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SOYBEAN YIELD, EVAPOTRANSPIRATION, WATER PRODUCTIVITY, AND SOIL WATER EXTRACTION RESPONSE TO SUBSURFACE DRIP IRRIGATION AND FERTIGATION

S. Irmak, J. E. Specht, L. O. Odhiambo, J. M. Rees, K. G. Cassman

ABSTRACT. *Soybean [*Glycine max *(L.) Merr.] yield, irrigation water use efficiency (IWUE), crop water use efficiency (CWUE), evapotranspiration water use efficiency (ETWUE), and soil water extraction response to eleven treatments of full, limited, or delayed irrigation versus a rainfed control were investigated using a subsurface drip irrigation (SDI) system at a research site in south-central Nebraska. The SDI system laterals were 0.40 m deep in every other row middle of 0.76 m spaced plant rows. Actual evapotranspiration (ET_a) was quantified in all treatments and used to schedule irrigation events on a 100% ET_a replacement basis in all but three of the eleven treatments (i.e., 75% ET_a replacement was used in two, and 60% ET_a replacement was used in one). The irrigation amount (I_a) applied at each event was 100% of the ET_a amount, except for two 100% ET_a treatments in which only 65% or 50% of the water needed to cover the treatment plot area was applied to enable a test of a partial surface area-based irrigation approach. The first irrigation event was delayed until soybean stage R3 (begin pod) in two 100% I_a treatments, but thereafter they were irrigated with either 100% or 75% ET_a replacement. Two 100% ET_a and 100% I_a treatments also were used to evaluate soybean response to nitrogen (N) application methods (i.e., a preplant method versus N injection using the SDI system). Soybean ET_a varied from 452 mm for the rainfed treatment to 600 mm (30% greater) for the fully irrigated treatment (100% ET_a and 100% I_a) in 2007, and from 473 to 579 mm (20% greater) for the same treatments, respectively, in 2008. Among the irrigated treatments, 100% ET_a and 65% I_a had the lowest 2007 ET_a value (557 mm), whereas 100% ET_a and 50% I_a had the lowest 2008 ET_a (498 mm). The 100%, 75%, and 60% ET_a treatments with 100% I_a had respective actual ET_a values that declined linearly in 2008 (i.e., 579, 538, and 498 mm), but not in 2007. Seasonal totals for ET_a versus I_a exhibited a linear relationship ($R^2 = 0.68$ in 2007 and $R^2 = 0.67$ in 2008). Irrigation enhanced soybean yields from rainfed yield baselines of 4.04 ton ha^{-1} in 2007 and 4.82 ton ha^{-1} in 2008) to a maximum of 4.94 ton ha^{-1} attained in 2007 with the delay to R3 irrigation treatment (its yield was significantly greater, p < 0.05, than that of the seven other treatments) and 4.97 ton ha^{-1} attained in 2008 with the 100% ET_a and 100% I_a preplant N treatment. Seed yield had a quadratic relationship with irrigation water applied and a linear relationship with ET_a that was stronger in the drier year of 2007. Each 25.4 mm incremental increase in seasonal irrigation water applied increased soybean yield by 0.323 ton ha^{-1} (beyond the intercept) in 2007 and by 0.037 ton ha^{-1} in 2008. Each 25.4 mm increase in ET_a generated a yield increase of 0.114 ton ha^{-1} (beyond the intercept) in 2007, but only 0.02 ton ha^{-1} in the wetter year of 2008. This research demonstrated that delaying the onset of irrigation until the R3 stage and practicing full irrigation thereafter for soybean grown on silt loam soils resulted in yields (and crop water productivity) that were similar to full-season irrigation scheduling strategies, and this result may be applicable in other regions with edaphic and climatic characteristics similar to those in south-central Nebraska.*

Keywords. Crop water productivity, Evapotranspiration, Full irrigation, Limited irrigation, Soybean, Subsurface drip irrigation, Water use efficiency, Yield production functions.

Soybean [*Glycine max* (L.) Merr.] seed is used worldwide as a source of protein for livestock feed rations, as a source of cooking oil, and for many other purposes. The majority of U.S. soybean production is located in three distinct regions: the Midwestern Corn Belt, the Mid-South or lower Mississippi River Delta, and the Southeast and Atlantic Coast. In 2011, soybean represented 56% of the world's total oilseed production and 33% of the total oilseed production in the U.S. In 2011, U.S. soybean producers planted approximately 30.3 million ha of soybean, generating nearly 83.2 million metric ton of seed that was valued at $35.7 billion (ASA, 2012). About 34.7 million metric ton of soybean seed were exported in 2011, which accounted for 37% of the world's soybean trade. Nebraska ranks sixth in the U.S. in terms of soybean production area (about 2 million ha), first in terms of average statewide yield (3.60 ton ha^{-1}), and fourth in terms of total production (7.03 million ton) (SoyStats, 2012). Nebraska is

unique among other soybean-producing states in that nearly half of its annual soybean production is irrigated, mainly using center-pivot irrigation systems. In 2011, 0.9 million ha (46%) were irrigated and 1.08 million ha (54%) were rainfed. Irrigated acreage, which in 1976 was less than 7%, rose to 30% in the late 1990s and increased to a peak of 48% in 2007 (USDA-NASS, 2009).

Water deficit is the most common abiotic stress that reduces soybean yields (Purcell and Specht, 2004). Irrigation during periods of low or no rainfall can significantly increase soybean seed yield (Heatherly, 1983), and seasonal rainfall deficits and their occurrence times during the growing season account for much of the annual variation in soybean yield. Scott et al. (1987) observed that high rainfall moderated soybean yield response to irrigation in a mid-south region in the U.S. Irrigated yield was 1.4 ton ha^{-1} greater than rainfed yield in a year receiving about 300 mm rainfall, but not in a year that received 570 mm of rainfall. Specht et al. (1999) noted that 36% of the variation in the yield differential between Nebraska's irrigated and rainfed soybean production could be explained by regression of that differential on annual rainfed yield. The negative effects of water stress are particularly important during the pod set and seed-filling periods, when stress can reduce yield because of pod abortion and reduced seed mass (Ashley and Ethridge, 1978; Doss and Thurlow, 1974; Sionit and Kramer, 1977; Korte et al., 1983; Kadhem et al., 1985; Klocke et al., 1989; Specht et al., 1989). Greater irrigation water productivity of soybean receiving full irrigation as compared with partial irrigation was reported even in a humid southeast region in the U.S. (Garcia et al., 2010).

Various irrigation methods and strategies have been used in soybean production systems. Overall, irrigation significantly increased seed yield and number of seed per unit harvest area for all cultivars in most experiments (Heatherly, 1992). Heatherly and Pringle (1991) reported that flood irrigation methods for every furrow and for alternate furrows resulted in significant yield increases of two soybean cultivars in years when rainfall was deficient during reproductive development. However, they also noted that three seasonal flood irrigation events resulted in significantly less seed yield than did one or two flood irrigation events, which indicated that relatively short periods of flooding can be detrimental to soybean yield if coupled with untimely rainfall. In a comparative study of irrigation methods, Colaizzi et al. (2006) observed that soybean yield and seasonal water use increased significantly as irrigation depth increased, but they also noted that soybean crop yield, crop water use efficiency (CWUE, also known as crop water productivity), and irrigation water use efficiency (IWUE) were higher with a subsurface drip irrigation (SDI) system when compared with sprinkler irrigation systems equipped with mid-elevation spray applicators (MESA), low-elevation spray applicators (LESA), or low-energy precision applicators (LEPA) in their I25, I50, and I75 irrigation treatments. The SDI system also exhibited the least seasonal crop water use. Camp (1998) and Ayars et al. (1999) also reported significant increases in CWUE with SDI in comparison to other irrigation methods. Appropriately managed SDI systems have potential irrigation effi-

ciencies as high as 95% to 100% (Schneider and Howell, 2001). Moreover, SDI systems have fertigation capabilities for a large number of crops, whereby fertilizer can be applied directly to the effective crop root zone at any growth stage during the growing season.

The greater CWUE observed for SDI versus other irrigation methods, particularly with respect to crops grown in arid and semi-arid climates, is primarily due to the fact that the soil surface is dry and surface evaporative losses are much less with buried drip lines than would be the case with aboveground irrigation methods. Moreover, the opportunity for rainfall infiltration is greater with SDI systems, given that the soil layer near the surface is not likely to be wetted or saturated after an irrigation event, thus allowing more of the water from rainfall events occurring just after irrigation events to infiltrate and become available for crop use. This should generally result in less water runoff from the field after such rainfall events. Both factors obviously increase the potential for storing more rainfall that could be used for transpiration, thereby increasing crop productivity, reducing irrigation water requirements, and ultimately increasing CWUE. In SDI systems, roots tend to proliferate around the drip line emitter zones (Machado et al., 2003), which can theoretically minimize the amount of root dry matter needed for water acquisition elsewhere in the soil. The degree of spatial root variability associated with the interactions between root system structure and soil conditions has been documented (Brown and Scott, 1984; Hamblin, 1985; Upchurch, 1987; Phene et al., 1992; Coelho and Or, 1996; Machado et al., 2003).

Although the foregoing summary of the literature indicates that an SDI system may improve crop yield and water use efficiency, the response of specific crop species to SDI can vary substantially among production areas that differ in seasonal climatic conditions, soil characteristics, and management practices. Such variation justifies the need to develop soybean yield and productivity functions that are pertinent for regional or local use of SDI for various crop species. Moreover, although SDI has been used in other states in the U.S. and at many other regions around the world for decades, this technology is relatively new to the U.S. Midwest, especially to Nebraska, where center-pivot irrigation systems are the norm. The research reported in this article is one of the first large-scale tests of using SDI for soybean irrigation production in Nebraska, and it is the first such evaluation of SDI in south-central Nebraska. Soybean growers in this region are seeking information that they can use in their practices to evaluate the costs and potential water use efficiency benefits associated with SDI. Some issues of informational interest to soybean growers in the region regarding this new irrigation method include soybean yield and productivity responses to SDI, the practicability of using a partial surface area as a basis for calculating the irrigation water requirement for a given irrigation event, crop water use for SDI-irrigated soybean, the dynamics involving the practice of delaying commencement of seasonal irrigation until the beginning of the R3 stage of soybean reproductive development, and the nature of soybean water extraction patterns when using this relatively new irrigation system in the region. SDI is of interest be-

cause of its potential for lessening the amount of water withdrawn from limited surface and ground water supplies while still maintaining or even potentially improving crop water productivity. Because these important SDI management topics have not been examined much in the Midwest, the objectives of this research were to: (1) measure and compare the CWUE, IWUE, and evapotranspiration water use efficiency (ETWUE) of subsurface drip-irrigated soybean under various irrigation levels and rainfed settings, (2) quantify the yield response to delayed irrigation and irrigation water amounts calculated based on full and partial surface areas, and (3) quantify seasonal soybean soil water extraction on a weekly basis in the varied irrigation treatment strategies and rainfed control with respect to the edaphic and climatic conditions at a south-central Nebraska research site.

MATERIALS AND METHODS
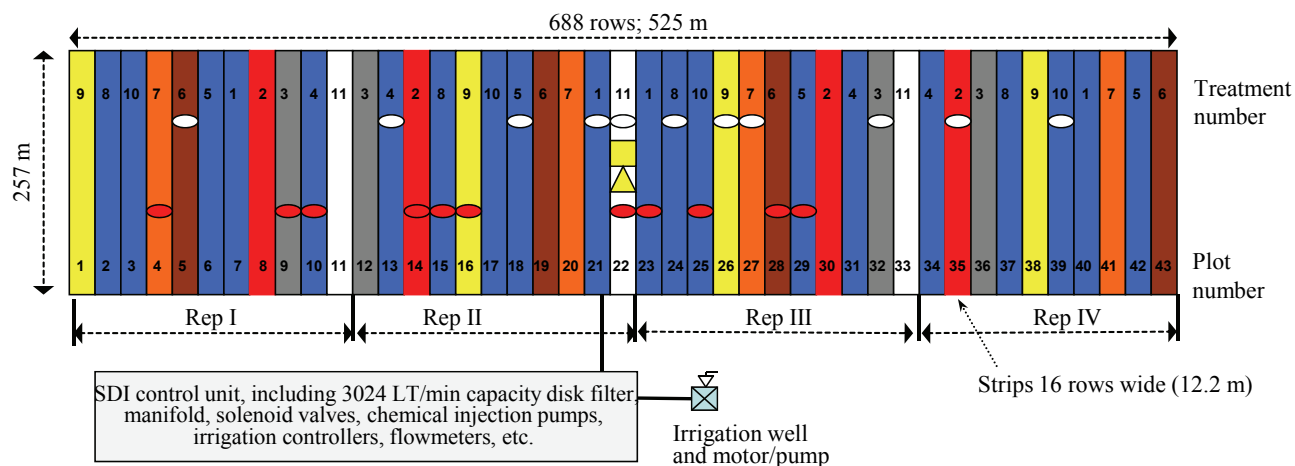
EXPERIMENTAL SITE CHARACTERISTICS

Field experiments were conducted in the 2007 and 2008 growing seasons at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (40° 43′ N, 98° 8′ W, elevation 552 m above mean sea level), near Clay Center, Nebraska. The soil at the site is a Hastings silt loam, which is a well-drained upland soil (fine, montmorillonitic, mesic Udic Argiustoll) that has a field capacity of 0.34 m^3

m^{-3}, a permanent wilting point of 0.14 m^3 m^{-3}, and a saturation point of 0.53 m^3 m^{-3}. The typical maximum effective soybean root depth attained during mid-season at the experimental location is about 1.20 m (Torrion et al., 2012). Total available water-holding capacity of the soil profile is about 200 mm m^{-1}. The particle size distribution in the top soil is 15% sand, 65% silt, and 20% clay with 2.5% organic matter content (Irmak, 2010).

EXPERIMENTAL AND TREATMENT DESIGNS

The research field and treatment plot layout therein are presented in figure 1. The 13.5 ha field was irrigated with a subsurface drip irrigation (SDI) system. Drip lines were installed approximately 40 cm below the soil surface, and the 257 m long east-west laterals had a south-north spacing of 1.52 m. Because the south-north plant row spacing was 0.76 m, the laterals were centered in the inter-row area of every other plant row pair. Drip emitters were spaced at 0.457 m apart along the laterals and were pressure-compensated with a 1 L h^{-1} discharge rate.

The experimental design was a randomized block with four replications (fig. 1). In each replication, each experimental unit (to which treatments were randomly assigned) was 257 m long and 12.2 m wide (i.e., 16 plant rows) and thus occupied an area of 0.314 ha. The treatment design was a partial factorial combination of three seasonal irrigation strategies, in which each irrigation event (date and

Figure 1. Diagram of the experimental field at the South Central Agricultural Laboratory near Clay Center, Nebraska, showing the (randomized) layout of the 11 treatments in each of the four replicates and the locations of the instruments used for measuring soil water status and microclimatic variables. A brief rational of the 11 treatments is also provided (I_a = irrigation amount, and ET_a = actual crop evapotranspiration). Smaller volumes of water were applied to T4 and T5 as compared with T1.

amount) was scheduled to achieve an in-season replacement of 100%, 75%, or 60% of cumulative actual crop evapotranspiration (ET_a), and three irrigation amount (I_a) calculation factors that were based on 100%, 65%, and 50% of the four-replicate sum of a treatment's plot area (i.e., 0.314 ha × 4 = 1.25 ha), thereby leading to 0%, 35%, and 50% reductions in the amount of irrigation applied (i.e., a partial surface area-based irrigation management strategy). In this research, because the SDI lines were installed between every other row pair, it was assumed in the partial surface area-based irrigation strategy that crops would be able to utilize the soil water supplied only from the drip line that is in the middle of the two crop rows, and the area remaining between two drip lines does not have to be fully accounted for in the irrigation water requirement calculations for irrigating soybean in deep silt loam soils using an SDI system. Since there is no surface soil wetting during irrigation with an SDI system, the soil surface is usually dry and there is minimal surface evaporation; it was therefore assumed that the evaporating surface area in an SDI field might differ from that of other sprinkler irrigation methods (in which the entire field surface is wetted during irrigation events), and a reduced field surface area could be used for irrigation requirement calculations. Thus, the hypothesis was that the reduction in irrigation water applied based on different percentages of total treatment surface area may not result in considerable reduction in yield, allowing further reduction in water withdrawal.

The partial surface area-based irrigation strategy investigated in this research is also considered as another limited irrigation strategy application using SDI. In figure 1, the 100% ET_a and 100% I_a treatment (T1) provided a season-long full-irrigation scheduling strategy that served as a comparative control for performance-based comparisons with two other season-long scheduling strategies in which ET_a replacement was lower (i.e., T2 with 75% ET_a and T3 with 60% ET_a) and with two additional season-long scheduling strategies in which the percentage of I_a applied in a 100% ET_a replacement strategy was calculated on the basis of less than 100% plot area (i.e., T4 with 65% I_a and T5 with 50% I_a). Treatments T2, T3, T4, and T5 were designed to be limited irrigation management strategies. In all remaining treatments, the I_a factor was 100%. On a seasonal total basis, Treatments T4 and T5 had the same irrigation depth but differed in terms of water supply volume available for the crops. While T4 accounted for 65% of the land area, T5 accounted for 50% of the land area, and T1 accounted for 100% of the land area. In other words, T4 had 15% more water in terms of volume than T5, and T1 had more water delivered through the system than T4 and T5. Therefore, T1, T4, and T5 had the same irrigation depth, but since the irrigation water volume is equal to the irrigation depth multiplied by the treatment area, the differences among these treatments are evident with the different treatment area percentages considered (assuming that the crop roots explored 100%, 65%, and 50% of the land area in T1, T4, and T5, respectively). Therefore, the actual volume of water applied was less as the percentage of I_a was reduced, and as a result, smaller volumes of water were applied to T4 and T5 as compared with T1. In T6 (100%

ET_a) and T7 (75% ET_a), irrigation did not commence until attainment of the soybean pod stage (R3), which is visually characterized as the presence of 4 to 5 mm long pods at one of the four uppermost main stem nodes just below a fully developed recent leaf (Torrion et al., 2011). The R3 stage typically occurs in early to mid-July for maturity group 3.0 cultivars planted in mid-May (Bastidas et al., 2008). These two delayed (until R3) irrigation treatments were designed to test the hypothesis that on deep silty clay loam or silt loam soils (in regions that have climatic and precipitation regimes similar to south-central Nebraska) brought to a field capacity water content at (or soon after) planting, a soybean crop can subsist solely on stored soil water until the R3 stage without much impact on seed yield (Specht et al., 1989). Treatment T9 was a rainfed (non-irrigated control) treatment.

Although it has been documented that soybean does not usually respond to nitrogen (N) fertilizer, two treatments were included in this research to demonstrate to soybean growers the fertigation management practices and capabilities of an SDI system and to specifically assess whether the use of an SDI system would impact the soybean yield response to applied N. To that end, a preplant N application was used in treatment T8 (100% ET_a), whereas SDI-injected N fertigation was used in T10 (100% ET_a). Details about the N applications are provided in the Agronomic Management section. Treatment T11 (100% ET_a) was maintained as non-water stress and non-nitrogen stress treatment that served as a comparative reference treatment. Because there were only 43 experimental units available as replicates within the field (fig. 1), T11 only had three replicates. See figure 1 for more detail on the randomized locations of each treatment in each block (i.e., replicates).

IRRIGATION MANAGEMENT

Seven irrigation events were scheduled in 2007 (July 23 and 26; August 7, 10, 13, 16, and 20) and four events in 2008 (August 7, 22, 26, and 29). As noted above, irrigation events in the treatment plots were scheduled on the basis of percentage (100%, 75%, or 60%) of to-date cumulative ET_a replacement for any given treatment. Thus, the irrigation management in both years was based on replenishing the soil water in the crop root zone according to different portions of the accumulated actual crop evapotranspiration for a two-day or three-day period. Irrigations were applied to meet two or three days of accumulated crop water use. Daily ET_a was calculated by the two-step approach, i.e., $ET_a = K_c \times ET_{ref}$, where K_c is the crop coefficient, and ET_{ref} is the reference (potential) evapotranspiration. Daily ET_{ref} was calculated using the Penman-Monteith combination-based energy balance equation (Monteith, 1965; Monteith and Unsworth, 1990) based on grass-reference surface using climatic variables measured using a Bowen ratio energy balance system (BREBS; Radiation and Energy Balance Systems, Bellevue, Wash.) that was installed in the middle of the research field. The FAO-56 soybean K_c values were used in the daily ET_a calculations. In the 100% ET_a treatments of T4 and T5, the I_a factor of 65% (T4) or 50% (T5) was to limit the amount of water available for ET_a replacement.

AGRONOMIC MANAGEMENT

The experimental field was maintained in a ridge-till condition in both years. Soybean cultivar Pioneer 93M11, which has a relative maturity group (MG) of 3.1, was planted on May 21, 2007, emerged on May 26, and was harvested on October 24, 148 days after planting (DAP). In 2008, the same cultivar was planted on May 19, emerged on May 24, and was harvested on October 1 (135 DAP). In both years, the planting depth was 2.5 cm, and the seeding density was approximately 388,000 seeds per hectare. The crop row direction was east-west. In 2007, 1.7 kg ha⁻¹ of Roundup WeatherMax herbicide was applied to all experimental plots on May 28 and July 13. In 2008, 1.5 kg ha⁻¹ of Roundup PowerMAX herbicide was applied to the experimental field on May 15 and June 26. In 2007 and 2008, 56.2 kg ha⁻¹ of nitrogen (UAN 28%) was applied as a pre-plant to treatment T8 on May 23 and May 26, respectively. Regular pest and disease control were undertaken as needed. Nitrogen fertilizer was applied to treatments T8, T10, and T11 in both years. In 2007, the total amount of N fertilizer (in liquid form) was injected through the SDI system to T10 and T11 as two applications on June 6 (28.1 kg ha⁻¹) and July 2 (28.1 kg ha⁻¹). In 2007, nitrogen fertilizer (28.1 kg ha⁻¹) was again injected through the SDI system to only treatment T11 on August 6. Treatment T10 did not receive the third N application. The same fertilizer management was practiced in 2008 as N fertilizer was injected through the SDI system to T10 and T11 as two applications on June 1 (28.1 kg ha⁻¹) and July 3 (28.1 kg ha⁻¹), and treatment T11 received another 28.1 kg ha⁻¹ of N on August 16. Thus, the main difference between T10 and T11 was one extra N application to T11 in both years.

ACTUAL EVAPOTRANSPIRATION USING SOIL-WATER BALANCE METHOD

Seasonal ET_a (mm) was calculated using a general water balance equation:

$$P + I + U + R_{on} = R_{off} + D \pm \Delta SWS + ETa \tag{1}$$

where P is rainfall (mm), I is irrigation water applied (mm), U is upward soil moisture flux (mm; assumed zero as the depth to the groundwater is approximately 33 m below the surface), R_{on} is surface runon (mm; assumed zero), R_{off} is surface runoff (mm), ΔSWS is the change in soil moisture storage in the soil profile (mm) from the beginning to the

end of the season, and D is deep percolation (mm) below the crop root zone. The soybean effective root zone was taken as 1.20 m. In equation 1, there are two unknown variables: deep percolation and ET_a. Deep percolation was estimated using software (EPIC model) that was written in Microsoft Visual Basic, as described by Bryant et al. (1992) and Payero et al. (2005, 2009). The program inputs include daily air temperature, incoming shortwave radiation, relative humidity, wind speed, rainfall and irrigation (dates and amounts), initial water content in the soil profile at crop emergence, and crop-specific and site-specific information such as planting date, crop maturity date, soil parameters, and maximum rooting depth. Once the deep percolation was determined from the Bryant et al. (1992) model, the universal soil water balance equation was solved for the remaining unknown (ET_a):

$$ET_a = P + I - R - D \pm \Delta SWS \tag{2}$$

The surface runoff from individual treatments was estimated using the USDA-NRCS curve number method (USDA-NRCS, 1985). Given the silt loam soil at the site, the known land use, the slope, and the ridge tillage practice, a CN value of 75 was used. In terms of irrigation amounts in the water balance analyses, the actual irrigation depths for each treatment were used (table 1).

CROP WATER EXTRACTION CALCULATIONS

Volumetric soil water content was measured at 0.30, 0.60, 0.90, and 1.20 m soil depths once a week throughout both growing seasons using a neutron attenuation soil moisture meter (model 4302, Troxler Electronics Laboratories, Inc., N.C.). The neutron probe measurements began in June and continued until physiological maturity. The neutron probe access tubes were installed between two plants in the plant row of two representative experimental units (replication) of each treatment. The neutron probe measurements were used for soil water content dynamics analyses and soil water balance calculations. Thus, in addition to ET_a estimation via the above-described soil water balance variables, soybean soil water extraction from each soil layer (0.30, 0.60, 0.90, and 1.20 m) was also calculated on a weekly basis. The distribution of a given amount of rainfall or irrigation water along a soil depth gradient was based on a cascading method, with the water deficit first calculated for each layer as the difference in average soil water status of

Table 1. Irrigation events in 2007 and 2008, indicating the amount of water (mm) applied (on the indicated calendar date) during the growing season in each of the 11 irrigation treatments. Smaller volumes of water were applied to T4 and T5 as compared with T1.

Irrigation Date		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
2007	23 July	8.8	6.6	5.3	5.9	4.4	0.0	0.0	8.8	0.0	8.8	8.8
	26 July	12.8	9.6	7.7	8.6	6.4	0.0	0.0	12.8	0.0	12.8	12.8
	7 August	16.7	12.5	10.0	11.2	8.4	16.7	12.5	16.7	0.0	16.7	16.7
	10 August	12.7	9.5	7.6	8.5	6.4	12.7	9.5	12.7	0.0	12.7	12.7
	13 August	25.9	19.4	15.5	17.3	13.0	25.9	19.4	25.9	0.0	25.9	25.9
	16 August	20.8	15.6	12.5	13.9	10.4	20.8	15.6	20.8	0.0	20.8	20.8
	20 August	10.6	8.0	6.4	7.1	5.3	10.6	8.0	10.6	0.0	10.6	10.6
	2007 total	108.2	81.2	64.9	72.4	54.2	86.7	65.0	108.2	0.0	108.2	108.2
2008	7 August	9.3	7.0	5.6	6.2	4.6	9.3	7.0	9.3	0.0	9.3	9.3
	22 August	12.7	9.5	7.6	8.5	6.4	12.7	9.5	12.7	0.0	12.7	12.7
	26 August	7.9	5.9	4.7	5.3	3.9	7.9	5.9	7.9	0.0	7.9	7.9
	29 August	16.2	12.2	9.7	10.8	8.1	16.2	12.2	16.2	0.0	16.2	16.2
	2008 total	46.0	34.5	27.6	30.8	23.1	46.0	34.5	46.0	0.0	46.0	46.0

the two neutron probe sampling dates and the field capacity of the layer (Lenka et al., 2009; Djaman and Irmak, 2012). Then, whenever the rainfall or irrigation amount was more than the water deficit of the upper layer, the remaining water was assumed to have moved to the next soil layer. Because the drip laterals were about 0.40 m below the soil surface, part of the irrigation water moves upward, so whenever the irrigation amount was more than the water deficit of the first and second layers, the remaining water was assumed to have moved to the next soil layer. This calculation was repeated for all other layers within the 1.20 m soil profile throughout the growing seasons. The change in soil moisture and the contribution of rainfall and/or irrigation water for each layer were summed to determine the water extraction from that particular soil layer on a weekly time step. These values were also summed throughout the growing season for each soil layer for each treatment and related to the treatment seasonal total soil water extraction amount.

SOYBEAN SEED YIELD AND WATER USE EFFICIENCY

Each plot was harvested, and the threshed seed was weighed to determine seed yield, which was adjusted to 13% standard seed moisture content and expressed as ton ha^{-1}. The CWUE, IWUE, and ETWUE values for each treatment were determined using the procedures outlined by Djaman and Irmak (2012). In general, CWUE is usually computed as the ratio of seed yield to total crop water use:

$$CWUE = Y / ET_a \qquad (3)$$

where CWUE is expressed in kg m^{-3} on a unit water volume basis or in g kg^{-1} on a unit water mass basis, Y is seed yield (g m^{-2}), and ET_a is actual crop evapotranspiration (mm). To distinguish the role that irrigation plays in crop water productivity, the parameters IWUE and ETWUE have been used (Viets, 1962; Bos, 1980, 1985; Howell, 2001; Djaman and Irmak, 2012) and were computed as:

$$IWUE = (Y_i - Y_r) / I_i \qquad (4)$$

$$ETWUE = (Y_i - Y_r) / (ET_{a,i} - ET_{a,r}) \qquad (5)$$

where IWUE and ETWUE have units of kg m^{-3}, Y is seed yield (g m^{-2}), and I_i is applied irrigation water (mm), with subscript i representing the irrigation level and subscript r representing the treatment with no seasonal irrigation (rainfed), such that $ET_{a,i}$ is the crop evapotranspiration for irrigation level i, and $ET_{a,r}$ is the crop evapotranspiration for the rainfed control treatment.

The experimental data for each measurement were subjected to an analysis commensurate with the experimental randomized complete block design, with blocks considered to be random effects and years considered as fixed effects. An alpha value of 0.05 was chosen as a Type I error significance criterion. The program PROC MIXED (Littell et al., 1996) of the SAS statistical package (SAS, 1999) was used for the analysis, with Duncan's multiple range option used to identify treatment mean differences.

RESULTS AND DISCUSSION
WEATHER CONDITIONS

Seasonal and annual precipitation at the research site were substantively variable in both magnitude and timing, and this is reflected in the rainfall patterns of the 2007 and 2008 growing seasons (fig. 2). Total seasonal rainfall was 534 mm in 2007 and 447 mm in 2008, although about a quarter of the 2007 amount was received in the month of October, after that year's soybean crop had attained physiological maturity. Long-term (1983-2010) average in-season rainfall from May 1 to October 30 at the research site is 517 mm. In 2007, a 78.6 mm rainfall event terminated a mostly rain-free period of 30 days and occurred simultaneously with that year's sixth irrigation event (August 16). In 2008, the greatest rainfall amount was 55 mm on July 16. Overall, the early-season rainfall amount was adequate for soybean growth and development, although seven irrigation events had to be scheduled during the 2007 low rainfall period of July 23 to August 20, corresponding to soybean stages R3.5 to R5 (62 to 92 DAP), and four irrigation events had to be scheduled during the 2008 period of August 7 to August 29 (81 to 103 DAP), which coincided with soybean stages R5 and R6. Less irrigation was needed in the second year of the research (46 mm in 2008 versus 108 mm in 2007 for the 100% ET_a treatments) due to more uniform distribution of rainfall in the 2008 growing season. Relative humidity, vapor pressure deficit, wind speed, and air temperature at the site did not differ much between the two growing seasons, except for August, when air temperature was considerably higher in 2007 than in 2008 (fig. 3). Seasonal average solar radiation was less in 2007 (17.9 MJ m^{-2} d^{-1}) than in 2008 (20 MJ m^{-2} d^{-1}) (fig. 4). Higher solar radiation and wind speeds (data not shown) in 2008 and the higher temperatures in Aug of 2007 may have had an impact on soybean growth and development, given that the growing season length was substantively less in 2008 (136 days) than in 2007 (157 days).

EFFECT OF IRRIGATION ON SOIL WATER DYNAMICS

The weekly change in soil water content in each of the four 0.30 m layers of the total 0-1.20 m soil profile were graphed for each of the experimental treatments over the course of the June 20 to September 26 growing seasons in 2007 (fig. 5) and in 2008 (fig. 6). The initial (late June) soil water content in each soil layer did not differ among treatments, suggesting that pre- and post-plant rainfall at the research site had resulted in a uniformly distributed soil water profile in the entire field before measurements were commenced.

In 2007, the lowest soil water contents for the irrigated treatments occurred during the period from late July to late August; in the rainfed treatment, that period began earlier and thus extended from mid-July to late August. From planting, at which time the soil was assumed to be at or near field capacity, to the start of the soil water content measurements in late June, crop soil water depletion was likely restricted to the topmost soil layer due to a combination of juvenile soybean plant root water uptake activity and soil surface evaporation. The soil water content in any
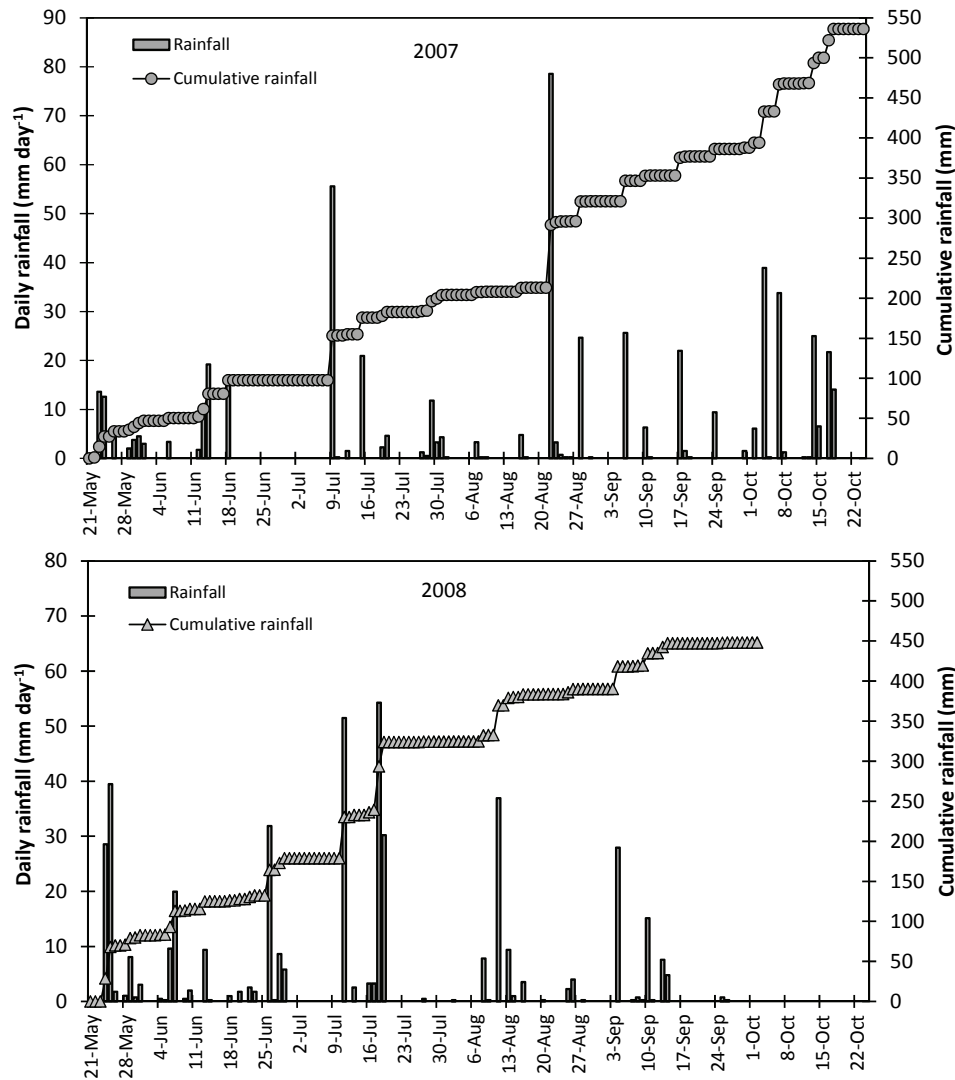
Figure 2. Daily rainfall and cumulative rainfall measured in the experimental field during the 2007 and 2008 growing seasons.

given soil layer was similar in all treatments until the first irrigation of the succession of irrigation events (fig. 5). Soil water depletion in the third (0.90 m) and fourth (1.20 m) soil layers of all treatments did not seem to be much affected by rainfall or irrigation events. The greatest soil water depletion occurred in the top soil layer, primarily because of active root water and nutrient uptake in this zone. However, unlike other irrigation systems that deliver water to the soil surface, the water applied in the SDI system is delivered by emitters on the drip laterals that are located 0.4 m below the soil surface. Because there is minimal upward movement of that water, the soil water content in the topmost zone of drip-irrigated treatments exhibited a seasonal change in depletion that did not differ much from the change in depletion that was occurring at the same time in a comparative rainfed treatment (fig. 5). Soil water contents in the topmost soil layer of all treatments usually reached a low of 16% to 19% vol at some point during the growing season. The soil water content impact of the limited irrigation treatments (i.e., less than 100% ET_a replacement and/or less than 100% applied I_a) seemed to be greatest in

the topmost soil layer. This was also true for the treatments in which irrigation did not commence until the R3 stage. Soil water content in the second soil layer remained high throughout the growing season in all irrigated treatments, primarily because of the 0.4 m drip line depth; however, in the absence of such drip line irrigation (e.g., the rainfed treatment), the second layer soil water content declined rather quickly to about 17% vol by July 19 and remained at that level until at least August 13. Soil water contents were not measured again until August 30 and were higher in all treatments due to a large (79 mm) rainfall event that occurred on August 26, 2007.

In 2008, the seasonal trends in soil water content per layer were similar over all treatments (fig. 6) but with some notable differences. The 2008 growing season was wetter than the prior year, with the result that 58% less irrigation water was needed. In all treatments, the topmost soil layer water content eventually attained 20% vol, except for treatment T5 (25% vol). Soil water content increased substantively in mid-August because of two rainfall events on
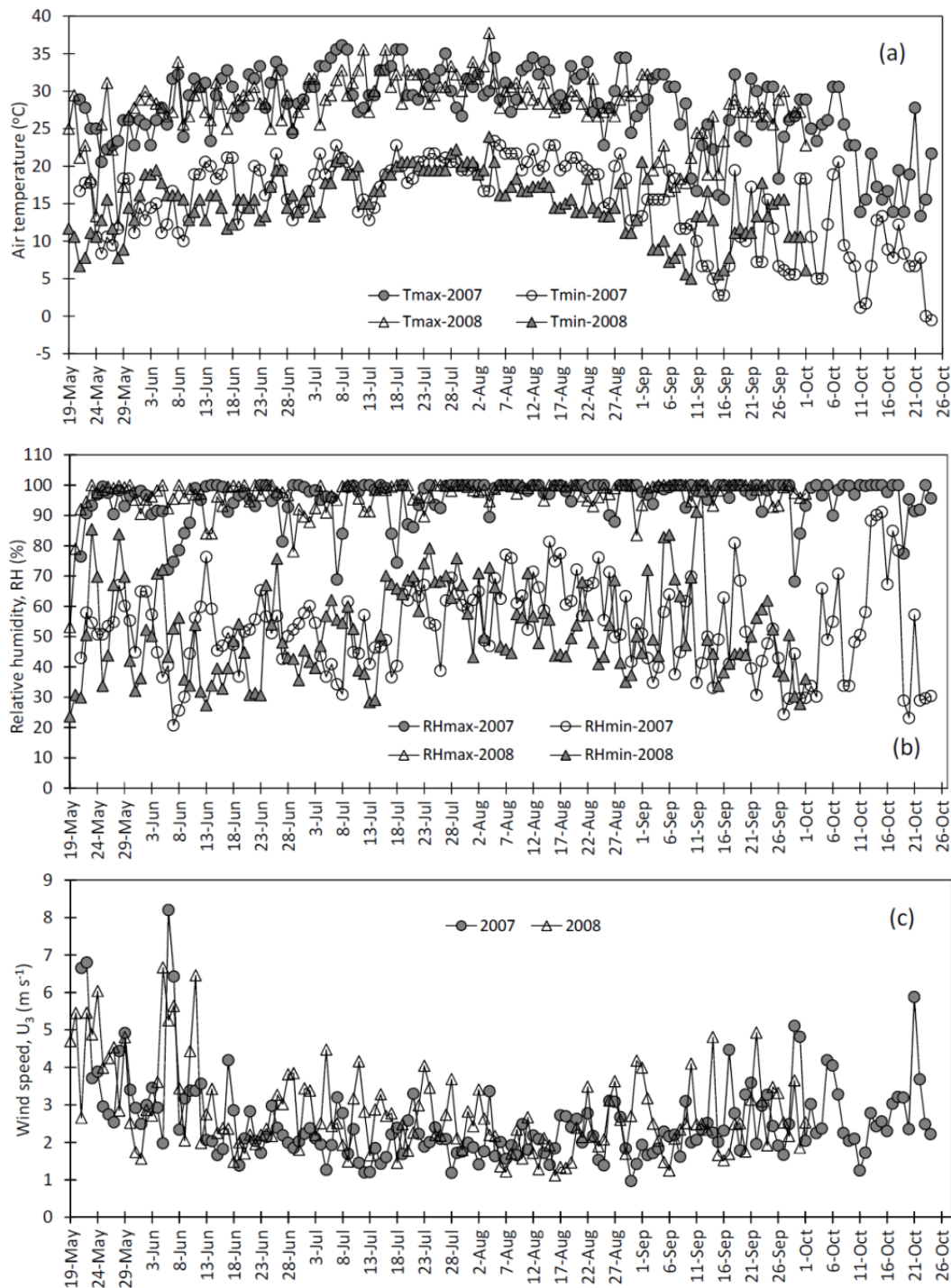
Figure 3. Seasonal change (on a five-day interval average basis) in the 2007 and 2008 measured variables of (a) daily maximum and minimum air temperatures (T_{max} and T_{min}), (b) daily maximum and minimum relative humidity (RH_{max} and RH_{min}), and (c) daily wind speed (at 3 m above ground over the soybean canopy) at the experimental site.

August 9 (37 mm) and August 11 (10 mm). The water content in the second soil layer (depth of drip line) exhibited only a small seasonal decrease (from 38% to 35% vol) in the irrigated treatments but decreased more substantively (from 38% to 33% vol) in the rainfed treatment, and, similar to the 2007 results, the second soil layer was the wettest layer in the crop root zone. The least seasonal reduction in soil water content occurred in the fourth layer in 2008, as was the case in 2007.

IRRIGATION AND ACTUAL EVAPOTRANSPIRATION

The amount of irrigation water applied to each treatment is presented in table 1. The total amount of water applied with seven irrigation events in 2007 was 108 mm, and the total amount applied with four irrigation events in 2008 was 46 mm. The 100% ET_a replacement treatments (T1, T4, and T5) received those two respective total seasonal amounts, whereas the 75% ET_a treatments (T2 and T7) and the 60% ET_a treatment (T3) received respective amounts of
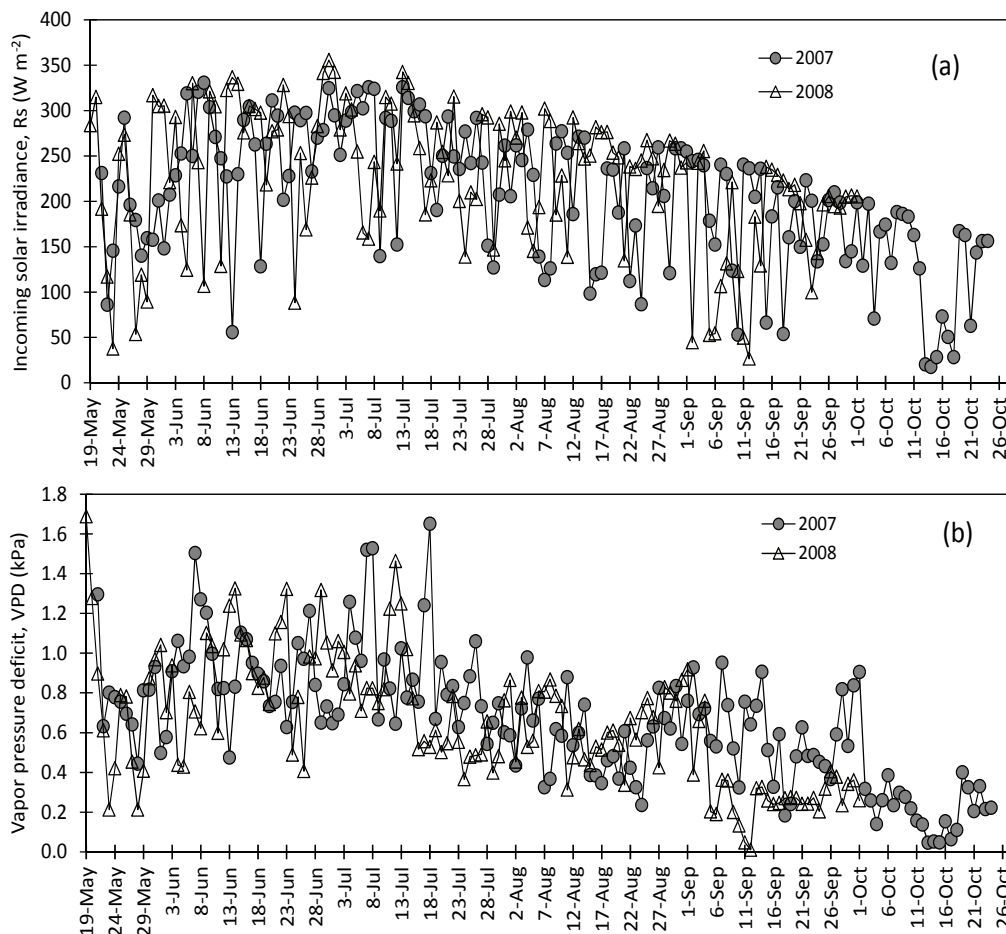
Figure 4. Seasonal change (on a five-day interval average basis) in the 2007 and 2008 measured variables of (a) incoming shortwave radiation (R_s) and (b) vapor pressure deficit (VPD) at the experimental site.

81, 65, and 65 mm in 2007 and 35, 35, and 28 mm in 2008. Although delaying irrigation until the R3 stage is not designed *per se* to be a deficit irrigation strategy, in practice it often results in the application of less water. Irrigation events scheduled before R3 in fully irrigated treatments have the potential to be rendered ineffective by an unexpected coincident (or soon after) rainfall event. In contrast, in a delay to R3 irrigation strategy, there are no pre-R3 irrigation events, so any unexpected pre-R3 rainfall amounts actually represent an opportunity to reduce the amount of water needed when irrigation is commenced at R3. In the present research, this was the case in 2007, when only 87 mm of total seasonal water was needed for the 100% ET_a treatment T6 (irrigation delayed until R3), compared to the 108 mm needed for the 100% ET_a treatment T1 (fully irrigated control). In 2008, an opportunity to evaluate the performance of the delayed irrigation treatment relative to the other treatments was precluded because adequate rainfall that year did not necessitate the commencement of irrigation before R3 in any treatment.

Soybean ET_a was affected by I_a (table 2). In 2007, treatment ET_a values ranged from the low 452 mm measured in the rainfed treatment (T9) to 601 mm measured in treatment T10 (100% ET_a and 100% of the area). In 2008, ET_a ranged from the low 473 mm in the rainfed treatment to 579 mm for the fully irrigated control treatment (T1).

Including the rainfed treatment, the all-treatment average ET_a was 568 mm in 2007 and 531 mm in 2008. When excluding the rainfed treatments, ET_a was 580 and 537 mm in 2007 and 2008, respectively. Treatment T10, in which fertilizer was injected through the SDI system, had about 3% greater ET_a than its counterpart treatment (T8), in which preplant nitrogen was applied. The T10 versus T8 difference in ET_a was minimal in the wetter year of 2008. Within the irrigated treatments, T4 (100% ET_a and 65% I_a) had the lowest ET_a value (557 mm) in 2007, whereas treatment T3 (60% ET_a and 100% I_a) had the lowest ET_a (498 mm) in 2008. For the treatments with the same 100% ET_a level but with 100%, 65%, and 50% I_a levels (i.e., T1, T4, and T5) or with the same I_a value but with 100%, 75%, and 60% ET_a replacement (i.e., T1, T2, T3), the measured 2008 ET_a values decreased from 579 mm (T1) to 549 mm (T4) to 515 mm (T5) in the former group and from 579 mm (T1) to 538 mm (T2) to 497 mm (T3) in the latter group. This 2008 trend was not evident in 2007. In this research, for every 1 mm increase in total season I_a, ET_a increased by 2.65 mm in 2007, by 1.88 mm in 2008, and by 2.42 mm when averaged over both years. This finding was not unexpected, given the greater leaf area in an irrigated (as opposed to a rainfed) soybean crop (Setiyono et al., 2007).

A linear function provided a good model fit ($R^2 = 0.68$ in 2007 and $R^2 = 0.67$ in 2008) to the data on the change in
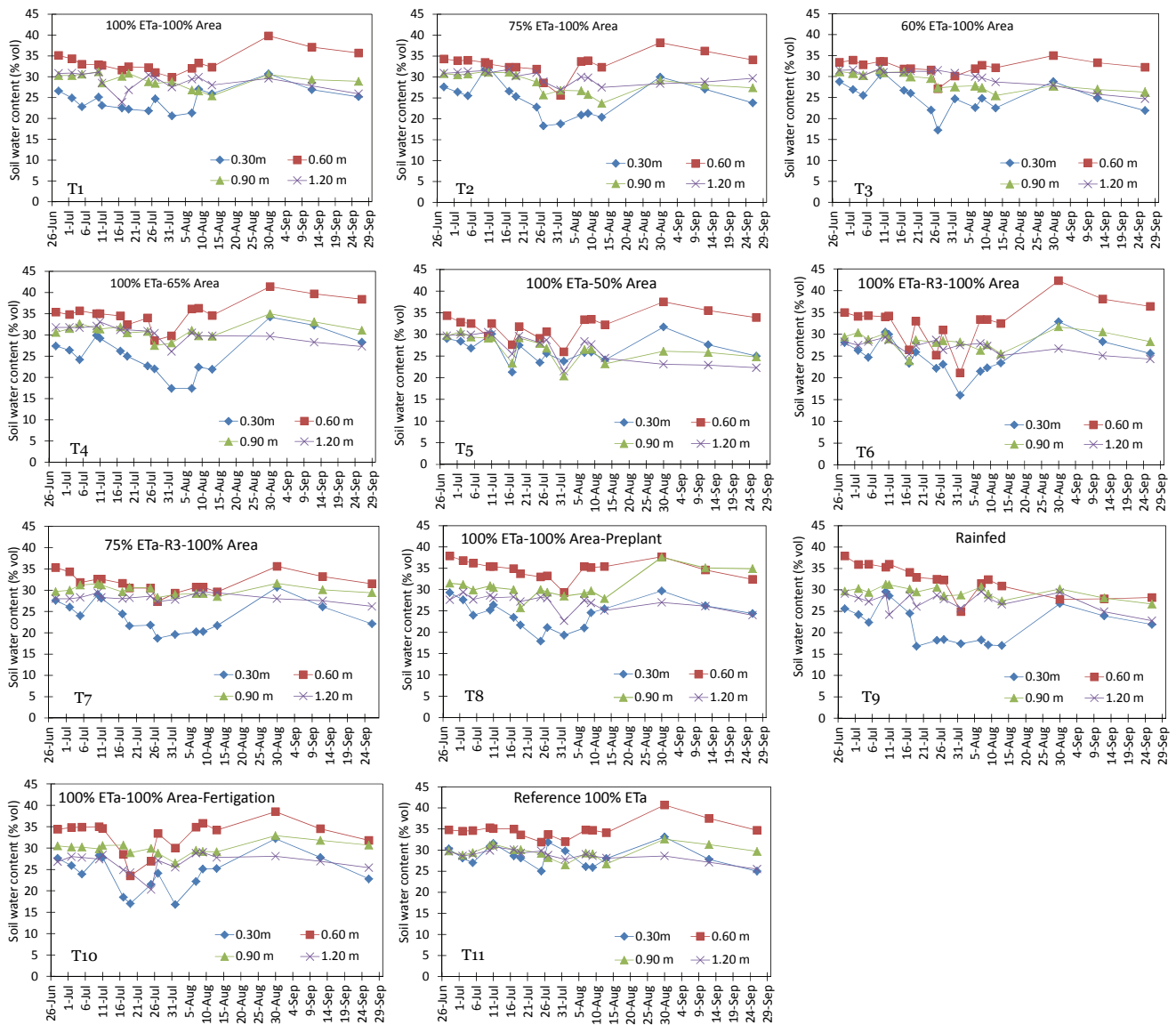
Figure 5. Seasonal change (on a five-day average basis) in the 2007 measured soil water content in each of four 0.30 m layers of the 1.20 m soil profile. The four-layer data are graphed on a per treatment (T1 to T11) basis and were acquired using neutron attenuation soil moisture meters in each treatment plot.

seasonal soybean ET_a amount per unit change in seasonal I_a (fig. 7). As expected, the lowest ET_a was measured in the rainfed treatment in both years. The ET_a values for all treatments were greater in the drier year (2007) than in the wetter year (2008), primarily because of the difference between the two years with respect to vapor pressure deficit patterns (fig. 4) and the fact that the length of the growing season was 157 days in 2007 but only 136 days (13% less) in 2008. The leaf-to-air vapor pressure deficit is, of course, the driving force for evapotranspiration, and greater daily ET_a values were observed after August 6 in 2007 (fig. 4). The seasonal soybean evapotranspiration values observed in this research were in agreement with soybean values (450 to 700 mm) reported by Doorenbos and Kassam (1979) and were within the range of those reported by Payero et al. (2005), who found substantial variation in soybean ET_a of between 261 and 506 mm for limited water conditions and between 569 and 801 mm for non-limited

water conditions in western Nebraska. Klocke et al. (1989) reported soybean evapotranspiration varying from 330 to 568 mm at the same experimental site and ranging between 175 (rainfed) and 511 mm in North Platte, Nebraska, and between 285 (rainfed) and 513 mm in Tryon, Nebraska. Hattendorf et al. (1988) reported a seasonal ET_a range for irrigated soybean in Kansas of between 491 and 591 mm for two growing seasons; using weighing lysimeters, Kanemasu et al. (1976) reported soybean ET of 651 mm in the same state. Howell et al. (2006) reported irrigated soybean ET_a values of 801, 771, and 611 mm in 1995, 2003, and 2004, respectively, at Bushland, Texas.

EFFECT OF SEASONAL IRRIGATION AMOUNT ON YIELD

Soybean yield increased with irrigation and varied from 4.04 ton ha^{-1} for the rainfed treatment (T9) to 4.94 ton ha^{-1} for the delay to R3 irrigation treatment (T6) in 2007, and
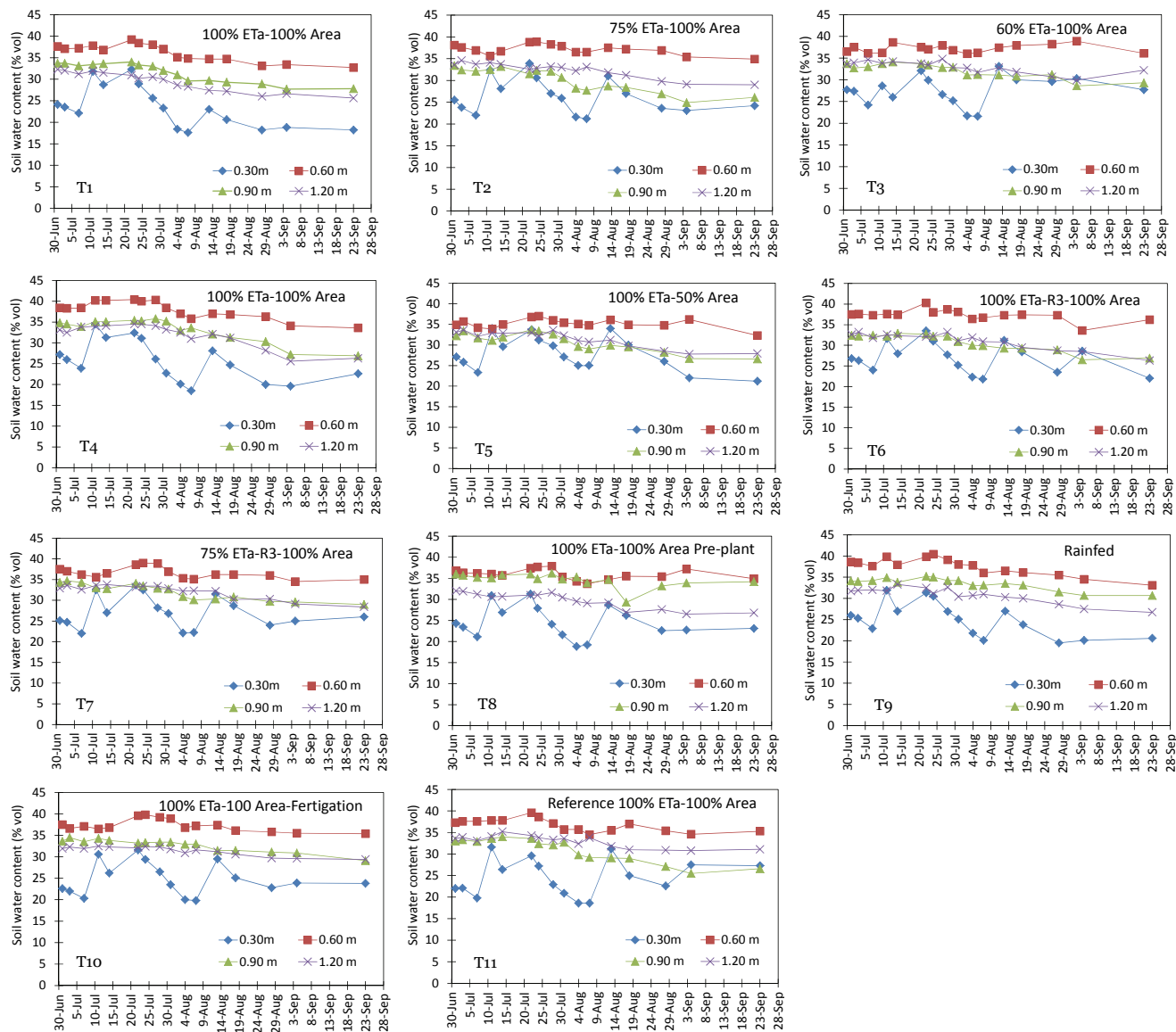
Figure 6. Seasonal change (on a five-day average basis) in the 2008 measured soil water content in each of four 0.30 m layers of the 1.20 m soil profile. The four-layer data are graphed on a per treatment (T1 to T11) basis and were acquired from neutron attenuation soil moisture meters in each treatment plot.

Table 2. Seasonal actual evapotranspiration (ET_a), seed yield, coefficient of variation (CV) for yield, crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE) for soybean grown in 11 treatments evaluated in 2007 and 2008 at the South Central Agricultural Laboratory, Clay Center, Nebraska. Smaller volumes of water were applied to T4 and T5 as compared with T1.

Treatment	ET_a (mm) 2007	ET_a (mm) 2008	Seed Yield (ton ha⁻¹)[a] 2007	Seed Yield (ton ha⁻¹)[a] 2008	Yield CV (%) 2007	Yield CV (%) 2008	CWUE (kg ha⁻¹ mm⁻¹) 2007	CWUE (kg ha⁻¹ mm⁻¹) 2008	IWUE (kg ha⁻¹ mm⁻¹) 2007	IWUE (kg ha⁻¹ mm⁻¹) 2008	ETWUE (kg ha⁻¹ mm⁻¹) 2007	ETWUE (kg ha⁻¹ mm⁻¹) 2008
T1	586	579	4.62 b	4.93 a	1.4	1.1	7.89	8.50	5.32	2.00	4.31	0.87
T2	566	538	4.65 b	4.93 a	2.1	1.4	8.21	9.16	7.47	2.67	5.30	1.42
T3	586	498	4.62 b	4.85 a	1.4	1.4	7.87	9.74	8.81	0.51	4.25	0.57
T4	557	549	4.67 b	4.82 a	1.2	1.0	8.37	8.78	5.77	-	5.92	-
T5	588	515	4.55 b	4.88 a	1.9	0.4	7.71	9.48	4.64	2.10	3.65	1.15
T6	571	558	4.94 c	4.88 a	4.4	1.2	8.65	8.75	10.35	1.03	7.53	0.56
T7	571	525	4.67 b	4.92 a	2.2	0.8	8.17	9.37	9.60	2.63	5.23	1.74
T8	586	535	4.77 bc	4.97 a	2.1	1.1	8.15	9.28	6.76	2.92	5.47	2.17
T9	452	473	4.04 a	4.82 a	2.2	1.0	8.94	10.22	-	-	-	-
T10	601	539	4.82 c	4.91 a	2.2	0.8	8.02	9.12	7.14	1.78	5.20	1.24
T11	588	531	4.60 b	4.82 a	6.1	5.1	7.82	9.07	5.15	-	4.10	-

[a] Values in the same column followed by different letters are significantly different (p < 0.05) at the 5% significance level.

Figure 8. Relationship between soybean seed yield and total seasonal irrigation amount in the 2007 and 2008 growing seasons.
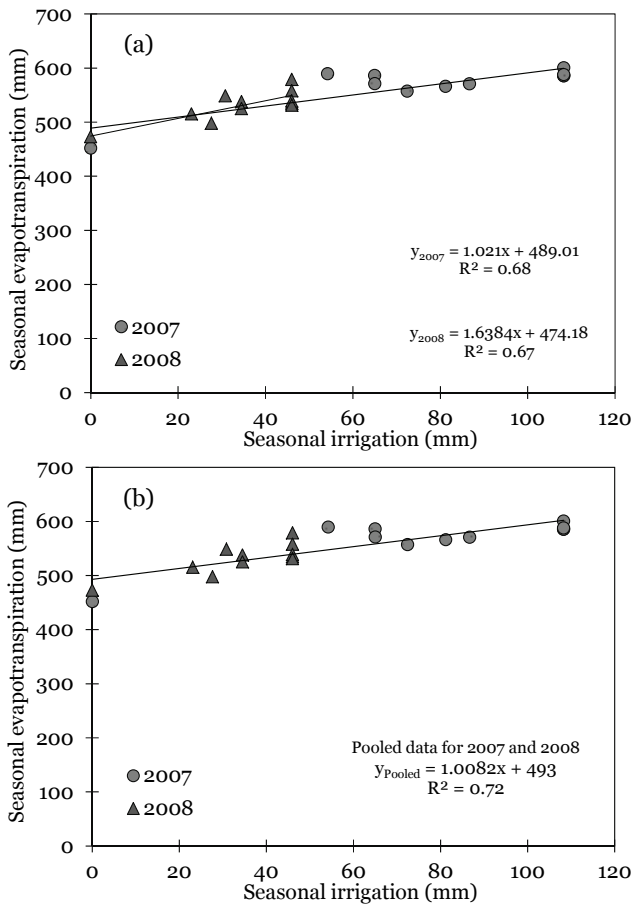
Figure 7. Relationship between seasonal actual evapotranspiration (ET$_a$) and total seasonal irrigation amounts in 2007 and 2008: (a) coordinate values for each year, and (b) coordinate values when the 2007 and 2008 data were pooled.

from 4.82 ton ha^{-1} for the rainfed treatment to 4.97 ton ha^{-1} for the 100% ET$_a$ and 100% I$_a$ treatment that received pre-plant nitrogen (T8) in 2008 (table 2), although the T8 yield was not significantly different from the 4.88 ton ha^{-1} yield attained for the delay to R3 irrigation treatment (T6). Statistically significant (p < 0.05) yield differences among treatments were not observed in the wetter year of 2008; in 2007, the delay to R3 irrigation treatment (T6) produced significantly greater yields than all treatments, except the N-fertilized treatments (T8 and T10). These results indicate that delaying irrigation until the R3 stage in soybean crops grown on silt loam soils in areas that have edaphic and climatic characteristics similar to south-central Nebraska does not decrease yield, may lead to greater yield despite the irrigation delay, and can actually result in less water needed for irrigation in the rest of the growing season. This finding is in agreement with prior research (at other eastern and central Nebraska sites) that documented little or no yield impact when the commencement of furrow or sprinkler irrigation was delayed until soybean stage R3, primarily because the silty clay loam soils at those sites were routinely recharged to field capacity by rainfall before the planting date or shortly thereafter (Korte et al., 1983; Kadhem et al., 1985; Klocke et al., 1989; Specht et al., 1989) under the climatic conditions in which the studies were conducted.
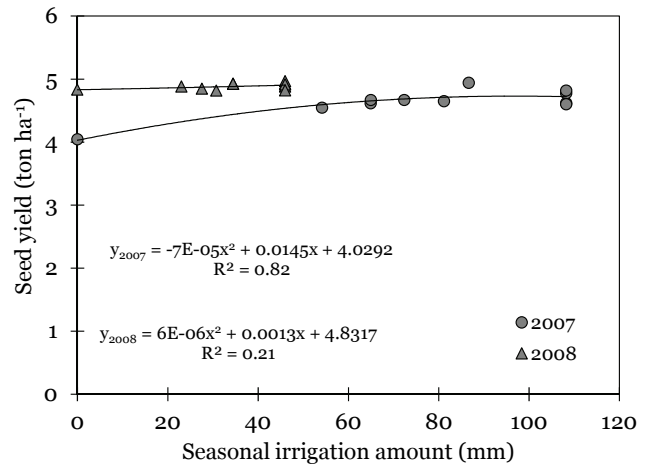
Treatment T10, in which nitrogen was applied via injection through the SDI system, produced a 2007 yield of 4.82 ton ha^{-1}, which was not statistically different (p > 0.05) from the 4.77 ton ha^{-1} seed yield of its counterpart (treatment T8), which involved a preplant N application (table 2). These two different nitrogen application methods also did not differ in their 2008 seed yields. Nitrogen application *per se* did increase soybean yield in both years (compared to most non-N-fertilized treatments, although only significantly so in 2007). It is known that direct N fertilization of soybean does not always result in predictable yield enhancement (Salvagiotti et al., 2009), and the results obtained in this research are in agreement with that unpredictability.

Soybean seed yield exhibited a quadratic relationship with total seasonal irrigation amount, although that relationship was very weak in 2008 (R^2 = 0.21) and in 2007 was conditional on the large gap between the rainfed data point and the irrigation treatment data points (fig. 8), with a strong R^2 of 0.82. Yield for the fully irrigated control treatment (T1) was less than the yield for the delay to R3 irrigation treatment (T6). The reason for this difference could be due to less aeration in the crop root zone because of the greater amount of seasonal irrigation applied in T1 (108 mm) compared to T6 (87 mm) in 2007. Or it could have arisen because the earlier irrigation in T1, as compared with T6, produced more vegetative dry matter in T1 and less seed dry matter, leading to a lesser harvest index for that treatment, although that variable was not measured in this research. When early irrigation was applied to maize in the same experimental area, Irmak and Rathje (2008) reported yield reductions of 0.94 ton ha^{-1} in 2006 and 0.51 ton ha^{-1} in 2007, which, because of greater-than-optimal water content in the crop root zone, altered the oxygen balance of the root environment. The 2007 quadratic model in this research also suggests that soybean yield peaked at about 85 to 90 mm of total seasonal irrigation and then began to diminish at higher seasonal water amounts. The yield-to-water relationship in 2008 was too weak to draw any conclusions of a similar kind as those noted for 2007.

Each 25.4 mm incremental increase in seasonal irrigation water increased soybean yield by 0.323 ton ha^{-1} (beyond the intercept) in 2007 and by 0.037 ton ha^{-1} in 2008. Specht et al. (1986, 2001) reported strong linear relationships between soybean yield and the amount of seasonal sprinkler irrigation applied in Nebraska. The yields attained in this research were much higher than the Nebraska county-average yields reported by Sharma et al. (2011), who showed that rainfed and irrigated soybean yields were demonstrably quite variable over a 13-year time span. The statewide rainfed yield average was 2.21 ton ha^{-1}, with a maximum of 2.86 ton ha^{-1} in Cuming County (northeast Nebraska) and a minimum of 0.64 ton ha^{-1} in Phelps County (south-central Nebraska), whereas the statewide irrigated yield average was 3.43 ton ha^{-1} but varied from 2.09 ton ha^{-1} in Cheyenne County (western Nebraska) to 3.91 ton ha^{-1} in Hayes County (southwest Nebraska). Pedersen and Lauer (2004) reported that soybean yield varied from 3.26 to 4.6 ton ha^{-1} based on treatments that differed in planting date, cultivars, and the management systems they evaluated in Wisconsin. They also reported that soybean yield variation from 4.1 to 4.6 ton ha^{-1}.

The relationship between soybean seed yield and total seasonal actual soybean evapotranspiration was weakly linear in both growing seasons (fig. 9a). This was not unexpected, given that the lower yields in the rainfed controls (first point in fig. 9a) effectively determine the start point in the regression analyses (Specht et al., 1986, 2001). Still, the data showed that each 25.4 mm increase in ET_a generated a yield increase of 0.114 ton ha^{-1} (beyond the intercept) in 2007 but only 0.02 ton ha^{-1} in the wetter year of 2008. Similar relationships were reported by Payero et al. (2005) and Karam et al. (2005). Based on R^2 values, the linear relationship between soybean seed yield and the ratio of actual evapotranspiration to maximum evapotranspiration (i.e., ET_a/ET_m, where ET_m is the ET_a for fully irrigated treatment T1) was stronger (fig. 9b). Payero et al. (2005), based on research conducted at North Platte, Nebraska, stated that it might be possible to obtain robust and more transferable functions between yield and seasonal ET_a by normalizing yields. Our results indicate that soil water storage at planting and the large amount of early in-season rainfall in 2008 provided almost enough water to attain the yields that were obtained in the irrigated treatments. Thus, irrigation-induced increases in crop ET_a could not contribute much more in terms of significantly increasing soybean yields beyond those attained in the rainfed control.

SOYBEAN CROP WATER USE EFFICIENCY (ALSO KNOWN AS CROP WATER PRODUCTIVITY)

Crop water use efficiency (CWUE) values for the 11 treatments were lower on average in 2007 (range: 7.71 to 8.94 kg ha^{-1} mm^{-1}) than in 2008 (range: 8.5 to 10.22 kg ha^{-1} mm^{-1}) (table 2), and as expected, the rainfed treatment (T9) had the highest CWUE value each year. It should be kept in mind that these treatment water use efficiencies are ratios in which the numerator is seed yield and the denominator is total seasonal water (or as subsequently discussed, total seasonal irrigation or ET_a itself). With that in mind, a linear regression coefficient is also a CWUE term, but for a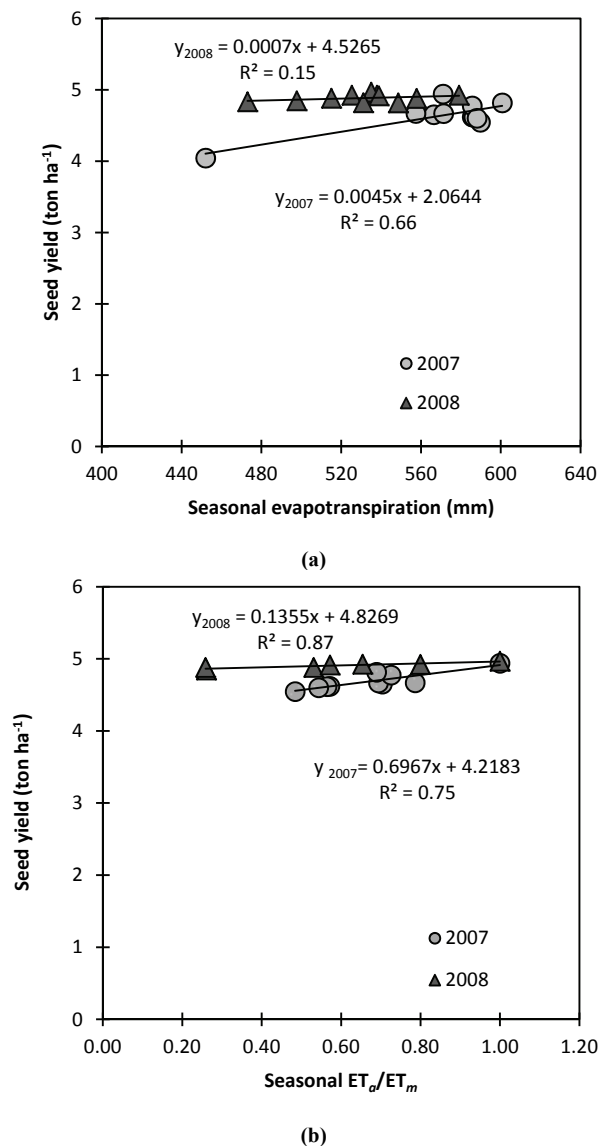ll of the treatment data points in a graph of seed yield versus seasonal rainfall plus irrigation water amount (not graphed here, but see Specht et al., 1986, 2001, for details). The relationship between CWUE and yield was weak in both years, although CWUE decreased with increases in seed yield (fig. 10a), whereas the relationship between CWUE versus ET_a (fig. 10b) was strong in both years, and CWUE decreased with ET_a in both years. Overall, the CWUE values obtained in the present research are somewhat greater than those reported in the literature, primarily because the high yields attainable at the Clay Center research site result in a larger numerator value in the CWUE ratio calculations, and also because of the high rainfed yields obtained in both years as a result of the large amount of precipitation. Payero et al. (2005) reported CWUE varying from 2.3 to 7.4 kg ha^{-1} mm^{-1} in North Platte, Nebraska, which has a drier climate than Clay Center. Karam et al. (2005) reported soybean CWUE varying between 3.9 and 5.7 kg ha^{-1} mm^{-1}, and they found that the CWUE values of

Figure 9. Relationships between soybean seed yield and (a) total seasonal actual evapotranspiration (ET_a) and (b) the ratio of actual ET to maximum ET (ET_a/ET_m) in the 2007 and 2008 growing seasons.
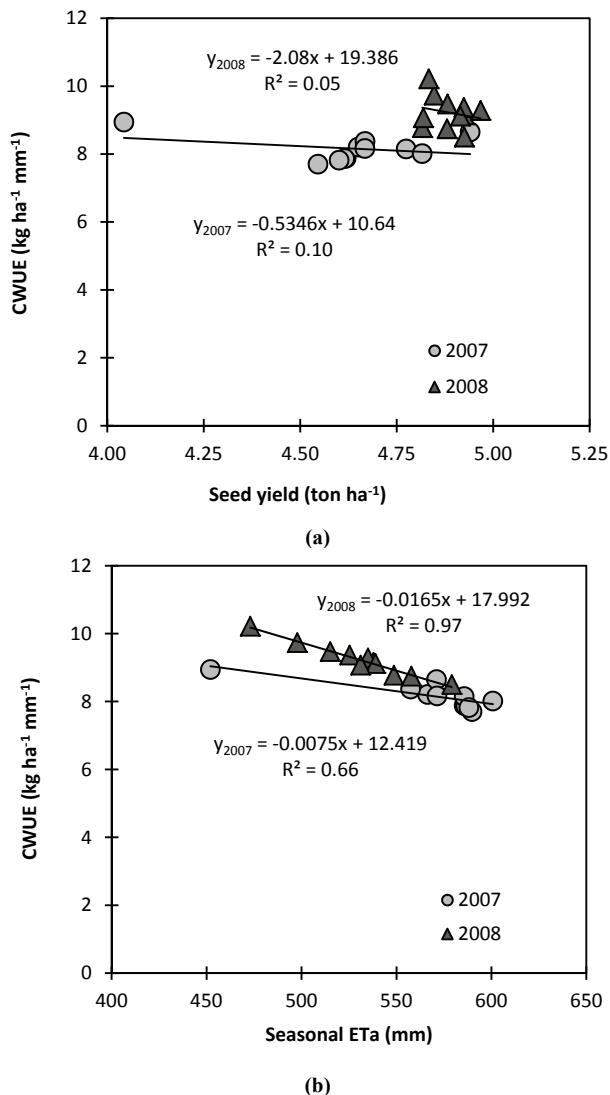
Figure 10. Relationships between soybean crop water use efficiency (CWUE, also known as crop water productivity) and (a) seed yield and (b) total seasonal actual evapotranspiration (ET_a) during the 2007 and 2008 growing seasons.

deficit-irrigated soybean were 13% and 4% higher than the CWUE of fully irrigated soybean. Scott et al. (1987) reported that the average CWUE of soybean was approximately 6.0 kg ha^{-1} mm^{-1} and also noted that the efficiency increased by 7.3 kg ha^{-1} for each mm of irrigation water used.

Soybean irrigation water use efficiency (IWUE) was much higher in 2007 than in 2008, ranging from 5.15 kg ha^{-1} mm^{-1} for T11 to 10.35 kg ha^{-1} mm^{-1} for T6 in 2007, and from 0.51 kg ha^{-1} mm^{-1} for T3 to 2.92 kg ha^{-1} mm^{-1} for T8 in 2008. In the drier year of 2007, the IWUE for the delay to R3 irrigation treatment (T6) was substantially greater than the IWUE values for all other treatments. If fact, it was nearly twice as large as the IWUE calculated for the fully irrigated control treatment (T1). IWUE increased linearly (weaker in 2007) with increased seed yield in both years ($R^2 = 0.08$ in 2007 and $R^2 = 0.62$ in 2008) (fig. 11a). Notably, IWUE decreased with increased irrigation in the drier 2007 but changed little with increased irrigation in the wetter 2008
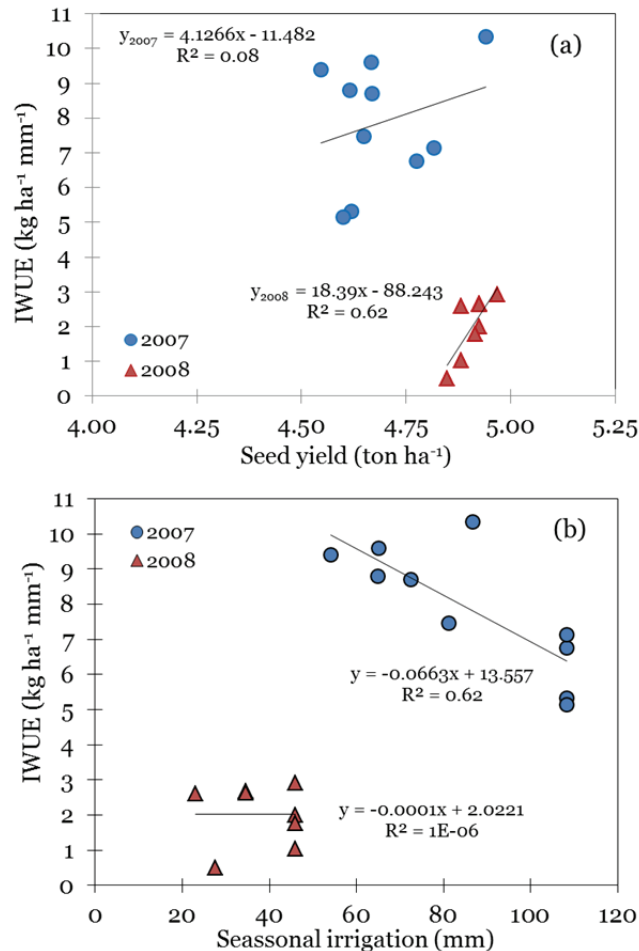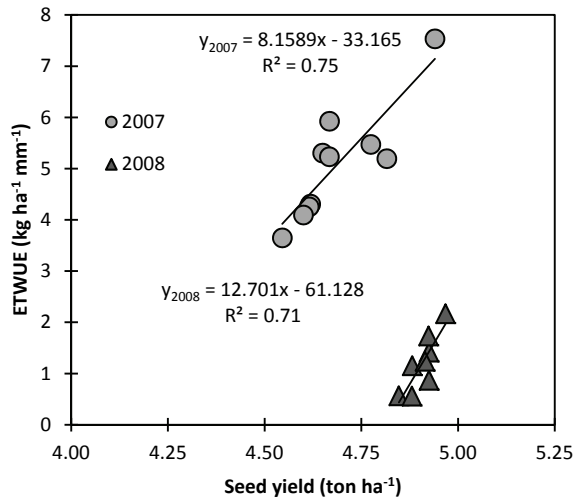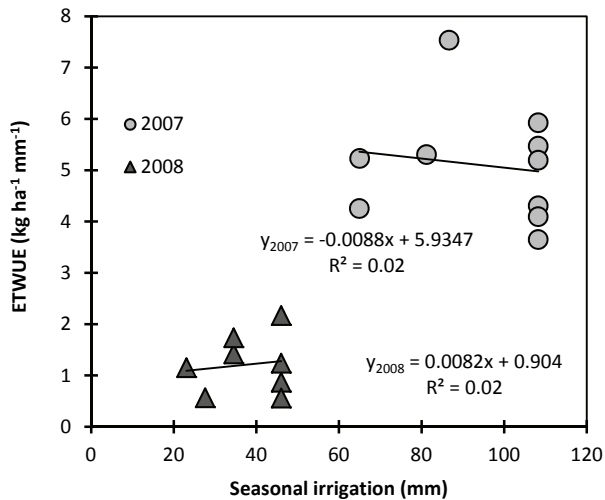

Figure 11. Relationships between soybean irrigation water use efficiency (IWUE) and (a) seed yield and (b) and total seasonal irrigation amount during the 2007 and 2008 growing seasons.

(fig. 11b). Because of the wet conditions in 2008, the rainfed treatment had a numerically higher yield than the irrigation treatments T4 and T11, so an IWUE value was not calculated (thus the reason for dashes in table 1). The IWUE values in this research are in agreement with the IWUE values of 5.5 and 11.4 kg ha^{-1} mm^{-1} reported by Garcia et al. (2010) for a site located in Georgia.

To more suitably assess the contribution of irrigation to transpiration, Djaman and Irmak (2012) proposed using evapotranspiration-based water use efficiency (ETWUE) as an additional WUE measurement. They measured ETWUE for fully irrigated and various levels of limited-irrigated (and rainfed) maize and compared the ETWUE values with the corresponding CWUE and IWUE values measured in south-central Nebraska. Djaman and Irmak (2012) discussed their findings and stated that the ETWUE parameter intrinsically reflects crop management components affecting the crop canopy and the potential impact of that canopy on ET_a. For that reason, they noted that ETWUE is likely a better indicator than CWUE or IWUE relative to fine-tuning crop management to achieve greater crop water productivity. Howell (2001) noted that ETWUE is generally improved with less irrigation, which is probably the result of better timing of fewer irrigation events (or less water per event), which likely

$y_{2007} = 8.1589x - 33.165$
$R^2 = 0.75$

$y_{2008} = 12.701x - 61.128$
$R^2 = 0.71$

(a)

$y_{2007} = -0.0088x + 5.9347$
$R^2 = 0.02$

$y_{2008} = 0.0082x + 0.904$
$R^2 = 0.02$

(b)

Figure 12. Relationships between soybean evapotranspiration water use efficiency (ETWUE) and (a) seed yield and (b) total seasonal irrigation amount during the 2007 and 2008 growing seasons.
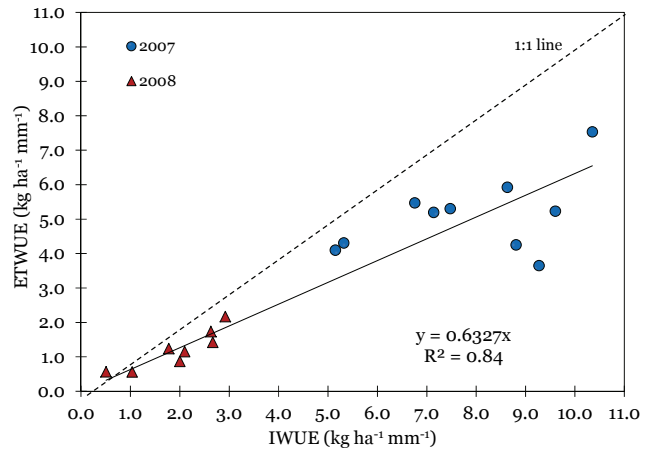

Figure 13. Relationship between soybean evapotranspiration water use efficiency (ETWUE) and irrigation water use efficiency (IWUE), using data from both years.

encourages deeper soil water extraction to make better use of both preplant stored soil water and post-plant in-season precipitation. In this research, ETWUE values for soybean were generated by considering the total seasonal water used for evapotranspiration. ETWUE increased linearly with seed yield in both years (fig. 12a), although the linear regression line in 2007 was not as steep as in 2008. There was no correlation between ETWUE and seasonal irrigation amounts in both years (fig. 12b). ETWUE values ranged from 3.65 kg ha^{-1} mm^{-1} for T5 to 7.53 kg ha^{-1} mm^{-1} for the T6 delay to R3 irrigation treatment in 2007 and from 0.56 kg ha^{-1} mm^{-1} for T6 to 2.17 kg ha^{-1} mm^{-1} for T8 in 2008. A 1:1 graphical plot of ETWUE versus IWUE indicates that ETWUE values have magnitudes that are fractionally less (0.63) than the coordinate IWUE values (fig. 13). These graphical data, when coupled with a consideration of the graphical data presented in figures 10a, 11a, and 12a, illuminates the conclusion that ETWUE is the better WUE ratio parameter for assessing the relationship between yield and the amount of water a crop transpires.

IMPACT OF IRRIGATION ON SEASONAL SOIL WATER EXTRACTION

Plant roots play an important role in the absorption and translocation of water and nutrients. To investigate the degree to which soybean soil water extraction is influenced by irrigation management practices under SDI, the soil water extraction from each soil layer (0.30, 0.60, 0.90, and 1.20 m) in the soybean root zone was quantified as a percentage of seasonal total water uptake in 2007 (fig. 14a), in 2008 (fig. 14b), and averaged over two years (fig. 14c). In all treatments, the soybean crop extracted soil water from each successive 0.30 m layer in the 1.20 m deep soil profile, although the majority of total seasonal water extracted (about 35% to 55%) was withdrawn from the top layer. Seasonal water extraction in the remaining three soil layers was about half the amount extracted from the top layer. When averaged over all treatments, the water extraction percentage in the 0.30, 0.60, 0.90, and 1.20 m layers averaged a respective 41%, 21%, 20%, and 17% in 2007 and 48%, 18%, 19%, and 16% in 2008. More water was extracted from the top 0.30 m soil layer in 2008 (range of 42% to 53%) than in 2007 (range of 37% to 44%), primarily because of more repetitive wetting of that top layer by more uniformly distributed rainfall events in 2008. Extraction in the top layer was highest for treatment T4 (100% ET$_a$ and 65% I$_a$) in 2007, while the same treatment had one of the lowest soil water extractions in the top layer in 2008. In general, soybean crops in the fully irrigated treatments preferentially extracted more water from the top layer in both years, whereas the soybean crops in the limited irrigation treatments and delay to R3 irrigation treatments extracted somewhat less water from that top layer but also balanced that deficit by withdrawing more water from the second and third layers. Other researchers have reported higher soybean root length density in the top layer (0-0.30 m) (Hulugalle and Lal, 1986; Myers et al., 2007; Gao et al., 2010; Farmaha et al., 2012). Barber (1995) stated that the natural morphological tendency of soybean roots is to grow into the soil zones between adjacent plant rows, and to proliferate in the surface soil layers rather than in subsur-
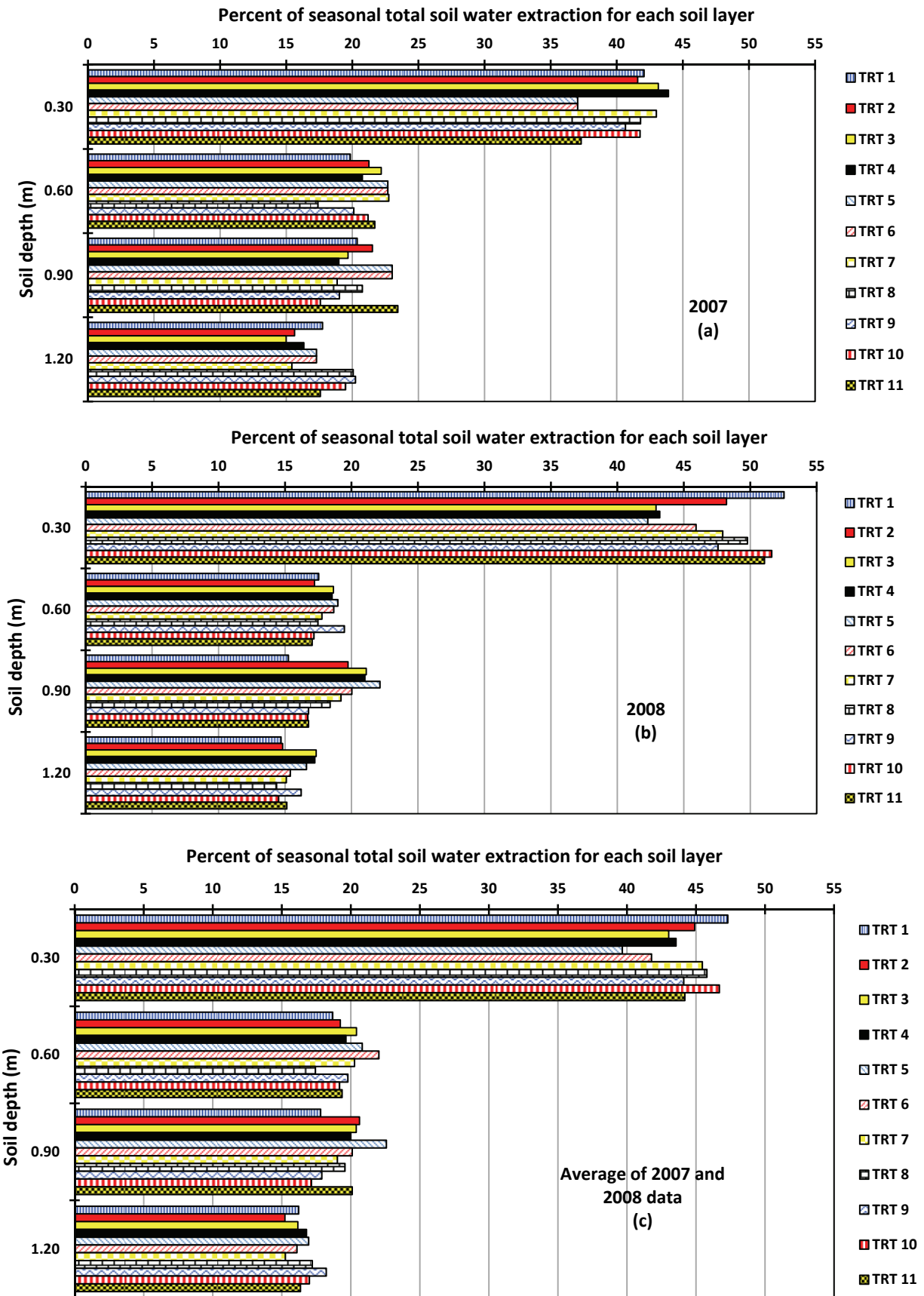
Figure 14. Seasonal soil water extraction by the soybean crop in each of the four 0.30 m successive soil layers as a percentage of soil water extraction totaled over all four layers (i.e., 1.20 m) in (a) 2007, (b) 2008, and (c) when pooled over both years.

face layers. Lenka et al. (2009) reported that, with increasing water input, water extraction took place mostly from uppermost soil layers. Although soybean roots are assumed to extend deeper into the soil in cases of water scarcity, recent research indicates that soybean taproots extend downward at a rate of 1.2 to 1.5 cm per day even in irrigated conditions, reaching 1.20 m depths in 100 days after planting (Torrion et al., 2012). Relative to other crops, most soil water extraction occurred in the top soil layer for maize (Djaman and Irmak, 2012), maize and wheat (Lenka et al., 2009), wheat (Bandyopadhyay and Mallick, 2003), and rice (Kondo et al., 2003). With respect to treatment variation in soil water extraction in other soil layers, the soil water extraction percentages in the second, third, and fourth soil layers respectively varied from 17% to 25%, from 19% to 23%, and from 15% to 20% in 2007 and from 17% to 19%, from 15% to 22%, and from 15% to 17% in 2008. The lack of treatment variation in the second layer (0.30-0.60 m) was due to the fact that the drip lines were located 0.4 m below the surface; because this was a point source of water, the upper second layer became a zone of root proliferation in all irrigated treatments. It is of interest to note that soybean crops in the rainfed, limited, and delay to R3 irrigated treatments extracted more water from the third layer (0.60-0.90 m) than did soybean crops in the fully irrigated treatments in 2008 (fig. 14b).

Irrigation management strategy impacted soybean soil water extraction patterns in 2007 (fig. 14a). In the delay to R3 irrigation treatment (T6), there was no irrigation prior to R3, so the topmost layer tended to be drier, causing the soybean plants in that treatment to extend their roots deeper into the soil layer. As a result, T6 (along with T5) had the least extraction (37%) of all treatments in the top soil layer among all treatments, but both T5 and T6 (along with T7) had the greatest extraction from the second soil layer. Like T6, treatment T7 was a delay to R3 irrigation strategy, except that after irrigation commenced upon attainment of the R3 stage, the soil profile in T7 was replenished at a 75% ET_a rate (instead of the 100% ET_a rate used for T6). Treatment T8 (preplant N application) had the least water extraction (17%) from the second soil layer (0.60 m). Its counterpart treatment T10 (in-season N fertigation via SDI injection) had the least amount of extraction (18%) from the third soil layer (0.90 m), whereas the delay to R3 irrigation treatment (T6) had the second largest extraction (23%) in the same layer. Treatments T3 (60% ET_a and 100% I_a) had the least crop water extraction (15%) in the 1.20 m soil layer. In 2007, treatments T1, T2, and T3 (which were all 100% I_a, but had respective 100%, 75%, and 60% ET_a) had similar soil water extraction levels in the top soil layer (42%, 41%, and 44%, respectively); however, in 2008, the crops in these three treatments had respective extractions values of 53%, 48%, and 43%. In 2008, the limited irrigation treatments had the highest water extraction from the third and fourth soil layers. On a two-year average basis (fig. 14c), rainfed soybean had the greatest soil water extraction from the fourth soil layer (0.90-1.20 m).

SUMMARY AND CONCLUSIONS

Subsurface drip-irrigated (SDI) soybean actual evapotranspiration (ET_a), seed yield, crop water productivity [irrigation water use efficiency (IWUE), crop water use efficiency (CWUE), and evapotranspiration water use efficiency (ETWUE)], soil water dynamics, and soil water extraction response to ten irrigation treatments with reference to a rainfed control were investigated in 2007 and 2008 in south-central Nebraska. In-season irrigation events were scheduled in most treatments on the basis of 100% ET_a replacement, although ET_a replacement was limited in three treatments to just 75% (two treatments) or 60% (one treatment) to evaluate deficit irrigation management strategies. Moreover, in two 100% ET_a treatments, the amount of irrigation water (I_a) needed for 100% ET_a replacement was purposely limited to 65% or 50% at each irrigation event to evaluate scenarios in which producers may choose to seasonally extend a limited irrigation water supply. In addition, the research included two 100% I_a treatments (T6 and T7) in which irrigation was delayed until the R3 stage (the beginning of pod formation) but commenced immediately thereafter with ET_a values of either 100% (T6) or 75% (T7). Soybean response to nitrogen application method (preplant nitrogen and nitrogen injected through the SDI system in two applications) was also investigated in two fully irrigated (100% ET_a and 100% I_a) treatments. The research results and conclusions are briefly summarized below along with the implications of the findings.

Actual soybean ET_a was substantively higher in the irrigation treatments compared to the rainfed control. The ET_a average of the four fully irrigated 100% ET_a and 100% I_a treatments in which irrigation was not limited or delayed (i.e., T1, T8, T10, and T11) was 30% greater (592 mm) than the rainfed ET_a (452 mm) in 2007 and 15% greater (546 mm) than the rainfed ET_a (473 mm) in the wetter year 2008. The highest ET_a values measured in each year were in the fully irrigated (100% ET_a and 100% I_a) treatments (i.e., 600 mm in T10 in 2007 and 579 mm in T1 in 2008). These ET_a results lead to the obvious inference that irrigated crops transpire more water than rainfed crops, primarily because irrigated crops are likely to produce more dry matter and thus more leaf area than rainfed crops, and of course have more water (from irrigation) available for that transpiration. It is also worth noting the advantage of a subsurface irrigation system, in which irrigation events do not wet soil surface, which means that more of the irrigation water used for crop ET is going to be used for transpiration rather than evaporation.

The N fertilization of irrigated soybean fields might be expected to result in more ET_a because of the hypothesis that extra N might stimulate the creation of extra leaf area (beyond that produced in a non-N-fertilized irrigated control). Suggestive evidence for this hypothesis was evident in the comparison of the ET_a average over the two N treatments of T8 and T10 (594 mm in 2007 and 537 mm in 2008) versus the ET_a average over the two comparable non-N controls of T1 and the N treatment of T11 (587 mm in 2007 and 510 mm in 2008). Regarding the method of N application, the ET_a of 601 mm for treatment T10 (N in-

jected through the SDI system) was about 3% greater than the ET_a of 586 mm of its counterpart treatment T8 (preplant N applied) but was only marginally higher (<1%) in 2008 (539 versus 535 mm, respectively). The 100%, 75%, and 60% ET_a replacement irrigation treatments (T1, T2, and T3) had 2008 actual ET_a values (i.e., 579, 538, and 498 mm) that translated into a linear decrease of 40 to 41 mm ET_a per 25% deficit in ET_a replacement. However, this downward trend was only partially evident in the 2007 actual ET_a values (i.e., 586, 566, and 586 mm) because of the high ET_a observed in T3. When the amount of irrigation water applied in the 100% ET_a treatment was varied using I_a values of 100% (T1), 65% (T4), or 50% (T5), the 2008 ET_a values (i.e., 579, 549, and 515 mm) also trended downward, but the 2007 ET_a values did not (i.e., 586, 557, and 588 mm) because of the high ET_a observed in T5, contradicting the finding that limited irrigation management strategies usually reduce actual ET_a.

All irrigation treatments resulted in significantly greater yield than the rainfed treatment yield (4.04 ton ha^{-1}) in 2007, but this was not true in 2008, primarily because a wetter growing season resulted in a relatively high rainfed treatment yield (4.82 ton ha^{-1}) that was not significantly different from any irrigated treatment yield. The highest-yielding irrigation treatment (4.97 ton ha^{-1}) in 2008 was T8 (preplant N-fertilized), whereas the highest-yielding treatment in 2007 (4.94 ton ha^{-1}) was T6 (irrigation delayed until R3), whose yield was, in statistical significance terms, greater than all other irrigation treatments except the two N-fertilized treatments of T8 (4.77 ton ha^{-1}) and T10 (4.82 ton ha^{-1}).

Nitrogen injection through the SDI system (T10) resulted in slightly greater, but non-significant (p > 0.05), yield than preplant applied N (T8) in 2007, but slightly less yield in 2008. Thus, the primary advantage of N injection would be mainly operational convenience, as well as less fuel use. When averaged over years, the combined mean yield (4.87 ton ha^{-1}) of the two N application treatments (T8 and T10) was greater (by about 3%) than the combined mean yield (4.74 ton ha^{-1}) of the two non-N controls (T1 and T11). That yield difference may not be economically worth the cost of the N fertilizer, unless the producer can contract the sale of the soybean seed at a commensurate price per ton.

Seed yield exhibited a quadratic relationship with total seasonal irrigation but a linear relationship with total seasonal ET_a in both growing seasons. The linear yield response to each 25.4 mm of ET_a replacement was 0.114 ton ha^{-1} (beyond intercept) in 2007 but only 0.02 ton ha^{-1} in 2008. Each 25.4 mm incremental increase in seasonal irrigation water applied increased soybean yield by 0.323 ton ha^{-1} (beyond the intercept) in 2007 and by 0.037 ton ha^{-1} in 2008.

In both years, CWUE decreased when seed yield or seasonal ET_a increased. In contrast, IWUE substantively increased with each incremental increase in seed yield, primarily because of a substantive soybean yield response (the numerator in the IWUE ratio) to per mm amounts of irrigation water. In the drier year (2007), the IWUE value of the T6 (delay to R3 irrigation) treatment (10.35 kg ha^{-1} mm^{-1})

exceeded the IWUE values of all other treatments and was, in fact, twice the IWUE value (5.32 kg ha^{-1} mm^{-1}) of the T1 (fully irrigated) control. The relationship of ETWUE with seed yield and with seasonal irrigation amount paralleled the pattern seen with IWUE. A 1:1 graph of ETWUE versus IWUE (using data from both years) revealed a regression coefficient of 0.63 for the IWUE parameter based on yield and seasonal ET_a data at this site. Because the numerator in both parameters is identical for the coordinate data point in the graph, one could infer that irrigation (by providing a source of water for ET_a) contributes to (or accounts for) a 0.63 fraction of the ET_a denominator that drives variation in ETWUE.

Water extraction in the four soil layers varied substantially among the treatments. Soybean extracted soil water from the entire 1.20 m soil profile in all treatments. The percentage of total soil water extraction, when averaged over all treatments, was 41%, 21%, 20%, and 17% in 2007 and 48%, 18%, 19%, and 16% in 2008 for the respective 0-0.30, 0.30-0.60, 0.60-0.90 and 0.90-1.20 m soil layers. In 2007, the percentage of total water extraction from the top soil layer ranged between 37% and 44%, with the highest percentage of extraction occurring in T4 (100% ET_a and 65% I_a). In the delay to R3 irrigation strategy (T6), soybean plant roots extended deeper into the soil layer in 2007; as a result, T6 (along with T5) extracted less water (37%) from the top soil layer than did all other treatments.

Overall, The delay to R3 irrigation strategy resulted in similar or greater productivity performance than the other irrigation strategies. Delaying irrigations until the R3 stage, but practicing full irrigation thereafter, for soybean crops grown on silt loam (or similar fine-textured) soils that have an adequate soil water-holding capacity can result in at least similar or even greater yields (and thus greater crop water productivity) compared to full-season irrigation scheduling practices. This finding may be useful for application by soybean producers in areas beyond the Clay Center research site that have similar edaphic and climatic characteristics where cultivars of maturity group 3.0 are grown.

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