Kaspar et al. (1990) studied the effect of removing residue cover from 8, 16, and 32 cm wide row zones for corn production on four soil types near Ames, Iowa. They found that the removal of some residue from the seed row reduced the time required for both plant emergence and anthesis, increased plant height, and increased yield. Corn yields were only reduced 3% from bare soil conditions when a 16 cm band of residue was removed from the row location.

The effects of conservation tillage practices on the root environment of corn may differ under deficit irrigation (Newell and Wilhelm, 1987; Hilfiker and Lowery, 1988). Corn roots tend to explore the lower soil profile to a greater extent under water stress conditions. This phenomenon, in conjunction with soil water conservation by no-tillage methods, may allow irrigators to increase water productivity by better use of stored soil water. Chaudhary and Prihar (1974) found that conventional tillage encouraged earlier and deeper penetration of corn roots into the soil profile than no tillage, but no-tillage corn had more roots in the top 0.20 m of soil during early growth stages. It is clear that tillage systems alter the soil environment, thus providing a potential for affecting corn root distribution within the soil. Under dryland and deficit-irrigated production in southwest Kansas, a no-tillage system increased corn yield by 0.56 Mg/ha and water productivity by 0.00096 Mg/ha-mm as compared to conventional tillage (Norwood, 2000). Norwood (2000) concluded that a combination of deficit irrigation and appropriate plant density and soil fertility could be a viable economic alternative to dryland production in an area of declining groundwater. Optimizing cultural management practices will be a key factor in managing deficit-irrigated corn production, so a study was initiated in 2004 to examine the effect of three tillage systems for corn production under three different irrigation capacities. Plant density was an additional factor examined because corn grain yield increases in recent years have been closely related to increased plant density.

GENERAL STUDY PROCEDURES

The study was conducted under a center-pivot sprinkler at the KSU Northwest Research-Extension Center at Colby, Kansas, during the years 2004 to 2007. Corn (*Zea mays* L.) was also grown on the field site in 2003 to establish baseline residue levels for the three tillage treatments. The study area had conventional tillage in 2003. The medium textured, deep, well drained, loessial Keith silt loam soil (Aridic Argiustoll; fine silty, mixed, mesic) can supply about 445 mm of available soil water for a 2.4 m soil profile. The soil is typical of many High Plains soils and is described in more detail by Bidwell et al. (1980). The region has an average annual precipitation of 481 mm with a summer pattern, resulting in an average corn cropping season precipitation of 299 mm. The average seasonal total crop evapotranspiration (ETc) for corn is 586 mm. The latitude is 39.39° north and the longitude is 101.07° west, with an elevation of 963 m above sea level.

A corn hybrid of approximately 110-day relative maturity (Dekalb DCK60-19 in 2004 and DCK60-18 in 2005 through 2007) was planted in 76 mm spaced circular rows on 8 May 2004, 27 April 2005, 20 April 2006, and 8 May 2007, respectively. The two hybrids differ only slightly, with the latter hybrid having an additional genetic modification of corn rootworm control. Three target seeding rates (64,000, 74,000, and 84,000 seeds/ha) were superimposed onto each tillage treatment in a complete randomized block design.

Irrigation was scheduled with a weather-based water budget but was limited to the three treatment capacities of 25 mm every 4, 6, or 8 days (IC-4, IC-6, and IC-8, respectively). This results in typical seasonal irrigation amounts of 300-500, 275-375, and 200-300 mm, respectively. The weather-based water budget was constructed using data collected from an NOAA weather station located approximately 600 m northeast of the study site. The reference evapotranspiration (ETr) was calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heermann (1974). The specifics of the ETr calculations used in this study are fully described by Lamm et al. (1987). A two-year (2005 and 2006) comparison using weather data from Colby, Kansas, of this estimation method to the ASCE standardized reference evapotranspiration equation, which is based on FAO-56 (Allen et al., 1998), indicates that the modified-Penman values are approximately 1.5% to 2.8% lower. This is well within the accuracy of the resultant scheduling and irrigation application procedures. Basal crop coefficients (Kcb) were generated with equations developed by Kincaid and Heermann (1974) based on work by Jensen (1969) and Jensen et al. (1970, 1971). The basal crop coefficients were calculated for the area by assuming 70 days from emergence to full canopy for corn with physiological maturity at 130 days. This method of calculating ETc as the product of Kcb and ETr has been acceptable in past studies at Colby (Lamm and Rogers, 1983, 1985). In constructing the irrigation schedules, no attempt was made to modify ETc with respect to soil evaporation losses or soil water availability, as outlined by Kincaid and Heermann (1974). Alfalfa-based

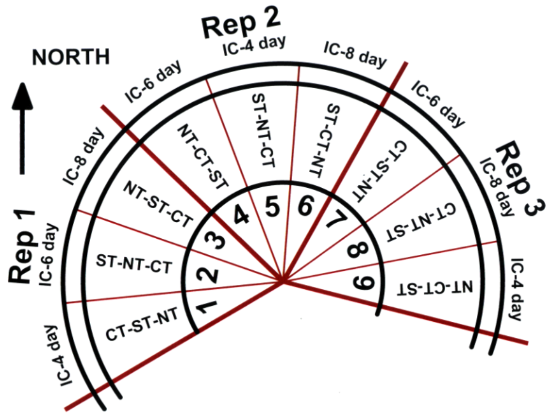

Figure 1. Physical arrangement of the irrigation capacity (IC-4, IC-6, or IC-8) for the nine different pie-shaped sectors and tillage treatments (CT, ST, or NT) randomized within the outer sprinkler span.

ETr is considered to give better estimates than short-grass ETo in this region (Howell, 2007).

Each of the irrigation capacities (whole plot) was replicated three times in pie-shaped sectors (25°) of the center-pivot sprinkler (fig. 1). Plot length varied from to 27 to 53 m, depending on the radius of the subplot from the center pivot point. Irrigation application rates (i.e., mm/h) at the outside edge of this research center pivot were similar to application rates near the end of full-size systems in the region. A small amount of preseason irrigation was conducted to bring the soil water profile (2.4 m) to approximately 50% of field capacity in the fall and as necessary in the spring to bring the soil water profile to approximately 75% in the top m prior to planting. The preseason irrigation was generally between 50 to 75 mm total for the years but was not kept constant between years. It should be noted that preseason irrigation is not a recommended practice for fully irrigated corn production, but it allowed the three irrigation capacities to start the season with somewhat similar amounts of water in the profile.

The three tillage treatments [conventional tillage (CT), strip tillage (ST), and no tillage (NT)] were replicated in a Latin-square type arrangement in 18 m widths at three different radii (centered at 73, 91, and 110 m) from the center pivot point (fig. 1). The various operations and their time period for the three tillage treatments are summarized in table 1. Planting was in the approximate same row location each year for the conventional tillage treatment to the extent that good farming practices allowed. The strip tillage and no tillage

Table 1. Tillage treatments, herbicide, and nutrient application by period.

Period Summer	Conventional Tillage	Strip Tillage	No Tillage
Fall 2003	1. One-pass chisel/disk plow at 0.20 to 0.25 m with broadcast N (13 Nov. 2003)	1. Strip till + fertilizer (N) at 0.20 to 0.25 m depth (13 Nov. 2003)	
Spring 2004	2. Plant + banded starter N and P (8 May 2004) 3. Pre-emergent herbicide application (9 May 2004)	2. Plant + banded starter N and P (8 May 2004) 3. Pre-emergent herbicide application (9 May 2004)	1. Broadcast N + plant + banded starter N and P (8 May 2004) 2. Pre-emergent herbicide application (9 May 2004)
2004	4. Roundup herbicide application near lay-by (9 June 2004) 5. Fertigate (N) (10 June 2004)	4. Roundup herbicide application near lay-by (9 June 2004) 5. Fertigate (N) (10 June 2004)	3. Roundup herbicide application near lay-by (9 June 2004) 4. Fertigate (N) (10 June 2004)
Fall 2004	1. One-pass chisel/disk plow at 0.20 to 0.25 m with broadcast N (5 Nov. 2004)	(Too wet, no tillage operations)	
Spring 2005	2. Plant + banded starter N and P (27 April 2005) 3. Pre-emergent herbicide application (8 May 2005)	1. Strip till + fertilizer (N) at 0.20 to 0.25 m depth (15 March 2005) 2. Plant + banded starter N and P (27 April 2005) 3. Pre-emergent herbicide application (8 May 2005)	1. Broadcast N + plant + banded starter N and P (27 April 2005) 2. Pre-emergent herbicide application (8 May 2005)
Summer 2005	4. Roundup herbicide application near lay-by (9 June 2005) 5. Fertigate (N) (17 June 2005)	4. Roundup herbicide application near lay-by (9 June 2005) 5. Fertigate (N) (17 June 2005)	3. Roundup herbicide application near lay-by (9 June 2005) 4. Fertigate (N) (17 June 2005)
Fall 2005	1. One-pass chisel/disk plow at 0.20 to 0.25 m with broadcast N (10 Nov. 2005)	1. Strip till + fertilizer (N) at 0.20 to 0.25 m depth (10 Nov. 2005)	
Spring 2006	2. Plant + banded starter N and P (20 April 2006) 3. Pre-emergent herbicide application (22 April 2006)	2. Plant + banded starter N and P (20 April 2006) 3. Pre-emergent herbicide application (22 April 2006)	1. Broadcast N + plant + banded starter N and P (20 April 2006) 2. Pre-emergent herbicide application (22 April 2006)
Summer 2006	4. Roundup herbicide application near lay-by (6 June 2006) 5. Fertigate (N) (13 June 2006)	4. Roundup herbicide application near lay-by (6 June 2006) 5. Fertigate (N) (13 June 2006)	3. Roundup herbicide application near lay-by (6 June 2006) 4. Fertigate (N) (13 June 2006)
Fall 2006	1. One-pass chisel/disk plow at 0.20 to 0.25 m with broadcast N (28 Nov. 2006)	1. Strip till + fertilizer (N) at 0.20 to 0.25 m depth (28 Nov. 2006)	
Spring 2007	2. Plant + banded starter N and P (8 May 2007) 3. Pre-emergent herbicide application (8 May 2007)	2. Plant + banded starter N and P (8 May 2007) 3. Pre-emergent herbicide application (8 May 2007)	1. Broadcast N + plant + banded starter N and P (8 May 2007) 2. Pre-emergent herbicide application (8 May 2007)
Summer 2007	4. Roundup herbicide application near lay-by (16 June 2007) 5. Fertigate (N) (21 June 2007)	4. Roundup herbicide application near lay-by (16 June 2007) 5. Fertigate (N) (21 June 2007)	3. Roundup herbicide application near lay-by (16 June 2007) 4. Fertigate (N) (21 June 2007)

treatments were planted between corn rows from the previous year.

Fertilizer N for all three treatments was applied at a rate of 225 kg/ha in split applications with approximately 95 kg/ha applied in the fall or spring application, approximately 35 kg/ha in the starter application at planting, and approximately 95 kg/ha in a fertigation event near corn lay-by. Phosphorus was applied with the starter fertilizer at planting at the rate of 50 kg/ha P_2O_5. Urea-ammonium-nitrate (UAN 32-0-0) and ammonium superphosphate (10-34-0) were utilized as the fertilizer sources in the study. Fertilizer was incorporated in the fall concurrently with the conventional tillage operation and applied with a mole knife during the strip tillage treatment. Conversely, N application was broadcast with the no tillage treatment prior to planting.

A post-plant, pre-emergent herbicide program of metolachlor, atrazine, and glyphosate was applied. Glyphosate was also applied post-emergence prior to lay-by for all treatments, but was particularly beneficial for the strip tillage and no tillage treatments. Insecticides were applied as required during the growing season for root worm and spider mite control.

Weekly to bi-weekly soil water measurements were made in 0.3 m increments to 2.4 m depth with a neutron probe. All measured data was taken near the center of each plot.

Crop residue cover of the soil surface was determined in April 2007 prior to planting by the point-intercept method (Morrison et al., 1993), modified by two sets of 50 knots at 0.3 m increments. Surface residue biomass was determined from the mean of three stratified samples of selected plots, representing minimum, median, and maximum residue cover within the plot. Residue collected from 0.76 × 0.76 m sampling area was washed in burlap bags, dried to constant weight, and weighed. Sampled units represented three replicates of the maximum plant population treatment within minimum and maximum irrigation capacities.

Corn yield was measured in each of the 81 subplots at the end of the season by hand-harvesting the ears from a 6 m section of one corn row near the center of each plot. Corn grain yield was adjusted to 15.5% wet basis. Water use and water productivity (i.e., grain yield divided by seasonal water use) were calculated for each subplot using the soil water data, precipitation, applied irrigation, and crop yield.

Responses were analyzed by Proc Mixed (SAS ver. 9.1.3 Service Pack 4, SAS Institute, Inc., Cary, N.C.), considering direct and interacting effects of irrigation capacity (ic), tillage (t), and population as fixed effects with replication (rep), ic*rep, radius from center pivot point, radius*rep, and t*radius*rep(ic) as random effects using the Kenward-Roger method to determine degrees of freedom. Differences among main effects of treatment means, determined by the lsmeans option, were evaluated by the Tukey-Kramer adjustment at the 0.05 probability level. Interacting effects were evaluated by the F-statistic associated with post-hoc contrast statements, using the Bonferroni criterion of α/k for significance, where $\alpha = 0.05$ and k is the number of pairwise comparisons in a contrast statement.

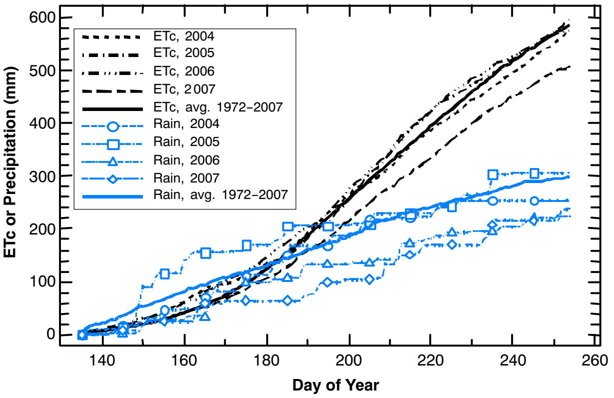

Figure 2. Calculated well-watered corn evapotranspiration and summer seasonal rainfall for the 120-day period 15 May through 11 September, KSU Northwest Research-Extension Center, Colby Kansas.

RESULTS AND DISCUSSION

WEATHER CONDITIONS AND IRRIGATION NEEDS

In general, conventional tillage treatments were observed to emerge earlier and have improved growth during May and June as compared to the strip tillage and no tillage treatments, probably because of warmer soil temperatures. However, by about mid-summer in most of the years, the conventional tillage treatments began to show greater water stress, particularly for the reduced irrigation capacities, as evidenced by some observed mid-day wilting. The conventional tillage plots also tended to senesce earlier in most years, with the exception of 2004. Summer seasonal precipitation was approximately 50 mm below normal in 2004, near normal in 2005, nearly 75 mm below normal in 2006, and approximately 65 mm below normal in 2007 at 253, 304, 228, and 238 mm, respectively, for the 120-day period from 15 May through 11 September (long-term average of 299 mm). In 2004, the last month of the season was very dry, but the remainder of the growing season had reasonably timely rainfall and approximately normal calculated well-watered crop evapotranspiration (fig. 2). In 2005, precipitation was above normal until about the middle of July, and then there was a period with very little precipita-

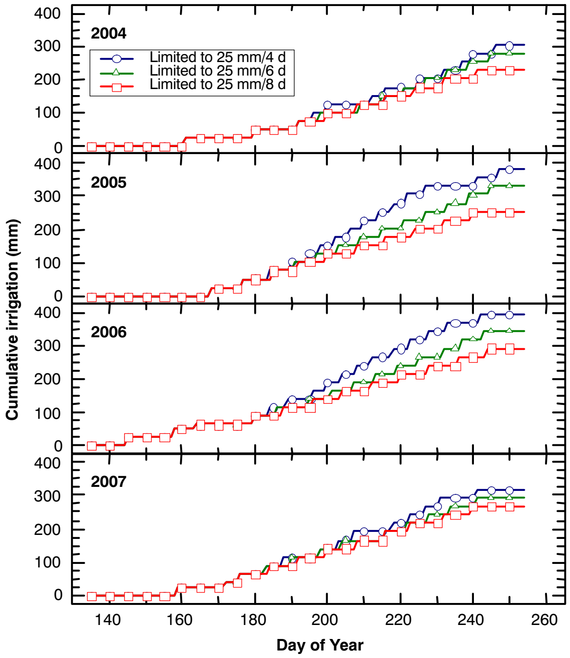

Figure 3. Cumulative irrigation by day of year for the three irrigation capacities during all four years of the tillage and irrigation capacity study of corn, KSU Northwest Research-Extension Center, Colby, Kansas.

Table 2. Corn grain yield and harvest plant density in a tillage and irrigation capacity study, KSU Northwest Research-Extension Center, Colby, Kansas, 2004-2007.[a]

Irrigation Capacity Limited to	Tillage System	Target Plant Density (1000 p/ha)	Grain Yield (Mg/ha)					Harvest Plant Density (plants/ha)				
			2004	2005	2006	2007	Mean	2004	2005	2006	2007	Mean
25 mm/4 d	CT	66.3	14.4	13.7	15.0	15.4	14.6	68888	58841	72475	68888	67273
		74.5	14.8	14.9	13.3	17.2	15.0	72475	68170	76781	79651	74269
		82.3	14.7	16.3	13.3	16.1	15.1	79651	74628	86827	86109	81804
	ST	66.3	15.4	14.9	14.6	15.9	15.2	68170	60277	72475	69605	67632
		74.5	14.6	15.7	14.8	16.9	15.5	75346	68888	77498	76781	74628
		82.3	14.9	15.9	16.3	17.5	16.1	81804	76781	81804	88980	82342
	NT	66.3	13.7	14.3	13.2	15.4	14.2	63864	61712	70323	66017	65479
		74.5	14.2	15.9	16.5	16.6	15.8	72475	66017	77498	78216	73552
		82.3	15.7	16.5	15.6	16.0	15.9	83239	77498	85392	86109	83060
25 mm/6 d	CT	66.3	14.2	12.7	10.1	15.3	13.1	62429	60994	71758	68888	66017
		74.5	13.9	13.8	13.0	15.2	14.0	73193	68170	78934	81086	75346
		82.3	15.3	13.1	10.6	14.8	13.4	80369	76781	83957	86109	81804
	ST	66.3	14.7	14.2	13.0	15.3	14.3	67452	60277	71758	65300	66197
		74.5	14.1	13.0	13.5	15.2	13.9	71040	69605	77498	79651	74449
		82.3	14.9	15.6	13.6	15.7	14.9	82522	78934	84674	87545	83418
	NT	66.3	14.1	12.9	14.4	14.4	13.9	65300	60994	72475	68170	66735
		74.5	13.9	14.1	13.7	16.1	14.4	71758	71758	74628	78934	74269
		82.3	14.3	14.7	14.0	15.5	14.6	79651	78216	81086	88980	81983
25 mm/8 d	CT	66.3	12.4	11.7	10.8	13.8	12.2	60994	60277	69605	68888	64941
		74.5	13.3	13.7	12.0	15.6	13.6	72475	67452	78216	81086	74808
		82.3	13.6	13.1	12.0	15.6	13.6	78216	78216	83957	84674	81266
	ST	66.3	14.3	13.3	13.4	15.2	14.1	63864	58841	72475	68170	65838
		74.5	14.4	13.5	13.8	16.0	14.4	73911	68170	78934	76781	74449
		82.3	14.7	15.0	14.5	16.8	15.2	81086	77498	85392	88980	83239
	NT	66.3	13.8	13.1	12.8	14.1	13.4	66735	59559	71040	68170	66376
		74.5	14.1	13.2	13.8	15.6	14.2	73193	68170	77498	79651	74628
		82.3	13.8	13.6	13.5	14.7	13.9	81086	76781	83957	86109	81983
Mean for 25 mm/4 d			14.7	15.3	14.7 a	16.3 a	15.3	73990	68090 a	77897	77817	74449
Mean for 25 mm/6 d			14.4	13.8	12.9 b	15.3 b	14.1	72635	69525 b	77419	78296	74469
Mean for 25 mm/8 d			13.8	13.4	13.0 b	15.3 b	13.9	72396	68329 a	77897	78057	74170
Mean for CT			14.1	13.7 a	12.2 a	15.4	13.8	72077	68170	78057	78376	74170
Mean for ST			14.6	14.6 b	14.2 b	16.1	14.9	73911	68808	78057	77977	74688
Mean for NT			14.2	14.2 ab	14.2 b	15.4	14.5	73034	68967	77100	77817	74229
Mean for 66,300 p/ha			14.1	13.4 a	13.0	15.0 a	13.9	65300 a	60197 a	71598 a	68010 a	66276
Mean for 74,500 p/ha			14.1	14.2 b	13.8	16.0 b	14.5	72874 b	68489 b	77498 b	79093 b	74489
Mean for 82,300 p/ha			14.6	14.8 b	13.7	15.9 b	14.8	80847c	77259 c	84116 c	87066 c	82322

[a] Main effect treatment means followed by different lowercase letters are significantly different at P = 0.05.

tion until the middle of August. This dry period in 2005 also coincided with a week of greater temperatures and elevated crop evapotranspiration near the reproductive period of the corn (17 to 25 July). In 2006, precipitation lagged behind the long-term average for the entire season. Fortunately, the calculated well-watered seasonal evapotranspiration was near normal, as was the case for 2004 and 2005 (long-term average of 586 mm). Although precipitation was much less than normal in 2007, crop evapotranspiration was also much less than normal at 507 mm, which resulted in reduced irrigation needs.

Irrigation requirements were least in 2004, with the 25 mm/4 day treatment receiving 305 mm, the 25 mm/6 day treatment receiving 279 mm, and the 25 mm/8 day treatment receiving 229 mm (fig. 3). The irrigation amounts in 2005 were 381, 330, and 254 mm for the three respective treatments. The irrigation amounts were greatest in 2006, at 394, 343, and 292 mm for the three respective treatments. Irrigation amounts in 2007 were 318, 292, and 267 mm for the three respective treatments, which were just slightly greater than the minimum irrigation values of 2004. Although seasonal precipitation was considerably less in 2007 compared to 2004, there was very little difference in irrigation requirements. This was because calculated evapotranspiration was considerably less than normal in 2007 due to light winds and moderate temperatures during much of the summer.

CROP YIELD, HARVEST PLANT DENSITY, AND RESIDUE

Corn yield ranged from 10.1 to 17.5 Mg/ha (table 2 and fig. 4). Greater irrigation capacity generally increased grain yield in all four years, but yield was only significantly greater for the larger 25 mm/4 d capacity in 2006 and 2007. When averaged over all irrigation capacities and plant densities, strip tillage produced significantly greater yields than conventional tillage in both 2005 and 2006 and numerically greater yields in all four years of the study. No tillage had significantly greater yields than conventional tillage in 2006 and numerically greater yields in all four years of the study. There

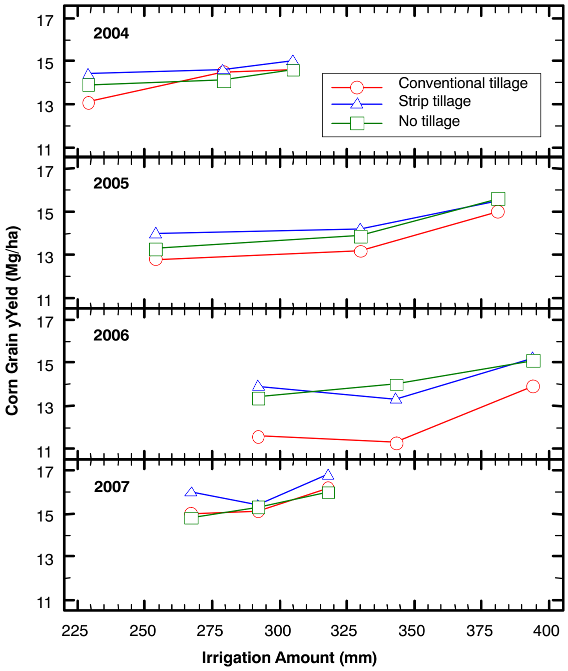

Figure 4. Corn grain yield as affected by irrigation amount and tillage, 2004-2007, KSU Northwest Research-Extension Center, Colby, Kansas. Irrigation amounts from left to right represent the three irrigation capacities with applications limited to 25 mm every 8, 6, or 4 days, respectively. The results are averaged across the three plant densities.

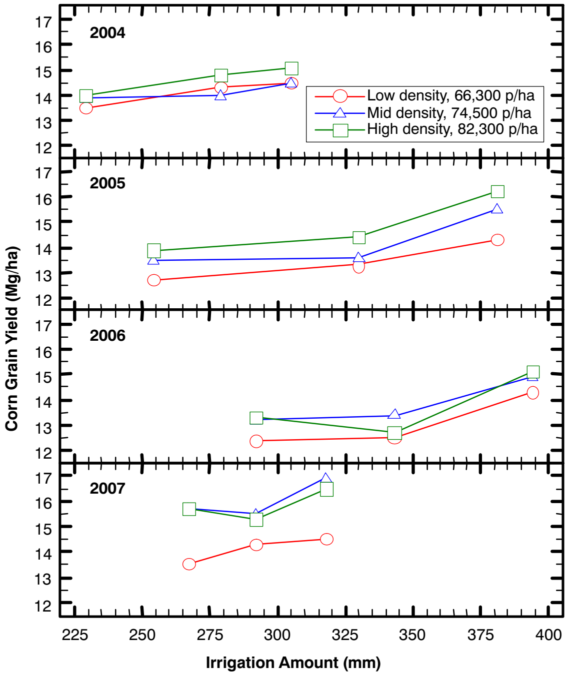

Figure 5. Corn grain yield as affected by irrigation amount and plant density, 2004-2007, KSU Northwest Research-Extension Center, Colby, Kansas. Irrigation amounts from left to right represent the three irrigation capacities with applications limited to 25 mm every 8, 6, or 4 days, respectively. The results are averaged across the three tillage treatments.

were no significant differences in yields between the strip tillage and no tillage treatments. Strip tillage tended to have the greatest grain yields for all three tillage systems, and the benefit of this tillage treatment was numerically greatest at the minimum irrigation capacity in all four years of the study (table 2 and fig. 4). The grain yield benefits of the reduced tillage systems were greatest in 2005 and 2006 (fig. 4), the years with greater irrigation requirements (fig. 3). There is the possibility that nitrogen fertilizer placement differences between the tillage systems may have affected yield results, but that is indeterminable in this study. In this study, fertilizer application and placement was based on typical practices for each tillage system. Strip tillage and no tillage also tended to have greater stability or less variation in grain yields than conventional tillage across the range of irrigation capacities, as evidenced by the flatter slopes in figure 4, with the exception of 2007 when all tillage treatments had somewhat similar stability in this year of less irrigation water requirements. Greater yield stability suggests that these reduced tillage treatments would be excellent choices when irrigation is deficit during the season.

There were no significant differences in the harvest plant density as affected by irrigation capacity or tillage system (table 2). Increasing plant density had a significant effect in increasing corn grain yields (table 2 and fig. 5) in both 2005 and 2007, and generally resulted in numerically greater corn yields in all four years. The greatest response to increased plant density was in 2007, the year with the greatest grain yields (fig. 5). This emphasizes that increased plant density allows producers to greatly increase gross economic returns when excellent corn production conditions exist. When averaged across tillage systems and all four years, increasing the plant density from 62,300 to 82,300 plants/ha increased corn grain yield by approximately 1 Mg/ha. Assuming a seed cost of US$ 2.00/1,000 seeds and corn harvest price of US$ 0.16/kg, this 1 Mg/ha yield advantage would increase net returns by US$120/ha for the increase in plant density of approximately 20,000 seeds/ha. However, it should be noted that most of the yield benefit from increased plant density was obtained by plant density increases to the intermediate 74,500 plants/ha level. The plant density results are similar to earlier results found at this location with subsurface drip-irrigated corn (Lamm and Trooien, 2001). Increasing plant density over the range of 55,600 to 85,300 plants/ha generally increased corn grain yield in the four years of that study, and even when the crop was non-irrigated within season, there was not much yield penalty for the increased plant density. In that earlier study, the maximum plant density resulted in an approximately 9% yield increase compared to the minimum plant density in 1998, a year characterized by nearly excellent growing conditions with mild temperatures and timely in-season precipitation.

Corn grain yield had an interesting three-way statistical interaction of irrigation capacity, tillage system, and plant density in 2006. Yields of the intermediate and maximum plant densities resulted in greater corn grain yields for the strip tillage and no tillage systems, while maximum yield under conventional tillage occurred for the minimum plant density for the maximum irrigation capacity. Yields were relatively similar across plant densities for the reduced tillage systems at reduced irrigation capacities. This effect may be the result of increased plant water stress and observed earlier plant senescence for the conventional tillage treatment when plant density was too great for the available plant water supply. Earlier plant senescence will curtail the amount of intercepted photosynthetically active radiation (IPAR) and thus net photosynthesis during the important grain filling stage of the corn. Rochette et al. (1996) found that intercepted photosynthetically active radiation (IPAR) accounted for 90% of the variation observed in net photosynthesis of corn, in the absence of water stress and with nutrient sufficiency. An interaction of irrigation management and corn plant density also occurred on a coastal plain loamy sand soil in South Carolina (Karlen and Camp, 1985) where increased plant density increased corn grain yields under irrigation but decreased corn yields under non-irrigated conditions in two of three years. Mixed results for increased plant density were also found for sandy loam soils in Georgia (Brown et al., 1970). Under irrigated conditions, grain yield increased with plant density for both wide (1.0 m) and narrow (0.5 m) row spacings, but under non-irrigated conditions plant densities greater than 50,000 plants/ha resulted in decreased yields for the narrow row spacings. The results from all of these studies suggest that grain yield response to plant density is influenced by site conditions and that this issue will affect recommendations for a given locale.

Crop residue amounts and the percentage of residue cover in April 2007 were similar for no tillage (22.4 Mg/ha and 99%) and strip tillage (16.0 Mg/ha and 92%) but much less for conventional tillage (5.8 Mg/ha and 79%). These results suggest that strip tillage can obtain the residue benefits of no tillage in reducing irrigation and rainfall runoff and evaporation losses without the yield penalty sometimes associated with the increased residue levels in irrigated no-tillage management.

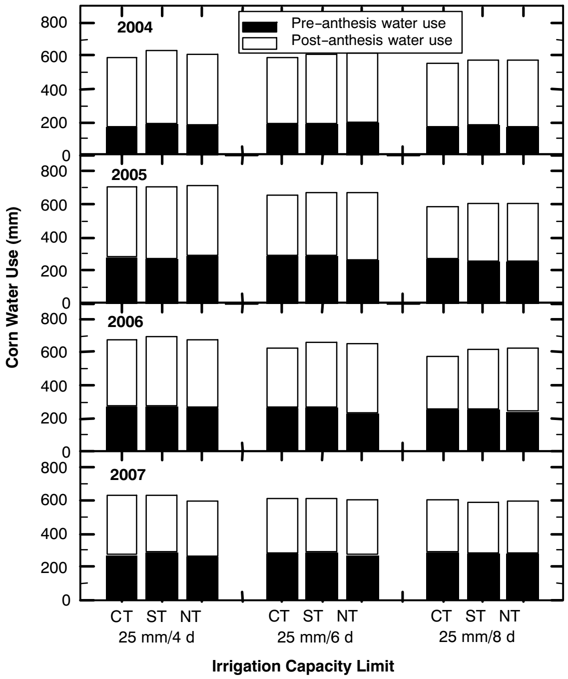

Figure 6. Pre-anthesis, post-anthesis, and total seasonal water use (sum of irrigation, precipitation, and seasonal changes in available soil water) as affected by irrigation capacity for conventional (CT), strip (ST), and no tillage (NT) systems, 2004-2007, KSU Northwest Research-Extension Center, Colby, Kansas. The results are averaged across the three plant densities.

CORN WATER USE, PLANT-AVAILABLE SOIL WATER, AND WATER PRODUCTIVITY

Total seasonal water use in this study was calculated as the sum of irrigation, precipitation, and the change in available soil water over the course of the season. As a result, seasonal water use can include non-beneficial water losses such as soil evaporation, deep percolation, and runoff. There were significant differences in seasonal water use as affected by irrigation capacity in three of the four years, with increased water use tending to occur for the maximum irrigation capacity. There were significant differences in post-anthesis water use attributable to irrigation capacity in all four years (fig. 6) but not in pre-anthesis water use. This would be the anticipated result because, as the season progresses and evapotranspiration needs increase due to hotter and drier weather conditions and a more extensive plant canopy, greater irrigation capacities would allow for greater water use. Although the average seasonal irrigation amount for the maximum irrigation capacity was 89 mm greater than the minimum irrigation capacity, there was only an average of 62 mm difference in water use. The small difference can probably be attributed to reduced non-beneficial water losses and also better root water uptake for the minimum capacity as compared to the maximum irrigation capacity.

Intuitively, one might anticipate that good residue management with strip tillage and no tillage would result in less water use than conventional tillage because of reduction in non-beneficial water losses. However, in this study, strip tillage and no tillage generally had slightly greater water use (table 3 and fig. 6). The small increases in total seasonal water use (average of less than 10 mm) for strip tillage and no tillage compared to conventional tillage corresponds with the greater grain yields for these tillage systems (approx. 0.9 mg/ha) and may result from the earlier canopy senescence observed under conventional tillage. There was a significant interaction of tillage and irrigation capacity on post-anthesis water use in 2006, with less water use for conventional tillage for the intermediate and minimum irrigation capacities in contrast to no tillage differences in post-anthesis water use at the maximum irrigation capacity. This difference can probably be explained by the observed earlier senescence for conventional tillage when water stress existed. This post-anthesis water use difference in 2006 may have further led to an interaction of tillage and irrigation capacity on total seasonal water use, with more crop water use for strip tillage and no tillage at the smallest irrigation capacity in contrast to no differences in water use between tillage treatments at the maximum irrigation capacity. No tillage had significantly less pre-anthesis water use than conventional tillage in two of the four years (2006 and 2007) and significantly greater post-anthesis water use than conventional tillage in two of the four years (2005 and 2006). Similarly, strip tillage had significantly greater post-anthesis water use than conventional tillage in two years (2004 and 2006). The shifting of water use to the post-anthesis period as tillage was reduced may be responsible for the generally improved grain yields for these treatments.

There were no significant differences in total seasonal water use attributable to changes in plant densities alone. However, there was a significant interaction of plant density and irrigation capacity in 2005, when for some unknown reason total seasonal water use was less for the maximum plant density at the intermediate irrigation capacity in contrast to similar water use values among plant densities for the minimum and maximum irrigation capacities. One possible reason may be unexplained differences in pre-anthesis water use in that

Table 3. Corn water use and water productivity in a tillage and irrigation capacity study, KSU Northwest Research-Extension Center, Colby, Kansas, 2004-2007.[a]

Irrigation Capacity Limited to	Tillage System	Target Plant Density (1000 p/ha)	Seasonal Water Use (mm)					Water Productivity (Mg/ha-mm)				
			2004	2005	2006	2007	Mean	2004	2005	2006	2007	Mean
25 mm/4 d	CT	66.3	610	718	690	627	661	0.0235	0.0190	0.0217	0.0246	0.0222
		74.5	601	727	679	661	667	0.0246	0.0205	0.0197	0.0260	0.0227
		82.3	584	693	686	619	646	0.0254	0.0236	0.0195	0.0260	0.0236
	ST	66.3	623	718	706	626	668	0.0248	0.0208	0.0206	0.0255	0.0229
		74.5	646	675	698	653	668	0.0226	0.0233	0.0212	0.0260	0.0233
		82.3	643	740	700	626	677	0.0232	0.0215	0.0234	0.0280	0.0240
	NT	66.3	584	713	670	573	635	0.0236	0.0202	0.0198	0.0270	0.0226
		74.5	624	703	700	619	662	0.0229	0.0227	0.0236	0.0268	0.0240
		82.3	615	724	688	607	658	0.0255	0.0228	0.0227	0.0263	0.0243
25 mm/6 d	CT	66.3	585	671	633	627	629	0.0244	0.0190	0.0159	0.0244	0.0209
		74.5	599	656	627	622	626	0.0233	0.0211	0.0208	0.0243	0.0224
		82.3	606	643	638	610	625	0.0252	0.0202	0.0166	0.0242	0.0215
	ST	66.3	592	679	664	610	636	0.0249	0.0208	0.0196	0.0252	0.0226
		74.5	619	689	660	625	648	0.0227	0.0187	0.0204	0.0242	0.0215
		82.3	619	666	675	615	644	0.0240	0.0233	0.0201	0.0257	0.0233
	NT	66.3	622	679	659	628	647	0.0227	0.0190	0.0219	0.0230	0.0216
		74.5	635	691	653	583	641	0.0219	0.0204	0.0210	0.0276	0.0227
		82.3	595	653	651	624	631	0.0242	0.0225	0.0215	0.0248	0.0233
25 mm/8 d	CT	66.3	563	579	600	612	588	0.0221	0.0204	0.0180	0.0226	0.0208
		74.5	570	572	561	607	578	0.0233	0.0240	0.0213	0.0260	0.0236
		82.3	559	629	576	620	596	0.0244	0.0207	0.0209	0.0253	0.0228
	ST	66.3	604	605	626	603	609	0.0238	0.0221	0.0216	0.0253	0.0232
		74.5	554	611	628	583	594	0.0260	0.0221	0.0220	0.0274	0.0244
		82.3	589	621	618	590	605	0.0249	0.0242	0.0234	0.0285	0.0252
	NT	66.3	571	625	621	606	606	0.0241	0.0209	0.0206	0.0233	0.0222
		74.5	589	582	627	609	602	0.0240	0.0229	0.0220	0.0256	0.0236
		82.3	574	627	635	591	607	0.0241	0.0217	0.0214	0.0249	0.0230
Mean for 25 mm/4 d			615 a	712 a	691 a	624	660	0.0240	0.0216	0.0213 a	0.0262	0.0233
Mean for 25 mm/6 d			608 a	670 b	651 ab	616	636	0.0237	0.0206	0.0197 b	0.0248	0.0222
Mean for 25 mm/8 d			575 b	606 c	610 b	602	598	0.0241	0.0221	0.0212 a	0.0254	0.0232
Mean for CT			586 a	654	632 a	623	624	0.0240	0.0209	0.0194 a	0.0248	0.0223
Mean for ST			613 b	667	663 b	617	640	0.0241	0.0219	0.0213 b	0.0262	0.0234
Mean for NT			598 ab	656	644 b	611	627	0.0237	0.0214	0.0216 b	0.0255	0.0230
Mean for 66,300 p/ha			595	665	652	612	631	0.0238	0.0202 a	0.0200 a	0.0245 a	0.0221
Mean for 74,500 p/ha			604	656	648	618	632	0.0235	0.0217 b	0.0213 b	0.0260 b	0.0231
Mean for 82,300 p/ha			598	666	652	611	632	0.0245	0.0223 b	0.0210 ab	0.0260 b	0.0234

[a] Main effect treatment means followed by different lowercase letters are significantly different at P = 0.05.

year. The intermediate and maximum plant densities had the least and greatest pre-anthesis crop water use for the minimum irrigation capacity in contrast to similar pre-anthesis water use for the greater irrigation capacities. There were also no significant differences in water use attributable to the single factor of plant density in either the pre-anthesis or post-anthesis period of the corn (data not shown). Apparently at these corn plant densities in this climatic region, the corn reaches a threshold leaf area index (LAI) quickly enough that water use differences were not detectable. At a threshold LAI of 2.7, corn transpiration is approximately 90% of the maximum value (Ritchie and Burnett, 1971). LAI of corn at anthesis ranged from approximately 3 to 5 during the four years of the study.

There were no significant differences in available soil water for the 2.4 m soil profile at crop emergence in May, corn anthesis in July, or physiological maturity in September attributable to irrigation capacity or plant density in any of the four years. When averaged across irrigation capacity and plant density treatments, available soil water amounts in the 2.4 m soil profile for no tillage treatments were significantly greater than conventional tillage in all four years at crop emergence in May, for three of the four years at anthesis in July, and for two of the four years at physiological maturity in September (table 4). Differences in available soil water for strip tillage and no tillage were much less, and where there were differences soil water was generally greater under no tillage. Increased plant-available soil water in the period leading up to corn anthesis for mulched treatments has been also reported by Tolk et al. (1999), and this led to a subsequently greater LAI after anthesis. Retaining a greater and non-senesced LAI after anthesis can lead to better grain filling and greater grain yields and biomass amounts. The water productivity of corn silage was 38% greater for no tillage as compared to conventional tillage in a study on a clay loam soil in North Carolina (Wagger and Cassel, 1993). In September 2004, there was a significant interaction between irrigation capacity and tillage treatment, with strip tillage having

Table 4. Plant-available soil water at selected times of the corn growing season in a tillage and irrigation capacity study, KSU Northwest Research-Extension Center, Colby, Kansas, 2004-2007.

Time of Season	Tillage Treatment	Available Soil Water (mm/2.4 m soil profile)[a]				
		2004	2005	2006	2007	Mean
Plant emergence in May	Conventional	236 a	274 a	266 a	359 a	284
	Strip tillage	274 b	313 b	321 b	384 ab	323
	No tillage	260 ab	321 b	346 b	386 b	328
Corn anthesis in July	Conventional	273	305 a	256 a	317 a	288
	Strip tillage	305	349 b	313 b	341 ab	327
	No tillage	291	362 b	357 c	353 b	341
Physiological maturity in September	Conventional	206	249	202 a	265 a	230
	Strip tillage	221	275	225 ab	298 ab	255
	No tillage	216	284	258 b	310 b	267

[a] Values followed by different lowercase letters are significantly different at P = 0.05.

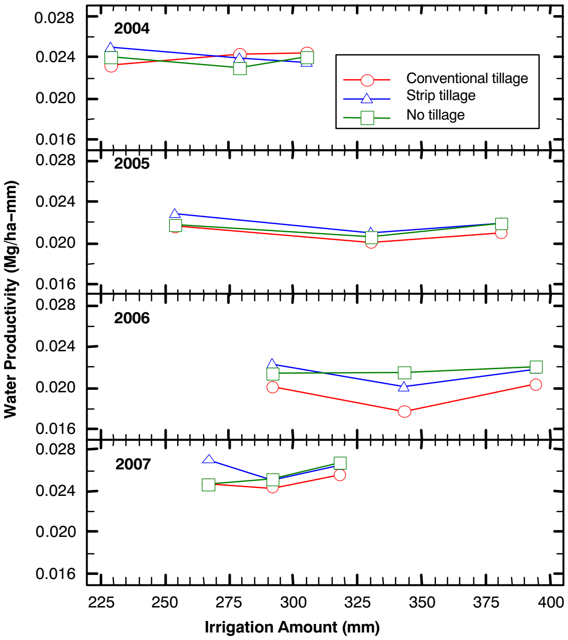

Figure 7. Water productivity for corn as affected by irrigation amount and tillage, 2004-2007, KSU Northwest Research-Extension Center, Colby, Kansas. Irrigation amounts from left to right represent the three irrigation capacities with applications limited to 25 mm every 8, 6, or 4 days, respectively. The results are averaged across the three plant densities.

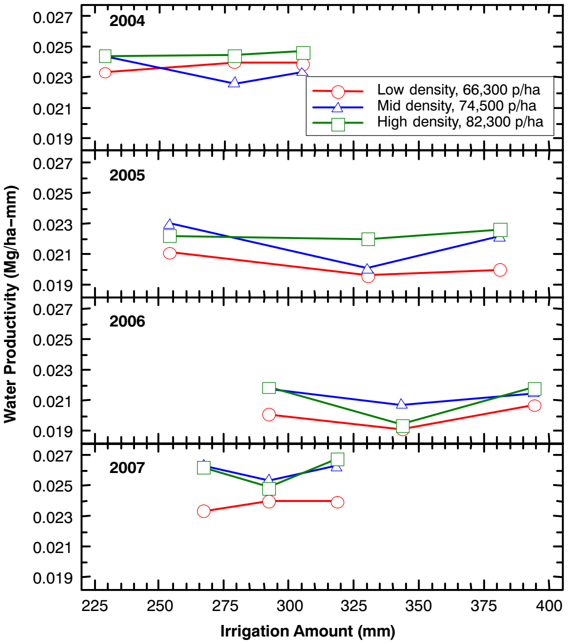

Figure 8. Water productivity of corn as affected by irrigation amount and plant density, 2004-2007, KSU Northwest Research-Extension Center, Colby, Kansas. Irrigation amounts from left to right represent the three irrigation capacities with applications limited to 25 mm every 8, 6, or 4 days, respectively. The results are averaged across the three tillage treatments.

the least available soil water in the 2.4 m soil profile at the maximum irrigation capacity (13% less) but having the greatest available soil water at the reduced irrigation capacities (17% greater) as compared to the other tillage treatments. These differences may be related to greater soil water extraction and crop production for strip tillage at the maximum irrigation capacity in 2004.

Water productivity as affected by irrigation capacity was significantly different only in 2006, when it was reduced for the intermediate irrigation capacity because of unexplained lower grain yields but similar for the minimum and maximum irrigation capacity (fig. 7). The general result of no significant effect of irrigation capacity on water productivity suggests that the irrigation scheduling procedures and these irrigation capacities do not grossly over- or under-apply irrigation. Over-application of irrigation will decrease water productivity by increasing the denominator through increased non-beneficial losses of water. Severe under-application of irrigation may result in all or some corn plants not reaching the yield threshold (i.e., the water use amount at which the first increment of grain yield is obtained), thus reducing the numerator of the water productivity equation. An irrigation capacity of 25 mm/4 d when scheduled with an in-season water budget will closely approximate a full irrigation regime in northwest Kansas (Lamm et al., 2007).

Water productivity as affected by tillage scheme was significantly greater for strip tillage and no tillage in 2006 as compared to conventional tillage and was numerically greater in three of the four years (fig. 7). The reason for greater water productivity for the reduced tillage systems was primarily that grain yield was increased rather than less water use. It should also be noted that the reduced tillage treatments had a greater effect on increasing water productivity in 2006 (fig. 7), the year with the greatest difference in seasonal precipitation and evapotranspiration. This emphasizes that good residue management under irrigation is more beneficial under more water-stressful conditions.

There was a statistically significant effect of plant density on water productivity in 2005, 2006, and 2007, with the intermediate and maximum plant densities generally having greater water productivity than the minimum plant density (fig. 8). This effect was caused by greater yield for the greater plant densities, because there were no significant differences in water use. These results contrast with those obtained on a sandy loam soil in northeast Colorado by Al-Kaisi and Yin (2003), who recommended that water productivity (defined as water use efficiency in that study) would be maximized at plant densities of 57,000 and 69,000 plants/ha as compared to their maximum value of 81,000 plants/ha. Their results may differ from those obtained in this Kansas study because of reduced yield potential at the Colorado location, where the maximum reported yield for their full irrigation regime was less than the yield obtained for the minimum irrigation capacity in this study (13.5 versus 13.9 Mg/ha, respectively). Increasing plant density generally increased water productivity of subsurface drip irrigated corn in a four-year study in Kansas with the exception of 1999, a wet year when mixed results occurred (Lamm and Trooien, 2001). These different results indicate that plant density is an important factor in maximizing water productivity and that plant density needs to be optimized with respect to grain yield optimization for that locale.

CONCLUSIONS

Greater irrigation capacity generally increased grain yield in a four-year study (2004 to 2007) with varying seasonal precipitation and crop evapotranspiration. Strip tillage and no tillage, the reduced tillage treatments, generally resulted in greater yields than conventional tillage, and significantly so in some years. These reduced tillage systems tended to have slightly greater crop water use but effectively used that water to generate greater yields. There were also trends in the patterns of water use, with conventional tillage tending to use more water before anthesis and the reduced tillage treatments having more crop water use after anthesis. These differences in patterns may be related to an observed earlier senescence of the conventional tillage due to greater water stress and also by the reduced tillage treatments retaining more soil water for the post-anthesis period when grain filling occurs. Water productivity tended to be greater for the reduced tillage treatments and was significantly so in one year. The grain yield and water productivity benefits of these reduced tillage systems were greatest in the years when irrigation requirements were greatest. These reduced tillage systems proved viable at this location for corn production and should be considered as improved alternatives to conventional tillage, especially when irrigation capacity is limited because of the tendency for greater grain yield stability.

Increasing the plant density from 66,300 to 82,300 plants/ha numerically increased grain yields at all three irrigation capacities in all four years of the study and significantly so in two years. Increased plant density did not significantly increase seasonal water use in any of the four years but did increase water productivity in three of the four years. The increased plant density is easily justified with today's seed costs and crop prices and is recommended as a method to improve overall economic and water productivity.

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