ALFALFA PRODUCTION WITH SUBSURFACE DRIP IRRIGATION IN THE CENTRAL GREAT PLAINS

F. R. Lamm, K. R. Harmoney, A. A. Aboukheira, S. K. Johnson

ABSTRACT. *Irrigated alfalfa production is gaining interest because of the growing number of dairies in the semi-arid U.S. Central Great Plains and its longstanding superior profitability compared to other alternative crops grown in the region. Irrigation requirements for alfalfa are great because of alfalfa's long growing season, so it is important that irrigation be utilized efficiently in this region where water is pumped from the declining Ogallala aquifer. A three-year yield study (2005-2007) was conducted at the Kansas State University Northwest Research-Extension Center in Colby, Kansas, to evaluate production of subsurface drip irrigated alfalfa on a deep productive silt loam soil. Three irrigation levels (randomized complete block design of three replications) designed to replace 70%, 85%, or 100% of the calculated crop evapotranspiration minus precipitation were compared in terms of alfalfa yield, irrigation amount, plant-available soil water, crop water use, and crop water productivity. Alfalfa yield was also evaluated at three perpendicular horizontal distances from the 1.5 m spaced driplines (0, 0.38, and 0.76 m). Annual alfalfa yields were unaffected by irrigation level, averaging 20.8 Mg ha^{-1} while irrigation amounts averaged 396, 484, and 586 mm for the 70%, 80%, and 100% ET irrigation levels, respectively. Seasonal crop water use was significantly greater with increased irrigation, but only by an average difference of 137 mm among irrigation levels as compared to the 190 mm difference in irrigation amount. Crop water productivity was significantly greater with decreased levels of irrigation, with values of 23.5, 22.0, and 20.4 kg ha^{-1} mm^{-1} for the 70%, 85%, and 100% ET irrigation levels, respectively. No significant differences existed in alfalfa yield with respect to horizontal perpendicular distance from the dripline with the exception of the 0.76 m distance, which yielded less in the drier and warmer year 2006. Large and significant decreases in alfalfa yield and crop water productivity occurred with successive harvests, with the first harvest having 272% and 196% of the fifth harvest yield and crop water productivity, respectively. Plant-available soil water decreased as the season progressed for all irrigation levels, but to a much greater extent for the 70% ET level, averaging at the time of the fifth seasonal harvest only 41% and 54% of the soil water for the 85% and 100% ET irrigation levels, respectively. These large seasonal decreases in soil water for the 70% ET irrigation level would be anticipated to be of even greater concern in extended multiple-year drought periods. This fact coupled with the 102 mm reduction in seasonal irrigation amount for the 85% ET irrigation level compared to the 100% ET irrigation level leads to a recommendation of scheduling replacement of 85% of the ET minus precipitation when subsurface drip irrigating alfalfa in the Central Great Plains. This study was conducted in a region with deep silt loam soils where approximately 60% of the average annual precipitation occurs during the summer months. Additionally, 125 mm of fall irrigation was applied during the dormant fall season to reduce root intrusion and rodent damage. These combined facts need to be considered when applying the results of this study to other regions and when using different irrigation management strategies.*

Keywords. Forage, Irrigation management, Microirrigation, Subsurface drip irrigation, Water productivity.

A lfalfa (*Medicago sativa* L.), a forage crop, has relatively large crop water needs, and thus highly efficient irrigation systems, such as subsurface drip irrigation (SDI), might substantially reduce total irrigation water demand. In some regions, the water allocation for irrigation is limited by hydrogeological or institutional constraints, so SDI can effectively increase alfalfa production by increasing the crop transpiration while reducing or eliminating irrigation runoff, deep perco-

lation, and soil water evaporation. Annual alfalfa dry matter yields are typically linearly related to crop evapotranspiration (ET), and within-season yields often decrease with successive harvests as the crop experiences more stressful drier and hotter climatic conditions (Bauder et al., 1978; Metochis, 1980; Grimes et al., 1992; Saeed and El-Nadi 1997). Since alfalfa is such a large water user and has a very long growing season, irrigation labor requirements can be reduced with SDI relative to less efficient alternative ir-

rigation systems that would require more irrigation and thus more irrigation events (Hengeller, 1995).

A major advantage of SDI on alfalfa is the ability to continue irrigating immediately before, during, and immediately after the multiple seasonal harvests. Continuation of irrigation reduces the amount of water stress on the alfalfa and thus can increase forage production, which is generally linearly related to transpiration. Transpiration on SDI plots that did not require cessation of irrigation was 36% higher during this period than on plots where irrigation was stopped for the normal harvest interval (Hutmacher et al., 1992). Yields with SDI were approximately 22% higher than surface flood-irrigated fields while still reducing irrigation amounts by approximately 6%. In a later summary of this same research study, Ayars et al. (1999) indicated that water productivity (WP, the alfalfa yield divided by the crop water use) was increased mainly due to increased yield, and not to less crop water use. When irrigation can continue, less physiological stress on the crown of the plants occurs, and weed competition can be reduced. On some soils with some SDI designs, irrigation with SDI may need to be reduced during the harvest interval to avoid wet spots and compaction by heavy harvesting equipment. Possible solutions to these problems might be deeper SDI installations or closer dripline and emitter spacings, thus resulting in more uniform water distribution (McGill, 1993; Hengeller, 1995).

Alfalfa can be very sensitive to foliar leaf burn from sprinkler irrigation of low-quality water. Yields can also be reduced by temporary ponding of irrigation water on the soil surface during periods of hot weather. SDI can avoid both of these issues entirely (Hengeller, 1995).

In drier regions, annual weed competition can also be reduced with SDI compared to surface and sprinkler irrigation since the soil surface is not wetted by irrigation. The weed control advantage is difficult to quantify in alfalfa but has been noted by numerous investigators (Bui and Osgood, 1990; Hengeller, 1995; Alam et al., 2002b). Fewer weeds can result in better quality hay, which then can receive a premium price in some regions.

On some soils under good irrigation management, it may be possible to use relatively wide dripline spacing for alfalfa because of its extensive and deep root system. In arid California on a silty clay loam, yields from driplines spaced at 2 m were nearly equal to those obtained with a narrower 1 m spacing after the first year of operation (Ayars et al., 1999). Alfalfa yield for the wider spacing was reduced by approximately 17% during the first year of that study when the root system was not well established. In semi-arid Kansas on a sandy loam soil, yields were 18% lower for 1.5 m spacing as compared to a narrower 1 m spacing for the second and third years of production (Alam et al., 2002b). It was concluded that the 1 m spacing was more economical. However, it is possible that irrigation applications with SDI on that soil type were too marginal to allow the alfalfa to fully develop under the wider 1.5 m spacing. Irrigation applications were only approximately 50% of the average reference evapotranspiration due to study constraints imposed on the producer-owned field. In Mexico, subsurface dripline spacings of 0.8 and 1.0 m were compared under three irrigation regimes (100%, 80%, and 60% of ET

replacement) in a two-year study (Avila et al., 2003). Annual alfalfa forage yields for the 1.0 m dripline spacing were 94%, 97%, and 92% of those obtained with the 0.8 m dripline spacing for the 100%, 80%, and 60% ET irrigation regimes, respectively. The researchers also found that irrigation amounts were reduced by 15% to 49% and yields were increased by 14% to 25% when comparing SDI to surface gravity irrigation. They recommended a dripline spacing of 1 m with irrigation regime scheduled to replace 80% of ET.

Although field corn is the primary irrigated crop in the Central Great Plains, a growing number of regional dairies are requiring good-quality alfalfa as a part of their feed. This demand, coupled with the longstanding superior profitability of irrigated alfalfa in the region, has led to renewed interest in alfalfa production, particularly with irrigation systems that can efficiently apply water to this high water use crop. A study was initiated to evaluate alfalfa production using SDI.

PROCEDURES

EXPERIMENTAL SITE DESCRIPTION

Three levels of subsurface drip irrigation (replacement of 70%, 85%, or 100% of the calculated evapotranspiration that was not replaced by precipitation) were compared (randomized complete block design of three replications) for alfalfa production in an experiment conducted at the Kansas State University Northwest Research-Extension Center (NWREC) at Colby, Kansas, during the period 2005 to 2007. The deep silt loam soil, as described in more detail by Bidwell et al. (1980), can supply about 445 mm of available soil water from a 2.4 m soil profile. The climate can be described as semi-arid with a summer precipitation pattern and a long-term average annual rainfall of approximately 480 mm. Average precipitation is approximately 400 mm during April through October, the typical active-growing period for alfalfa. The latitude is 39.39° north and the longitude is 101.07° west, with an elevation of 963 m above sea level.

The field site was approximately 120 m wide and 25 m long, consisting of 13 field plots approximately 9 m × 25 m in dimension. The two most northern and southern plots were not used in the field study and served as crop buffers. The area was thoroughly disked with a tandem disk and firmed with a spring-tooth cultivator prior to planting of the inoculated alfalfa seed. The alfalfa (Pioneer HiBred brand 54Q25) was planted on 12 September 2003 in 0.25 m spaced rows with a Great Plains disk drill at an approximate seeding rate of 13 kg ha^{-1}. After planting, a 25 mm application of irrigation was applied to the site with hand-set sprinkler lines on a 9.1 m × 9.1 m spacing with an application rate of approximately 7.5 mm h^{-1}. Stand establishment was insufficient with the fall 2003 planting, so on 20 April 2004 the established alfalfa stand was interseeded at an approximate seeding rate of 13 kg ha^{-1} using a 0.25 m spaced disk drill at an approximately 15° angle to the original drill rows. Hand-set sprinkler lines were used to apply approximately 25 mm of irrigation after this interseeding to improve germination. Stand establishment after this second seeding was sufficient for good alfalfa production. The subsurface drip irrigation system was not used for stand estab-

lishment for either planting due to the deep SDI installation depth of 0.5 m. Although the crop was harvested three times during the summer and irrigated using the SDI system, no irrigation treatments were imposed nor were harvest data collected during 2004 while the alfalfa was becoming more fully established. During the rest of the year 2004, the crop was irrigated as needed with a water-budget irrigation schedule designed to apply approximating 100% of the alfalfa evapotranspiration not replaced by precipitation for a total seasonal irrigation amount of approximately 375 mm.

The subsurface drip irrigation (SDI) system was installed in the fall of 2003 before planting of the alfalfa. Low-flow (0.6 L h^{-1} per emitter) dripline with a 0.3 m emitter spacing, 381 μm wall thickness, and 20 mm inside diameter (Ro-Drip XL 12-15, Roberts Irrigation Products, Inc., San Marcos, Cal.) was installed with a 1.5 m dripline spacing using a shank-type injector at a depth of 0.5 m. The emitter exponent for this dripline as measured in the laboratory at NWREC was 0.59, which was slightly greater than the manufacturer's specified value of 0.57. Six driplines approximately 25 m long were oriented from east to west in each plot. Each plot was instrumented with a municipal-type flowmeter (model C-700, ABB, Zurich, Switzerland, nominal size of 16 mm) to record accumulated flow. Mainline pressure entering the driplines was first reduced to 138 kPa with a pressure regulator (model PMR 20LF, Senninger Irrigation, Inc., Clermont, Fla.) and then further reduced with a throttling valve to the nominal flow rate of 0.088 L s^{-1} for each plot, coinciding with an operating pressure of approximately 69 kPa. Filtration to the SDI system was provided by a manual screen filter with 75 μm (200 mesh) filtration, which agreed with the dripline manufacturer's recommendation. The filtration system was typically flushed at the beginning of each irrigation event. The water source for the study was fresh groundwater pumped from the Ogallala aquifer with a water temperature of approximately 14°C.

CULTURAL PRACTICES AND HARVEST PROCEDURES

No fertilizer was applied to the field site during the course of the study, but small amounts of nitrogen and sulfur were applied through the dripline in the form of urea-sulfuric acid (N-pHuric 15/49, Agrium U.S., Denver Colo., 15% nitrogen and 49% sulfuric acid by weight). Undiluted urea-sulfuric acid was injected at a rate of approximately 8 L h^{-1} into the SDI system water flow of approximately 1.5 L s^{-1} prior to entering the driplines. The urea-sulfuric acid was injected annually in the late fall at an approximate rate of 35 L ha^{-1} to help maintain emitter performance and to help prevent alfalfa root intrusion. The amounts of N and S provided annually in this maintenance treatment were approximately 8 and 8.5 kg ha^{-1}, respectively. Alfalfa is a legume crop and can fix its own nitrogen requirements through *Rhizobium* bacteria. Although alfalfa uses a considerable amount of phosphorus, it was felt that previous cropping at the site had left adequate residual levels of P in the soil for the duration of this study. Sodium hypochlorite (7.5% concentration) was also applied as a dripline maintenance treatment twice a year (early spring and late fall) at an approximate rate of 25 L ha^{-1}. The sodium hypochlorite

was injected into the water flow (1.5 L s^{-1}) of the SDI system at an injection rate of approximately 7 L h^{-1}.

Five harvests occurred each year (table 1) with the first harvest occurring near the end of May, approximately 54 days from the beginning of spring green-up, which typically began around 1 April. Each of the five annual alfalfa forage harvests was accomplished in three phases. During the first phase, an approximately 6.5 m buffer zone on both the east and west sides of the plot area was removed with a bulk forage harvester, allowing for an approximately 11.5 m plot length of uniform height alfalfa to be harvested with a plot forage harvester from the center of each 25 m plot length. During the second phase of each harvest, plot samples were obtained from each replicated treatment whole plot at three horizontal distances from the dripline (0, 0.38, and 0.76 m) to examine the effect of the 1.5 m dripline spacing on alfalfa yield. A self-propelled plot harvester used a flail chopper 0.91 m in width to cut the alfalfa to a residual height of 10 cm. The harvested material was blown into a container mounted on load cells on the harvester for mass determination. Samples centered at the fixed horizontal distances (0, 0.38, and 0.76 m) from the dripline were obtained from the second, third, and fourth driplines of the six-dripline plots, respectively, to avoid overlap of the harvester, which had width greater than the

Table 1. Harvest dates and pertinent comments concerning alfalfa production in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Year	Harvest	Date (DOY)	Period	Comment
2005	1	27 May (147)	56	Last spring date with temperature less than 0°C was 3 May.
	2	29 June (180)	33	
	3	28 July (209)	30	
	4	29 Aug. (241)	32	
	5	9 Nov. (313)	72	First fall date with temperature less than 0°C was 29 Sept., but alfalfa was still growing on 9 Nov.
2006	1	25 May (145)	54	Last spring date with temperature less than 0°C was 26 April.
	2	23 June (174)	29	Hail storm on 16 June.
	3	19 July (200)	26	
	4	18 Aug. (230)	30	
	5	13 Sept. (256)	26	Harvest approximately one week early to help avoid later possible frost damage to alfalfa.
2007	1	23 May (143)	52	A hard freeze with a temperature of -7°C that occurred on 12 April may have suppressed alfalfa yields.
	2	25 June (176)	33	
	3	23 July (204)	28	
	4	20 Aug. (232)	28	
	5	25 Oct. (298)	66	First fall date with temperature less than 0°C was 16 Oct. Alfalfa was harvested before a predicted hard freeze on 27 Oct.

[a] DOY = day of year. Period for harvest 1 is elapsed time since 1 April.

sampling distance interval. The plot area and wet mass were recorded, and a grab sample of approximately 1.2 kg of the wet mass was used for water content determination. Wet samples were weighed in the laboratory, dried at approximately 50°C until no further change in mass occurred (approximately two days), and then reweighed for forage water content determination. Harvested wet forage yields were corrected to dry matter yield for each horizontal distance from the dripline. A composite plot yield was calculated as the average of the combined sum of the measured yields at horizontal distances of 0 and 0.76 m and twice the measured yield at 0.38 m (i.e., 4 yield terms divided by 4 to accurately mirror samples around the distance 0 sample and to fully represent the 1.5 m dripline spacing). Immediately after completion of the second phase (plot harvest sampling) of each harvest, the residual unharvested areas at the field site were removed with the bulk forage harvester to prepare the site for normal alfalfa regrowth.

IRRIGATION WATER MANAGEMENT

The irrigation treatments (three levels of irrigation replicated three times in three randomized complete blocks, for a total of nine whole plots) were designed to apply 100%, 85%, or 70% of the calculated evapotranspiration that was not replaced by precipitation. Each whole plot was controlled and monitored for accumulated irrigation amount independently of all other whole plots.

Irrigation was scheduled using a weather-based water budget constructed using data collected from a NOAA weather station located approximately 500 m northeast of the study site. The schedules were started each year on 1 April and continued thorough the end of October or the first killing frost, whichever came first. The reference evapotranspiration (ET_r) was calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heermann (1974). The specifics of the ET_r 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, indicates that the modified Penman values using this estimation method are approximately 1.5% to 2.8% smaller than those obtained with the ASCE standardized reference evapotranspiration equation, which is based on FAO-56 (Allen et al., 1998). The accuracy of the modified Penman values is well within the requirements of the resultant scheduling and irrigation application procedures. Daily crop coefficients (single K_c) were generated using FAO-56 (Allen et al., 1998) as a guide, with periods adjusted to northwest Kansas growing period lengths. Specifically, K_c values for the initial 40-day period beginning 1 April were allowed to increase linearly from 0.2 to a maximum of 1.0, remain at 1.0 until harvest, and then increase linearly from 0.2 to a maximum of 1.0 in a 17-day period after that and following subsequent harvests during the season. Crop evapotranspiration (ET_c) was calculated as the product of K_c and ET_r. In constructing the irrigation schedules, no attempt was made to modify ET_c with respect to soil evaporation losses or soil water availability, as outlined by Kincaid and Heermann (1974). Alfalfa-based ET_r is considered to give better estimates than

short-grass ET_o in this region (Howell, 2007). Typically, weekly or twice-weekly irrigations were scheduled whenever the calculated soil water depletion in the profile exceeded approximately 50 mm. The few exceptions to this scheduling frequency were related to the unavailability of the pumping water source due to its concurrent use on another study site. Gross irrigation amount ranged from approximately 6 to 25 mm for each event, depending on availability of pumping system for the given event.

In the late fall of each year following the dormancy of the alfalfa top growth, an irrigation amount of 125 mm was applied with the SDI system to reduce the chance for root intrusion and/or rodent damage during the long overwinter period. This large irrigation amount, which was separate from the urea-sulfuric-acid and sodium hypochlorite injections, would affect the year-to-year sustainability of the alfalfa under the more deficit-irrigated treatments but should not greatly affect the in-season differential responses of the various irrigation treatments.

WEATHER AND WATER-RELATED EXPERIMENTAL DATA AND CALCULATED PARAMETERS

Additional study data collected during the growing season included irrigation and precipitation amounts, weather data, and soil water data. Volumetric soil water content was measured in each irrigation whole plot weekly or biweekly with a neutron attenuation moisture meter in 0.3 m increments to a depth of 3.0 m at a single location, a distance of 0.76 m horizontally from one of the center driplines. Plant-available soil water for the different depth increments was calculated from the measured volumetric water content and using standard bulk density and unavailable soil water contents established at NWREC from long-term studies. Calculated values from the data collection included crop water use and water productivity (both seasonal totals and values for the five individual harvests). Crop water use was calculated as the sum of soil water depletion between the initial and final soil water measurements, and precipitation and irrigation between the initial and final soil water measurements. Calculating crop water use in this manner would inadvertently include any deep percolation and rainfall runoff and is sometimes termed the field water supply. Water productivity was calculated as dry matter alfalfa yield divided by the total crop water use.

STATISTICAL TREATMENT

The experimental data were analyzed as mixed models using the PROC MIXED procedure with repeated measures (SAS, 1996). Year, harvest, irrigation level, distance from the dripline, and their interactions were considered fixed effects, while replication was the random effect. Year and harvest were used as the repeated measures in the models since five repeated harvests were annually conducted in three sequential years at each of the three dripline distances within each irrigation level plot. Main effects and their interactions were considered to be significant at $p < 0.05$. Mean separations at $p < 0.05$ were conducted within significant effects using the LSMEANS and PDIFF options of the MIXED procedure.
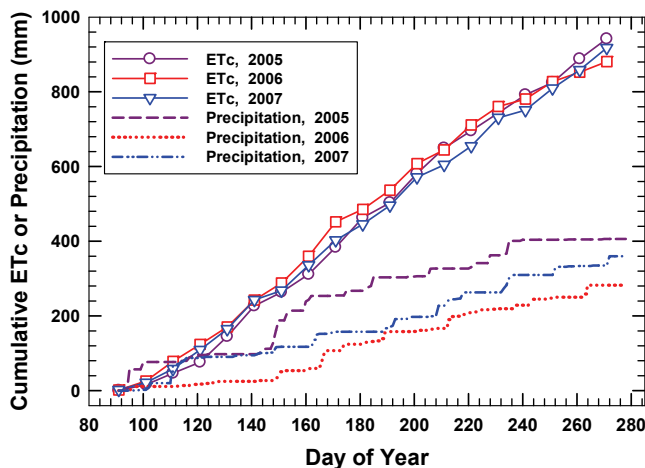
Figure 1. Cumulative calculated evapotranspiration for alfalfa and precipitation from 1 April (DOY 91) through 5 October (DOY 278) for 2005-2007 in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.

RESULTS AND DISCUSSION

WEATHER CONDITIONS AND IRRIGATION AMOUNTS

Weather conditions during the three years of the study were generally favorable for alfalfa production. Two weather events that were less than favorable to production were a hail storm that occurred midway (16 June) between the first and second harvest in 2006 and a hard freeze (12 April) that occurred approximately two weeks after the initiation of spring green-up in 2007 (table 1). Very little difference was observed in seasonal calculated ET_c for the three years of the study (fig. 1), but seasonal precipitation differed by nearly 125 mm between the wettest year (2005) and the driest year (2006). Weather patterns differed between the years with greater calculated ET_r and greater average air temperature during May and June of 2006 as compared to the other two years (table 2), while the latter part of the 2006 season generally had less ET_r and milder air temperatures. Precipitation was above the long-term average in three of the five months in 2005 (May, June, and August) and for only June and September in 2006 (table 2, fig. 1). Although May through mid-July of 2007 was very dry, precipitation during the latter part of the season was well above normal. Irrigation amounts were somewhat similar among the three years (fig. 2), with the seasonal amount for the fully irrigated treatment being 574, 634, and 550 mm for 2005, 2006, and 2007, respectively. When averaged across all three years, the irrigation amounts were 586, 484, and 396 mm for the 100%, 85%, and 70% ET irrigation levels, respectively. Overall, the years provided a relatively good variety of seasonal weather conditions for the study, and the varying conditions were typical of the Central Great Plains.
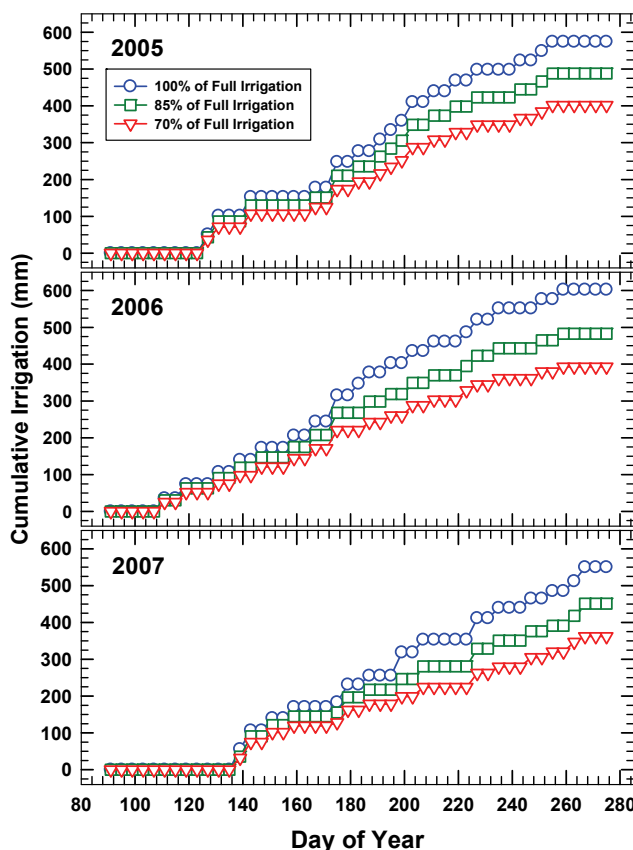

Figure 2. Cumulative irrigation amounts for alfalfa for the various irrigation levels from 1 April (DOY 91) through 5 October (DOY 278) for 2005-2007 in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas. These graphs do not show the 125 mm of irrigation water applied annually in the late fall to help prevent root intrusion and rodent damage of the SDI system.

EFFECT OF IRRIGATION LEVEL ON ANNUAL ALFALFA YIELD, CROP WATER USE, AND WATER PRODUCTIVITY

Alfalfa yields were excellent compared to a regional norm of approximately 9.6 Mg ha^{-1} (Rogers, 2012) for all three years of the study (table 3, fig. 3). Better producers may have average yields closer to 15 Mg ha^{-1} during the early years after establishment, and the normal lifespan of alfalfa in the region is approximately four to five years. No statistically significant differences existed in dry matter yields as affected by irrigation level, but significant differences occurred between years, with greatest dry matter yield in the first year of the study (2005) and the smallest dry matter yield in 2006. Yields for the second harvest in 2006 were reduced by a hail storm on 16 June and by an earlier final harvest on 13 September. The first harvest yields in 2007 may have been suppressed by a hard freeze on 12 April with a temperature of -7°C. The average dry matter yields from this study were approximately 10%

Table 2. Average monthly reference evapotranspiration, daily air temperature, and monthly precipitation during the primary alfalfa growing months for 2005-2007 as compared to the long-term (LT) 1972-2009 values, KSU Northwest Research-Extension Center, Colby, Kansas.

Month	ET_r (mm)				Air Temperature (°C)				Precipitation (mm)			
	2005	2006	2007	LT	2005	2006	2007	LT	2005	2006	2007	LT
May	209	228	202	180	16	18	17	16	96	26	29	85
June	224	268	221	223	22	23	22	21	79	81	41	75
July	260	245	230	240	25	26	25	25	60	43	69	92
August	187	181	206	205	24	24	26	23	77	62	83	66
September	179	143	175	158	21	16	20	18	2	54	50	35

Table 3. Annual alfalfa dry matter yield, seasonal crop water use, and water productivity as affected by irrigation levels in a subsurface drip irrigation study, 2005-2007, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Irrigation Level (% of ET)	2005	2006	2007	Mean
Dry matter yield (Mg ha^{-1})				
100%	22.1	20.0	20.5	20.9
85%	22.5	19.8	20.7	21.0
70%	22.1	19.8	20.0	20.6
Mean	22.2 A	19.9 C	20.4 B	20.8
Seasonal crop water use (mm)				
100%	1069 a	943 c	1061 a	1024 ψ
85%	1014 b	851 d	1010 b	958 θ
70%	989 b	742 e	930 c	887 λ
Mean	1024 A	845 C	1000 B	957
Water productivity (kg ha^{-1} mm^{-1})				
100%	20.7 c	21.3 c	19.3 d	20.4 ψ
85%	22.2 b	23.3 b	20.5 c	22.0 θ
70%	22.4 b	26.7 a	21.6 bc	23.5 λ
Mean	21.7 B	23.7 A	20.5 C	22.0

[a] Values for a parameter (dry matter yield, seasonal crop water use, or water productivity) for the various years and irrigation levels followed by different lowercase letters are significantly different at p < 0.05. Column values for the parameters for the various years followed by different uppercase letters are significantly different at p < 0.05. Row values for the parameters for the various irrigation levels followed by different Greek letters are significantly different at p < 0.05.

greater than those reported by Alam et al. (2002a) for alfalfa grown on a sandy loam in southwest Kansas. The annual yields also compare well with the maximum yields from several western U.S. states summarized by Grismer (2001), which ranged from approximately 17 to 22 Mg ha^{-1}.

The lack of significant differences in total seasonal alfalfa dry matter yield as affected by irrigation level is probably related to the extensive root system of the alfalfa being able to sufficiently and effectively mine the plant-available soil water from the deep silt loam soil without experiencing severe water stress. Although available soil water decreased throughout the season and more so with reduced irrigation levels (fig. 4), the decreasing late summer crop growth and less crop water use during the latter part of the season (fall) would tend to buffer out yield differences between the treatments. Plant-available soil water started each year at a relatively high level (fig. 4) because of overwinter precipitation and because of the 125 mm of late fall irrigation applied to minimize overwinter root intrusion and rodent

damage of the SDI system. However, the 70% ET irrigation level started each of the latter two seasons (2006 and 2007) with less plant-available soil water, suggesting that soil water reserves might be greatly depleted for this irrigation treatment under extended (multiple year) droughts. Seasonal crop water use within a given year was significantly different and increased with increasing irrigation level (table 3), averaging approximately 11% greater for the fully irrigated treatment (100% of ET$_c$) compared to the most deficit irrigated treatment (70% of ET$_c$). Seasonal crop water use was also significantly different between years, with greater crop water use in 2005 and the smallest crop water use in 2006.

Water productivity tended to be greater for the deficit-irrigated treatments and was significantly greater in both 2006 and 2007 for the 70% ET treatment as compared to the fully irrigated treatment (table 3). Although the greatest dry matter yield occurred in 2005, that year had a significantly lower WP, and the greatest WP occurred in 2006, which had the smallest annual dry matter yield. Water productivities in this study were somewhat greater than the values of 16 to 17 kg ha^{-1} mm^{-1} that were reported by Grismer (2001) and also greater than the 18 kg ha^{-1} mm^{-1} value reported by Hengeller (1995). However, greater WP values are possible, and Grimes et al. (1992) reported an average WP value of 23 kg ha^{-1} mm^{-1}, which is similar to
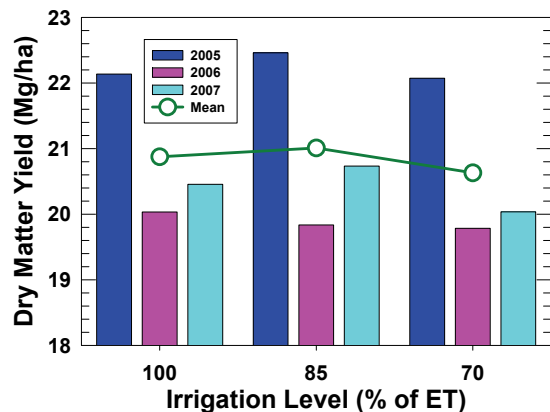

Figure 3. Annual dry matter yields for alfalfa as affected by irrigation level for 2005-2007 in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.
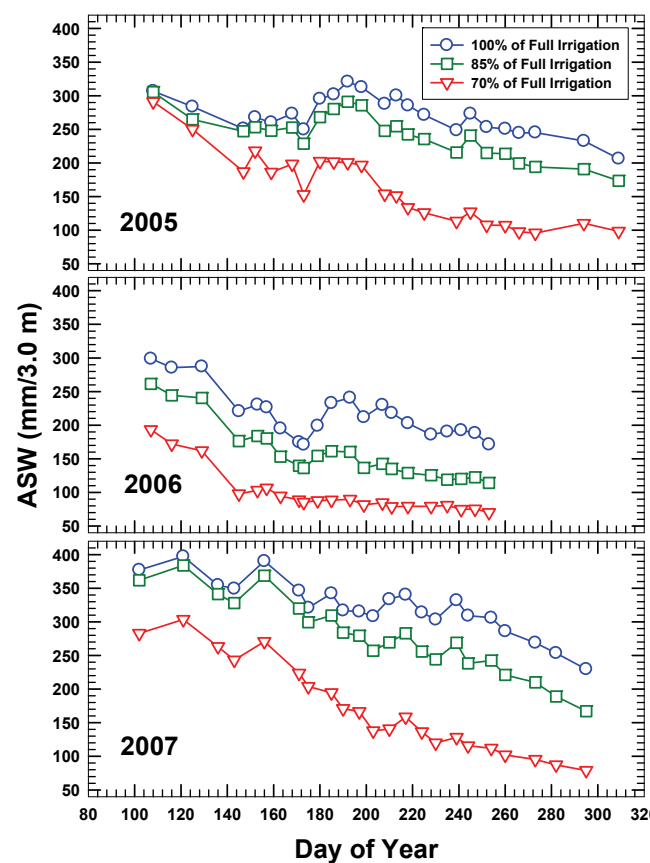

Figure 4. Seasonal progression of plant-available soil water within the 3 m soil profile for the various irrigation levels from 1 April (DOY 91) through 5 October (DOY 278) for 2005-2007 in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.

the values in this study (table 3). These greater WP values are probably indicative of reduced soil water evaporation (the E component of ET_c) when alfalfa is grown with SDI.

EFFECT OF DISTANCE FROM DRIPLINE ON ANNUAL ALFALFA DRY MATTER YIELDS

Generally no appreciable differences (<0.2 Mg ha^{-1}) occurred in annual alfalfa dry matter yields as affected by horizontal perpendicular distance from the dripline when averaged over all the years (table 4, fig. 5), but differences existed between years. Although no statistically significant differences in alfalfa yield as affected by distance from the dripline occurred in 2005 and 2007, a gradual and statistically significant decrease in yield occurred as distance from the dripline increased in the drier and warmer 2006 season. The small yield differences in 2006 that were related to increased distance from the dripline tended to increase slowly with successive harvests. As the plant-available soil water decreased throughout the season (fig. 4), the alfalfa plants farther from the dripline would have increased difficulty scavenging for the limited soil water resources. It was also visually observed that plants at the midway point between driplines tended to show greater water stress as the season progressed, particularly for the 70% ET irrigation level. The general results of no appreciable differences in alfalfa dry matter yield as affected by distance from the dripline for this 1.5 m dripline spacing appear to conflict with the results of Alam et al. (2002a), who found an approximately 19% yield increase for driplines spaced at 1 m as compared to driplines spaced at 1.5 m. The sandy loam soil texture of that demonstration study in southwest Kansas may have increased in-season water stress for alfalfa plants with the wider 1.5 m spacing, and plant stands were also negatively affected by the wider dripline spacing (Alam et al., 2002a). Additionally, in the current study, 125 mm of dormant season subsurface drip irrigation was applied to help prevent
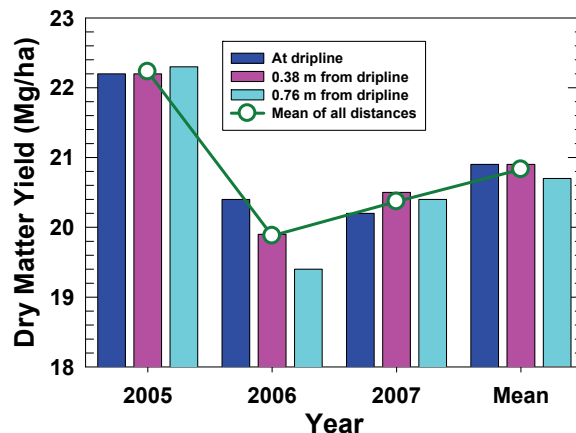

Figure 5. Annual dry matter yields for alfalfa as affected by perpendicular distance from the dripline for 2005-2007 in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.

root intrusion and rodent damage and therefore may have increased profile soil water at greater distances from the dripline as compared to the Alam et al. (2002a) study. However, the results of the current study are somewhat similar to the results of a study by Hutmacher et al. (1992) for the arid Imperial Valley of California on a silty clay loam, which found that yields with driplines spaced at 2 m were nearly equal to yields obtained with a narrower 1 m spacing after the first year of operation. The results from the current study are also similar to those reported by Avila et al. (2003) who found less than 8% difference in yields when comparing dripline spacings of 0.8 and 1.0 m under irrigation regimes designed to replace 60%, 80%, or 100% of ET.

EFFECT OF SUCCESSIVE HARVESTS ON ALFALFA YIELD, AVAILABLE SOIL WATER, CROP WATER USE, AND WATER PRODUCTIVITY

Large and statistically significant differences in alfalfa dry matter yields occurred between successive harvests (table 5). Yields from the first harvest averaged 72% greater than the second harvest and 272% greater than the fifth harvest. On average, only 20% of the seasonal irrigation was required before the first harvest, which emphasizes the importance of stored soil water and dormant-season and early-season precipitation on alfalfa production in this semi-arid region. It should be restated that dormant-season irrigation (125 mm) was applied in the late fall of each year in this study to reduce the possibility of root intrusion and rodent damage in the SDI system. The 100% ET irrigation level had a small but significantly lower yield for the first harvest (table 5), which was somewhat surprising given that overall irrigation amounts prior to the first harvest each year in this study were less than approximately 125 mm (average of three years for the 100% ET irrigation level). Irrigation level did not significantly affect yield for the second and third harvests each year (table 5, fig. 6), but a small and statistically significant decrease in yields occurred with decreased irrigation level for the fourth and fifth harvest. Similarly, a trend toward slightly decreased yields was observed with increased distance from the dripline for the later harvests (fig. 6), although these yield

Table 4. Annual alfalfa dry matter yields as affected by distance from dripline and irrigation level, 2005-2007, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Year	Irrigation Level (% of ET)	Distance from Dripline		
		0 m	0.38 m	0.76 m
2005	100%	22.1	22.0	22.3
	85%	22.0	22.7	22.4
	70%	22.6	21.8	22.0
	Mean	22.2 a	22.2 a	22.3 a
2006	100%	20.2	20.3	19.4
	85%	20.0	19.7	19.9
	70%	21.0	19.7	18.8
	Mean	20.4 b	19.9 bc	19.4 c
2007	100%	20.5	20.5	20.4
	85%	20.3	20.9	20.8
	70%	19.8	20.2	20.0
	Mean	20.2 b	20.5 b	20.4 b
All years	100%	20.9	20.9	20.7
	85%	20.8	21.1	21.1
	70%	21.1	20.6	20.3
	Mean	20.9 A	20.9 A	20.7 A

[a] Alfalfa dry matter yields for the various years and distances from the dripline followed by different lowercase letters are significantly different at p < 0.05. Overall average alfalfa dry matter yields for the distances from the dripline followed by different uppercase letters are significantly different at p < 0.05. No significant differences in dry matter yields attributable to irrigation level occurred for the various distances from the dripline.

Table 5. Dry matter yields (Mg ha^-1) for the five seasonal harvests for 2005-2007 as affected by irrigation level in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Year	Irrigation Level (% of ET)	Harvest 1	2	3	4	5
2005	100%	7.21	4.61	4.06	3.55	2.74
	85%	7.25	4.86	4.21	3.33	2.74
	70%	7.30	4.83	4.13	3.32	2.57
	All	7.25 A	4.76 B	4.13 C	3.40 D	2.68 E
2006	100%	8.14	2.97	3.42	3.20	2.22
	85%	8.37	3.03	3.34	3.04	2.09
	70%	8.50	2.95	3.34	2.83	2.19
	All	8.34 A	2.98 C	3.37 B	3.02 C	2.17 D
2007	100%	5.57	4.68	3.94	3.19	3.06
	85%	5.84	4.68	3.82	2.94	2.72
	70%	5.84	4.68	3.82	2.94	2.72
	All	5.77 A	4.66 B	3.88 C	3.09 D	2.98 D
All	100%	6.97 b	4.09 a	3.80 a	3.31 a	2.67 a
	85%	7.17 a	4.17 a	3.81 a	3.17 b	2.66 a
	70%	7.21 a	4.15 a	3.76 a	3.03 b	2.49 a
	All	7.11 ψ	4.11 θ	3.79 λ	3.17 β	2.61 Δ

[a] Alfalfa yields for the various harvests within a given year followed by different uppercase letters are significantly different at $p < 0.05$. Alfalfa yields for various irrigation levels within a given harvest followed by different lowercase letters are significantly different at $p < 0.05$. Alfalfa yields for various harvests followed by different Greek letters are significantly different at $p < 0.05$.

Table 6. Available soil water (mm per 3.0 m soil profile) at the time of the five seasonal harvests for 2005-2007 as affected by irrigation level in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Year	Irrigation Level (% of ET)	Harvest 1	2	3	4	5
2005	100%	251	295	288	249	206
	85%	247	268	248	216	173
	70%	187	202	154	113	98
	All	228 B	255 A	230 AB	193 C	159 D
2006	100%	221	171	212	186	171
	85%	176	136	136	125	114
	70%	98	85	82	79	70
	All	165 A	131	143 AB	130 B	119 B
2007	100%	350	321	308	304	230
	85%	328	299	257	244	167
	70%	243	204	138	120	79
	All	307 A	275 B	234 C	223 C	159 D
Mean	100%	274 a	262 a	269 a	246 a	203 a
	85%	250 a	235 a	214 b	195 a	152 a
	70%	176 b	164 b	124 c	104 b	82 b
	All	233 ψ	171	202 θ	182 λ	146 β

[a] Available soil water amounts for the various harvests within a given year followed by different uppercase letters are significantly different at $p < 0.05$. Available soil water amounts for various irrigation levels within a given harvest followed by different lowercase letters are significantly different at $p < 0.05$. Available soil water amounts for various harvests followed by different Greek letters are significantly different at $p < 0.05$.

reductions were only statistically significant (table 4) in 2006, the warmer and drier year (fig. 1, table 2).

Plant-available soil water generally decreased between successive harvests (fig. 4, table 6). When averaged over all irrigation levels, it was a statistically significant decrease. A seasonal trend toward decreasing available soil water existed even for the 100% ET treatment. In this region, early-season precipitation exceeds crop water use, so some of this excess water is added to storage in the 3 m soil profile. A second and probably more important factor is that irrigation application by the 1.5 m spaced driplines does not uniformly wet the soil profile, so the soil is drier between the driplines, which increases as the season progresses into drier conditions. This rationale is supported by the trend of decreasing alfalfa yields with increasing distance from the

dripline as the summer progressed to the later harvests. Generally, less difference in plant-available soil water occurred for the 85% and 100% ET irrigation levels as compared to the 70% ET irrigation level. The greater irrigation levels more closely match the irrigation needs of alfalfa in this semi-arid region with summer-pattern precipitation, while the deficit 70% ET irrigation level essentially mines the soil water as the season progresses. Although irrigation level did not significantly affect alfalfa yield in this study, the 85% ET irrigation level would be a safer long-term alternative to the 70% ET level because it better maintains adequate soil water reserves under extended drought conditions (both intra- and inter-seasonal droughts). This is illustrated in figure 4 by the nearly parallel progression of ASW for the 85% and 100% ET levels, while ASW begins to diverge for the 70% ET level. Averaged over the entire season, the 85% ET irrigation level had approximately 60% more plant-available soil water at harvest and 84% more soil water at the time of the final annual harvest as compared to the 70% ET irrigation level. The greater soil water levels for the more fully irrigated treatments might also allow for greater utilization of soil nutrients.

Available soil water in the spring varied between seasons. In 2005, all three treatments started the season with approximately 300 mm of ASW within the 3 m soil profile. However, with the seasonal progression through that first year of different irrigation levels, ASW levels varied, and this variation carried through to the next spring even though there had been 125 mm of irrigation applied in the fall of 2005. Soil water depletions tended to be greater in 2006 than in 2005 due to less in-season precipitation, but differences in soil water levels that occurred during the 2006 season were greatly minimized for the 85% and 100% ET levels by overwinter recharge due to precipitation and
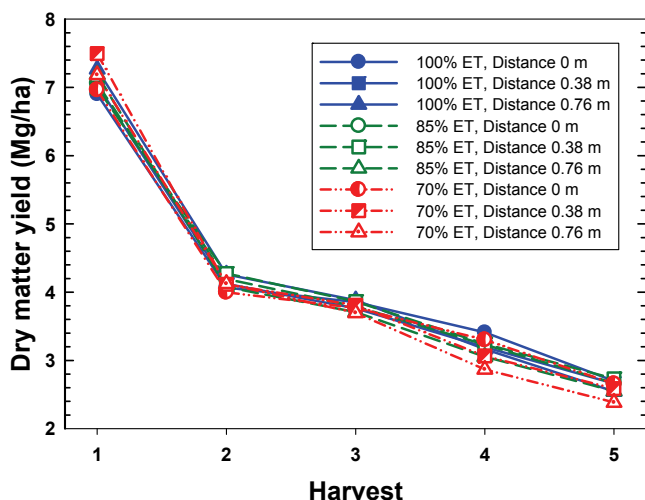

Figure 6. Alfalfa dry matter yields for successive harvest periods as affected by irrigation level (% of ET) and horizontal perpendicular distance from the dripline in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas, 2005-2007.

Table 7. Alfalfa crop water use (mm) for the five seasonal harvest periods for 2005-2007 as affected by irrigation level in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Year	Irrigation Level (% of ET)	Harvest 1	2	3	4	5
2005	100%	244	206	230	204	185
	85%	224	215	218	183	174
	70%	247	206	222	179	135
	All	238 A	209 C	223 B	189 D	165 E
2006	100%	234	234	169	203	103
	85%	220	209	162	175	86
	70%	209	166	144	146	77
	All	221 A	203 B	158 D	175 C	89 E
2007	100%	179	216	188	163	315
	85%	165	209	173	161	302
	70%	167	196	176	147	244
	All	170 C	207 B	179 C	157 D	287 A
Mean	100%	219 a	219 a	196 a	190 a	201 a
	85%	203 b	211 a	184 b	173 b	187 b
	70%	208 b	189 b	181 b	157 c	152 c
	All	210 ψ	206 ψ	187 θ	173 β	180 λ

[a] Alfalfa crop water use amounts for the various harvests within a given year followed by different uppercase letters are significantly different at $p < 0.05$. Alfalfa crop water use amounts for various irrigation levels within a given harvest followed by different lowercase letters are significantly different at $p < 0.05$. Alfalfa crop water use amounts for various harvests followed by different Greek letters are significantly different at $p < 0.05$.

Table 8. Alfalfa water productivity (kg ha^{-1} mm^{-1}) for the five seasonal harvest periods for 2005-2007 as affected by irrigation level in a subsurface drip irrigation study, KSU Northwest Research-Extension Center, Colby, Kansas.[a]

Year	Irrigation Level (% of ET)	Harvest 1	2	3	4	5
2005	100%	29.8	22.5	17.6	17.5	14.8
	85%	32.6	22.6	19.4	18.2	15.9
	70%	29.8	23.4	18.6	18.6	19.3
	All	30.7 A	22.8 B	18.5 C	18.1 CD	16.7 D
2006	100%	34.9	12.7	20.3	15.7	22.2
	85%	38.1	14.6	20.7	17.4	24.4
	70%	40.7	17.8	23.3	19.4	28.3
	All	37.9 A	15.0 E	21.4 C	17.5 D	25.0 B
2007	100%	31.2	21.7	21.1	19.6	9.7
	85%	35.8	22.2	22.4	19.5	10.4
	70%	35.0	23.9	21.7	20.0	11.2
	All	34.0 A	22.6 B	21.7 B	19.7 C	10.4 D
All	100%	31.9 a	18.9 a	19.7 a	17.6 a	15.6 a
	85%	35.5 a	19.8 a	20.8 a	18.4 a	16.9 a
	70%	35.2 a	21.7 a	21.2 a	19.3 a	19.6 a
	All	34.2 ψ	20.1 θ	20.1 θ	18.4 λ	17.4 β

[a] Alfalfa water productivity values for the various harvests within a given year followed by different uppercase letters are significantly different at $p < 0.05$. Alfalfa water productivity values for various irrigation levels within a given harvest followed by different lowercase letters are significantly different at $p < 0.05$. Alfalfa water productivity values for various harvests followed by different Greek letters are significantly different at $p < 0.05$.

the 125 mm of fall irrigation. The 70% ET level did not fully recharge overwinter to the same level as the 85% and 100% ET irrigation levels.

Alfalfa crop water use generally decreased between successive harvests, similar to the trends for alfalfa yield and plant-available soil water (table 7). Averaged across all irrigation levels, the first two harvests had significantly greater crop water use than the other three harvests, which probably reflects the much greater alfalfa yields for these two harvests (i.e., combined first and second harvest alfalfa yields were 117% of the remaining three harvests combined). The 100% ET irrigation level had significantly greater crop water use in all of the harvests except the second harvest, where the 85% and 100% ET irrigation levels were similar. Differences in crop water use among irrigation levels tended to increase with successive harvests, with an approximately 50 mm crop water use difference between the 70% and 100% ET irrigation levels for the fifth harvest, indicative of the gradual mining of the root zone soil water by the alfalfa that occurred in the more deficit irrigation treatment.

Alfalfa crop water productivity was significantly greater for the first harvest and generally decreased with successive harvests (table 8). This is because the reduction in alfalfa yield was greater than the reduction in crop water use (tables 5 and 7) that occurred with successive harvests. The results suggest that, when irrigation water is limited, it may be best to concentrate the scheduled amounts (i.e., irrigation requirements as indicated by irrigation scheduling procedures) toward the earlier growth periods and then apply just the amounts necessary to maintain plant stands during the later parts of the season. Similarly, many publications on irrigation in semi-arid and arid regions often suggest such a strategy when water is limited (Orloff et al., 1997;

Guitjens, 1993; Hanson and Putnam, 2000; McWilliams, 2002). Crop water productivity was not significantly affected by irrigation level within a given harvest, but a slight numerical trend existed toward greater water productivity with less irrigation. The absence of a strong difference in water productivity suggests that applied irrigation was used efficiently by this crop with the SDI system. In a study of furrow and subsurface drip irrigated alfalfa in Brawley, California, it was concluded that SDI water productivity increases were more related to yield increases than to changes in crop water use (Ayars, et al., 1999).

CONCLUSIONS

Alfalfa yields were not significantly affected by in-season irrigation levels (70%, 85%, or 100% replacement of ET minus precipitation) in a three-year study of varying summer weather in the Central Great Plains. Crop water use was significantly greater with increased irrigation, and crop water productivity generally was reduced with greater irrigation (in most cases statistically) but to a lesser extent than the differences in crop water use. The lack of significant differences in alfalfa yield as affected by irrigation regime can be attributed to the inherent characteristic of alfalfa to explore the deep soil profile for soil water, the dormant-season application of 125 mm of irrigation that was applied to reduce root intrusion and rodent damage, the semi-arid and summer pattern precipitation that helped buffer water stress, and the efficient SDI application method that helped minimize water losses such as soil water evaporation, runoff, and deep percolation. Water productivity was in the higher range of reported values, with an average value of 22 kg ha^{-1} mm^{-1}.

Alfalfa yield was not affected by horizontal perpendicu-

lar distance from the dripline (overall 1.5 m dripline spacing) when averaged over all irrigation levels, but yield was significantly reduced at the midway point between driplines (0.76 m) for the 70% ET irrigation level in the drier and warmer year, 2006. Generally, as the season progressed through successive harvests (five each year), plants farthest from the dripline, with less access to the applied irrigation water, tended to exhibit the most mid-day plant water stress (visual observations only). Dripline spacing of 1.5 m is acceptable on the deep silt loam soils of the Central Great Plains provided that adequate plant stands can be obtained. It should be noted that this region has a summer precipitation pattern, with nearly 60% of the average annual precipitation of 480 mm occurring during May through August. The results of this study are likely to be less applicable in arid regions or on coarser-textured soils with less water-holding capacity.

Large and significant differences in alfalfa yield and crop water productivity as affected by harvest occurred in this study, with earlier harvests having much greater yield and crop water productivity. This suggests, as has been reported elsewhere, that when irrigation is limited (e.g., institutional or geohydrological constraints), it may be beneficial to concentrate the water toward the earlier growth periods whenever irrigation is required.

Although no appreciable differences in alfalfa yield occurred with irrigation levels ranging from 70% to 100%, it is concluded that an irrigation level of 85% (replacement of ET minus precipitation) is recommended because this level maintained approximately 60% greater plant-available soil water throughout the season compared to the 70% ET level, while reducing the irrigation amount by 102 mm (17%) from the 100% ET irrigation level.

REFERENCES

Alam, M., T. P. Trooien, T. J. Dumler, and D. H. Rogers. 2002a. Using subsurface drip irrigation for alfalfa. *J. American Water Resources Assoc*. 38(6): 1715-1721.

Alam, M., T. P. Trooien, D. H. Rogers, and T. J. Dumler. 2002b. An efficient irrigation technology for alfalfa growers. *J. Extension* 40(3): 1-9.

Allen, R. G., L .S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. Rome, Italy: United Nations FAO.

Avila, C. G., F. L. Trujillo, C. A. T. Estrada, S. J. A. Gaxiola, and R. I. Juarez. 2003. Water consumption, water relations, and yield in alfalfa with subsurface drip irrigation. *Agricultura Tecnica en Mexico* 29(2): 113-123.

Ayars, J. E., C. J. Phene, R. B. Hutmacher, K. R. Davis, R. A. Schoneman, S. S. Vail, and R. M. Mead. 1999. Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. *Agric. Water Mgmt*. 42(1): 1-27.

Bauder, J. W., A. Bauer, J. M. Ramirez, and D. K. Cassel. 1978. Alfalfa water use and production on dryland and irrigated sandy loam. *Agron. J*. 70(1): 95-99.

Bidwell, O. W., E. E. Banbury, W. L. Barker, and G. E. Muilenburg. 1980. The Colby Branch Experiment Station and agriculture in northwest Kansas with special mention of soils. KAES Bulletin 635. Manhattan, Kans.: Kansas Agricultural Experiment Station.

Bui, W., and R. V. Osgood. 1990. Subsurface irrigation trial for alfalfa in Hawaii. In *Proc. 3rd Natl. Irrig. Symp.*, 658-660. St. Joseph, Mich.: ASAE.

Grimes, D. W., P. L. Wiley, and W. R. Sheesley. 1992. Alfalfa yield and plant water relations with variable irrigation. *Crop Sci*. 32(6): 1381-1387.

Grismer, M. E. 2001. Regional alfalfa yield, ET_c and water value in western states. *J. Irrig. and Drain. Eng*. 127(3): 131-139.

Guitjens, J. C. 1993. Alfalfa irrigation during drought. *Irrig. Drain Eng*. 119(6): 1092-1098.

Hanson, B., and D. Putnam. 2000. Can alfalfa be produced with less water? In *Proc. 29th Natl. Alfalfa Symp. and 30th California Alfalfa Symp*. Davis, Cal.: University of California, Department of Agronomy and Range Science Extension.

Hengeller, J. 1995. Use of drip irrigation on alfalfa. In *Proc. Central Plains Irrigation Shortcourse*, 160-167. Manhattan, Kans.: Kansas State University, Department of Biological and Agricultural Engineering Extension

Howell, T. A. 2007. Personal communication concerning alfalfa-based reference evapotranspiration.

Hutmacher, R. B., C. J. Phene, R. M. Mead, D. Clark, P. Shouse, S. S. Vail, R. Swain, M. van Genuchten, T. Donovan, and J. Jobes. 1992. Subsurface drip irrigation of alfalfa in the Imperial Valley. In *Proc. 22nd California/Arizona Alfalfa Symp.*, 20-32. Davis, Cal.: University of California, Department of Agronomy and Range Science Extension.

Kincaid, D. E., and D. F. Heerman. 1974. Scheduling irrigation using a programmable calculator. Publication ARS-NC-12. Washington D.C.: USDA Agricultural Research Service.

Lamm, F. R., D. A. Pacey, and H. L. Manges. 1987. Spreadsheet templates for the calculation of Penman reference evapotranspiration. Presented at the 1987 ASAE Mid-Central Regional Meeting. ASAE Paper No. MCR-87106. St. Joseph, Mich.: ASAE.

McGill, S. 1993. Buried drip for alfalfa. *The Furrow* 98(7): 26-27.

McWilliams, D. 2002. Drought strategies for alfalfa. Circular 581. Las Cruces, N.M.: New Mexico State University Cooperative Extension.

Metochis, C. 1980. Irrigation of lucerne under semi-arid conditions in Cyprus. *Irrig. Sci*. 1(4): 247-252.

Orloff, S. B., H. L. Carlson, and B. R. Hanson. 1997. Chapter 4: Irrigation. In *Intermountain Alfalfa Management*, 25-40. S. B. Orloff, H. L. Carlson, and L. R. Teuber, eds. Pub. 3366. Davis, Cal.: University of California, Division of Agriculture and Natural Resources.

Rogers, D. H. 2012. Personal communication of summarization of alfalfa yields from western Kansas using Kansas Farm Facts as a data source.

Saeed, I. A. M., and A. H. El-Nadi. 1997. Irrigation effects on the growth, yield, and water use efficiency of alfalfa. *Irrig. Sci*. 17(2): 63.

SAS. 1996. SAS systems for mixed models. Cary, N.C.: SAS Institute, Inc.