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Corn Water Use and Yield for Various Limited Irrigation Treatments

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Abstract. *With limited water resources, it becomes more critical to know how much and when to irrigate. The objective of this study was to determine the effect of the amount and timing of irrigation on corn (Zea mays L.) yield using subsurface drip irrigation (SDI). A field study was conducted at North Platte, Nebraska in 2007 - 2009, using two SDI systems. The study was replicated eight times on the older SDI system (SDI1) and four times on the newer SDI system (SDI2). On SDI1, there were nine treatments to impose different irrigation regimes, ranging from dryland to fully irrigated. Five of the nine treatments allowed for various degrees of water stress, but only after tasseling and silking. On SDI2, there were eight treatments that were very similar to those on SDI1.*

In 2007, on SDI1, mean corn yield ranged from 7.8 Mg ha^{-1} with a season total of 57 mm of irrigation water to 11.1 Mg ha^{-1} for the fully irrigated treatment (253 mm of irrigation water). On SDI2, yield increased from 8.9 Mg ha^{-1} with 41 mm to 11.5 Mg ha^{-1} with 264 mm (fully irrigated). The least-irrigated treatment (158 mm) of the four treatments allowing water stress only after tasseling and silking, had a mean yield of 10.9 Mg ha^{-1}, only 0.6 Mg ha^{-1} less than the fully irrigated treatment (264 mm), even though soil water content fell well below 0.20 m^3 m^{-3} (50% depletion of soil available water) in the second part of August and in September for the former treatment (158 mm).

In 2008, yields were suppressed across the irrigation treatments. Amount or timing of irrigation did not have much effect on yields, except for the dryland treatment where yield was substantially less than for the other treatments. In 2009, yields ranged from 12.6 to 13.5 Mg ha^{-1} - there were no significant differences in yield among the irrigation treatments. There may have been several reasons for this. First, there was more in-season precipitation in 2009 than in 2007

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and 2008, requiring less irrigation water. Second, the cooler weather in 2009, with a lower atmospheric evaporative demand, also contributed to the lower irrigation requirements. Third, much of the irrigation water was applied after mid-August, after the most water-stress sensitive stages of tasseling, silking, and pollination. After mid-August, the soil in the low-irrigation treatments dried out well below 50% depletion without causing yield losses. Finally, the lower atmospheric demand in 2009 may have been another reason why soil water contents well below 50% depletion did not cause any yield losses.

Seasonal evapotranspiration (ET) stayed below 600 mm in all three years for all irrigation treatments, which is rather low. Limited evaporation may have kept ET low. Evaporation was likely limited because of the soil surface staying dry when irrigating with these SDI systems, and because of the no-till practices that were used with a nearly 100% cover of corn residue covering the soil surface all the time.

Keywords: corn, soil water, water stress, evapotranspiration, subsurface drip irrigation

Introduction

In western Nebraska, as in many other parts of the USA, irrigation water is becoming scarcer. Groundwater levels have been falling (McGuire, 2004; McGuire and Fischer, 1999), and stream flow has been decreasing, leading to some conflicts between political entities. For example, it has been a challenge for Nebraska to supply the required amount of water to Kansas through the Republican River. Irrigated agriculture is a major water user and a reduction in use of irrigation water throughout the Republican Basin would be additional water that could help meet stream flow requirements in the Republican River. Also, by pumping less irrigation water, irrigators will be able to reduce pumping cost and more water could be available for competing needs including those of wildlife, endangered species, and hydroelectricity plants.

Water shortages have led to irrigation allocations: government-imposed restrictions on irrigation that are common in western Nebraska. These allocations are expected to become more restrictive and more widespread throughout the state. Corn, the most important crop in Nebraska, is affected by these developments more than other crops because of its high water requirements. Corn producers need to make tough choices: fully irrigate less land area; deficit-irrigate more land area; and/or grow crops that require less water, but are also less profitable, such as winter wheat.

If applying less than full irrigation, it becomes more critical to know when to irrigate; how to time irrigation applications. Payero et al. (2009) conducted a two-year study at North Platte, Nebraska, on the timing of irrigation with a fixed seasonal amount, 150 mm, of irrigation water in each irrigation treatment. The fixed amount was used to mimic an irrigation allocation of 150 mm per year. They found that timing of irrigation did matter: corn yields were highest when most of the 150 mm was applied in July and lowest when most was applied in September.

The need for irrigation is often determined based on soil water content. A rule of thumb for the irrigation of many crops is that the crop experiences no water stress as long as plant available water is greater than 50%, halfway between field capacity and permanent wilting point. However, this point of beginning water stress depends on a number of factors, including the type of crop, the crop growth stage, and the atmospheric evaporative demand. On a hot, dry day, when atmospheric demand is high, the soil needs to hold more water than on a cool, humid day to avoid water stress on a crop (Allen et al., 1998).

More efficient irrigation systems may contribute to the goal of water conservation. Subsurface drip irrigation (SDI) has the potential of being a more efficient irrigation system compared to systems such as center pivot and furrow irrigation. With SDI, the soil surface is not wetted when irrigating, which eliminates runoff of irrigation water and greatly reduces water losses by evaporation from the soil surface. With proper management, deep percolation of water below the root zone can be minimized, so that application efficiency with SDI can be close to 100%.

However, the cost of an SDI system is high. Currently, SDI may not be competitive with a center pivot for irrigating a row crop such as corn on a quarter section (800 m by 800 m) of land, which is a typical irrigation scenario for the western US Great Plains region. Also, rodents are often a problem with SDI (Lamm and Camp, 2007). They chew on the underground drip tape, causing leaks that may be difficult to find and repair. There is no easy solution to this problem. Maintaining less crop residue on the field may help – providing a less attractive habitat for the rodents. However, this would counteract the water-conservation objective of having an SDI system; maintaining more residue has been shown to conserve water (Steiner, 1989; Todd et al., 1991; van Donk et al., 2004; Klocke et al., 2009; van Donk et al., 2010). Nonetheless, with water becoming scarcer, SDI may become more interesting, even for large-scale, relatively low-value, row-crop production.

The response of a crop to irrigation may be affected by the system (surface, center pivot, SDI) used for irrigation. Past research focus in west-central Nebraska has been mostly on the more common sprinkler and surface irrigation systems (Payero et al., 2005; Payero et al., 2006a, Payero et al., 2006b; Schneekloth et al., 2006). Local information on the response of SDI-irrigated corn is limited. The objective of this study was to determine the effect of the amount and timing of irrigation on corn (*Zea mays L.*) yield using SDI.

Methods

The study was conducted from 2007 through 2009 at the University of Nebraska-Lincoln, West-Central Research and Extension Center (WCREC) in North Platte, Nebraska (41^o 10’ N, 100^o 45’ W, 861 m elevation above sea level) on a Cozad silt loam (fine-silty, mixed, mesic Fluventic Haplustoll) with an average water content at field capacity of 0.29 m^3 m^{-3} and at wilting point of 0.11 m^3 m^{-3} (Klocke et al., 1999). The climate at North Platte is semi-arid, with an average annual precipitation of 508 mm and a reference evapotranspiration of 1403 mm. On average, approximately 80% of the annual precipitation occurs during the growing season, which extends from late April to mid October (USDA, 1978).

The experiment was conducted on a set of plots planted to field corn. No-till practices were used in all three years. Two SDI systems were used for irrigation. The study used a randomized complete block design and was replicated eight times on the older SDI system (SDI1) and four times on the newer SDI system (SDI2). On SDI1 there were nine treatments to impose different irrigation regimes (Table 1). On SDI2 there were eight treatments, which were essentially the same as the SDI1 treatments, except that the SDI1 treatment B1 was omitted. The rationale for the A and B treatments was to allow no water stress during the critical period of tasseling and silking (Table 2) and to allow various levels of water stress before and after this period. In 2009, the study was only conducted on SDI2 and the A1 treatment was replaced by a 125% ET treatment.

During late spring and summer, precipitation was measured using several rain gauges located at the SDI plots. For the rest of the year precipitation data from a High Plains Regional Climate Center (HPRCC, http://www.hprcc.unl.edu/) weather station, located less than one km from the study site, were used. Measurement of precipitation in the form of snow at this HPRCC station did not appear very reliable. Therefore, for water equivalent data from snow, we used data from the WCREC dryland farm, which is located a few km NW of the SDI plots. Thus, using these three data sources, a precipitation record was constructed for the entire three years of 2007 – 2009 (Figures 1 and 2).

The SDI1 system applies 25.4 mm (1 inch) of water in approximately 13 hours and the SDI2 system applies this amount in approximately 17.5 hours. We irrigated three times a week unless rain made irrigation unnecessary. For example, there was no irrigation between 7/27 and 8/10/2007 (Figure 3) because of abundant rain (Figure 1) and low evapotranspiration values. In 2007 and 2009, the dryland treatment was not exclusively rainfed, because all plots, including the dryland plots, were fertigated at the beginning of the irrigation season (Figures 3 and 5).

The first irrigation of the season was determined by not allowing the mean soil water content of the top 0.9 m (approximately representing the rooting depth at this time) to drop below 0.20 m^3 m^{-3}. For our silt loam soil, a soil water content of 0.20 m^3 m^{-3} is halfway between soil water content at field capacity (0.29 m^3 m^{-3}) and that at wilting point (0.11 m^3 m^{-3}). In other words, half of the available water is depleted at a soil water content of 0.20 m^3 m^{-3}. As a general rule, crop water stress can be expected when soil water content falls below this point. In all three years, the spring was so wet, that it was not necessary to start irrigation much before tasseling. Thus, the crop in the A and B treatments was not subjected to water stress before tasseling as prescribed by the treatments (Table 1).

In SDI 2, soil water content was measured approximately once a week during the growing season in each of the 32 plots at six depths (0.15, 0.46, 0.76, 1.07, 1.37, and 1.68 m) using a neutron probe (CPN Hydroprobe) (Evett and Steiner, 1995). There was one neutron tube per plot, always located within a row of corn. Corn rows were 0.76 m apart. The drip tape is spaced 1.52 m apart, which is twice the corn row spacing. Thus one drip tape, located approximately 0.40 m below the soil surface, supplies water to two rows of corn.

Data from the HPRCC weather station were used to obtain daily corn crop evapotranspiration for fully watered conditions (ET_c) (Table 3). The HPRCC algorithm for calculating ET_c uses emergence date as an input. Actual emergence dates (Table 2) were used for this ET_c calculation. During the growing season it was verified that the actual observed crop growth stage did not differ significantly from the growth stage calculated by the HPRCC algorithm. This ET_c was used to determine the amount of irrigation for the 100% ET treatment. Measured soil water content was used as a check to ensure that the 100% ET treatment was not falling below 50% depletion (0.20 m^3 m^{-3}) on average in the top 0.9 m of soil or that that this treatment would be overirrigated; we never had to correct for the irrigation scheduling based on ET_c. The irrigation amounts for all other treatments were based off of the 100% ET treatment (Figures 3-5). Note that 50% ET or 75% ET does not mean that 50% or 75% of the irrigation amount delivered to the 100% treatment was applied. This would have been the case only if precipitation would have been zero. Both irrigation and precipitation contribute to meet the 50% and 75% ET criteria.

Total season ET, between emergence and maturity, was estimated for each irrigation treatment using measured water balance components (change in soil water content, precipitation, and irrigation, Table 4). Before the date of the first soil water measurement, ET was estimated using HPRCC data. In 2009, ET was also estimated using HPRCC data after the date of the last soil water measurement because maturity occurred several weeks after this date. Irrigation in Table 4 is irrigation between the first and the last soil water measurement. For 2007 and 2008 this was equal to the total season irrigation. For 2009, this is a little less than the total season irrigation, because there was one irrigation (applied on Sept. 3) after the last soil water measurement (Sept. 2).

Corn yield was measured on both SDI1 and SDI2. A 3-row plot combine was used to harvest the corn crop. Corn that was harvested in two combine passes (six corn rows) in each plot was used in the yield calculation. Rows on the plot borders were excluded from the yield calculation. Grain weight and percent grain moisture were measured and recorded with a combine computer. Yield was standardized (adjusted) to 15.5 % grain moisture content. Statistical analysis of yield was conducted with SAS statistical software (SAS Institute, Inc., Cary, NC) using proc GLM. Separation of means was done with the Least Significant Difference method using alpha = 0.05.

Results and discussion

All three years were wetter than average years. The long term annual average precipitation of 508 mm was exceeded before November 1 in all three years (Figures 1 and 2). In all years, spring and early summer were wet, ensuring that the soil profile was approximately filled to field capacity with water at the beginning of each growing season. Atmospheric evaporative demand was the least in 2009 (Table 3).

In 2007, there was a rain event of over 40 mm in late July (Figure 1). The effect of this rain can be seen in the soil water content in all eight irrigation treatments: soil water content increased at several of the measured depths (Figure 6). The corn crop in the dryland treatment started depleting substantial amounts of soil water later in July down to a depth of approximately 1.07 m (Figure 6a). In August, the crop also used a significant amount of water from the 1.37 and 1.68 m depths. It is not clear from these data how much of the soil water depletion at these lower depths was direct water uptake by corn roots and how much was soil water redistribution (water moving upwards towards drier soil).

In the second half of July in the dryland treatment, soil water content dropped below 0.20 m^3 m^{-3} (below 50% available soil water depletion) for the first time in the season, although at the deeper depths, it was still well above 0.20 m^3 m^{-3} at this time (Figure 6a). The crop may have experienced some stress at this time, because soil water at these deeper depths is not the most accessible to the crop. In the middle of August, soil water content was well below 0.20 m^3 m^{-3} at all depths, except for the 1.68 m depth, suggesting that the dryland crop most likely experienced water stress at this time.

The corn crop in the 50% ET treatment may have been stressed for water also during the second part of July since soil water content fell below 0.20 m^3 m^{-3} for the top two measured depths and was exactly at 0.20 m^3 m^{-3} for the 0.76 m depth (Figure 6b). Soil water content at the deeper depths was still above 0.20 m^3 m^{-3}, as it was for the dryland treatment, but that could probably not prevent the crop from experiencing water stress at this time. Crop water stress during this critical period of tasseling and silking (Table 2) is undesirable and can have a serious negative impact on crop yield. At the end of July crop stress was relieved by the 40 mm rain. After this, soil water content decreased again and water stress was likely back in the 50% ET treatment by mid August staying into September.

Soil water content for the 75% ET treatment (Figure 6c) was somewhat greater than that for the 50% ET treatment (Figure 6b). Thus, from the soil water data, it is expected that the crop on the 50% ET treatment would have been under greater water stress than the crop on the 75% ET treatment. Indeed, the crop yield on the 50% ET treatment was lower than that on the 75% ET treatment (Table 5). Soil water content in the 100% ET treatment stayed above 0.20 m^3 m^{-3} for the entire season (Figure 6d), thus it is not expected that the crop in this treatment experienced water stress at any time during the growing season. As expected, the 100% ET treatment yielded higher than the 0.75% ET treatment (Table 5).

All A and B treatments received full irrigation (the same as the 100% ET treatment) until August 10 (Figure 3) when pollination was complete and silks were brown (Table 2). The A4 treatment received full irrigation until August 17. After this, in the last three weeks of the irrigation season, it received less than full irrigation, so that at the end of the season it had received 33 mm less than the 100% ET treatment (Figure 3b). This resulted in a soil water content being somewhat lower towards the end of the season (Figure 6h) than in the full irrigation treatment (Figure 6d), but yields for both treatments were the same at 11.5 Mg ha^{-1} (Table 5). Thus, this lower soil water content apparently did not impose water stress on the crop.

The A3 treatment received full irrigation until August 15. After this, it received less than full irrigation, so that at the end of the season it had received 68 mm less than the 100% ET treatment (Figure 3b). This resulted in a soil water content being lower towards the end of the season (Figure 6g) than in the full irrigation treatment (Figure 6d) and also somewhat lower compared to the A4 treatment (Figure 6h), which may have resulted in some water stress, but yield for the A3 treatment was only a little less (11.2 versus 11.5 Mg ha^{-1}, difference not statistically significant, Table 5). Soil water content fell below 0.20 m^3 m^{-3} in the second part of August and in September for the A1 (Figure 6e) and A2 (Figure 6f) treatments, but yields for these treatments were not much less than those for the A4 and 100% ET treatments (Table 5), suggesting that some drying out of the soil below 0.20 m^3 m^{-3} towards the end of the growing season has a minimal impact on corn yield.

In 2007, there was a clear response of corn yield to total season irrigation amount on SDI1, from a mean yield of 7.8 Mg ha^{-1} for the DL treatment to 11.1 Mg ha^{-1} for the 100% ET treatment (Table 5, Figure 9a). The 100% ET treatment received a total of 253 mm of irrigation water for the season (Figure 3a). The DL treatment was not truly dryland (rainfed) in 2007, because at the beginning of the irrigation season it received 57 mm of irrigation with fertigation through the SDI system. Corn yield increased steadily with increasing irrigation water in the treatments from B1 (8.7 Mg ha^{-1} with 113 mm of irrigation water) through B5 (10.5 Mg ha^{-1} with 241 mm of irrigation water) (Table 5, Figure 9a).

On SDI2, there was also a clear response to irrigation water when going from DL to full irrigation: yield increased from 8.9 Mg ha^{-1} with a seasonal irrigation total of 41 mm to 11.5 Mg ha^{-1} with an irrigation total of 264 mm (Table 5, Figure 9b). Because of fertigation, the DL treatment on SDI2 was not truly dryland (rainfed) in 2007 either. There was only a slight yield increase for the A treatments going from 10.9 Mg ha^{-1} with158 mm of irrigation water for the season for A1 to 11.5 Mg ha^{-1} with 231 mm of irrigation water for A4.

Little irrigation was needed before tasseling, so the effect of water stress before tasseling on corn yield could not really be evaluated in this experiment. A strong linear relationship (r^2 = 0.96 for SDI1 and 0.94 for SDI2) of corn yield as a function of total seasonal irrigation water was found (Figure 9). Yield increase per mm of additional irrigation water was 16 kg ha^{-1} for SDI1 and 12 kg ha^{-1} for SDI2.

In 2008, as in 2007, the soil profile was approximately filled to field capacity with water at the beginning of the growing season (Figure 7). Soil water content in the dryland treatment was also close to field capacity at the beginning of the season (Figure 7a), even though the same dryland plots were well depleted of soil water at the end of the 2007 growing season (Figure 6a).

In 2008, corn in the dryland treatment started depleting substantial amounts of soil water in July down to a depth of about 1.07 m (Figure 7a). In August, the crop also used a significant amount of water from the 1.37 and 1.68 m depths. In the middle of July, soil water content dropped below 0.20 m^3 m^{-3} for the first time in the season, but only at the 0.46 m depth. At the other depths, it was still well above 0.20 m^3 m^{-3} at this time, so it is unlikely that the crop experienced water stress. At the beginning of August, soil water content was well below 0.20 m^3 m^{-3} at the 0.46, 0.76, and 1.07 m depths, suggesting that the crop most likely experienced water stress at this time. Soil water content in the 100% ET treatment stayed above 0.20 m^3 m^{-3} for most of the season, as it should to avoid water stress on the crop (Figure 7d). Only in late July did it drop slightly below this level, but only at the 0.46 m depth, so it is not expected that the crop experienced water stress at any time during the growing season.

In 2008, amount or timing of irrigation did not have much of an effect on yields, except for the dryland treatment where yield was substantially less than for the other treatments (Table 5, Figure 9). Yields were suppressed across the irrigation treatments. These low yields were not unique to our experiment; the majority of the fields at WCREC had low yields, similar to the ones in this study. There was probably not one single culprit, but a number of factors may have played a role. A hail storm in July damaged many leaves. Also, planting was later than average, because of the wet and cool spring weather. The corn only emerged in the beginning of June (Table 2).

It is unlikely that the low 2008 yields were caused by water stress: more irrigation water on the 100% ET treatment did not increase yield compared to e.g. the yields on the 75, A1, A2, A3 treatments (Table 5). Also, soil water content does not suggest crop water stress on the 100% ET treatment (Figure 7d). Only towards the end of July soil water content dropped slightly below 0.20 m^3 m^{-3} and only for one of the six measured depths.

In 2009 the near-surface soil was wetter (Figure 8) than in 2007 (Figure 6) and 2008 (Figure 7) for much of the growing season, because there was more in-season (June, July, August) precipitation (Figures 1 and 2). Soil in the DL (Figure 8a) and 50% ET (Figure 8b) treatments did not get as dry as in 2007 and 2008. Soil water measurements suggest that the 125% ET treatment was overwatered (Figure 8e). Because there was more in-season precipitation in 2009, less irrigation water was applied compared to 2007 and 2008 (Figure 5). Because of this higher in-season precipitation, the 50% and 75% ET treatments especially required little irrigation in 2009. Precipitation provided most of the 50% ET requirement so that only a season total of 30 mm of irrigation water was applied in this treatment. Similarly, only a little over 100 mm water was applied in the 75% ET treatment (Figure 5). The cooler weather in 2009, with a lower atmospheric evaporative demand for ET (Table 3), also contributed to the lower irrigation requirements.

Much of the irrigation water was applied after mid-August (Figure 5), after the most water-stress sensitive stages of tasseling, silking, and pollination. After mid-August, the soil in the DL and 50% ET treatments dried out considerably (Figure 8a, b), but this did not lead to yield losses (Table 5). Apparently, in this later stage the corn crop was able to tolerate greater soil water depletion without suffering any yield loss. This was also observed in 2007 with some of the A treatments as discussed above. They received less than full irrigation in the last few weeks of the irrigation season without suffering much yield loss.

In addition, the lower atmospheric demand in 2009 (Table 3) may have been another reason why low soil water contents, e.g. in the DL and 50% ET treatments, did not cause crop water stress with subsequent yield loss. This effect has been documented by several researchers (Denmead and Shaw, 1962; Allen et al., 1998; Orfanus and Eitzinger, 2010). They showed that crop water stress does not simply occur once soil water content drops below a certain level, e.g. 50% depletion of available soil water, but that this level depends on atmospheric demand, with the level being lower at a lower atmospheric demand.

The range in ET among the irrigation treatments was small in 2009, from 505 to 564 mm (Table 4, Figure 10). Seasonal ET for the DL and 50% ET treatments was not less than that of the other treatments (Table 4), indicating that, even in the low-irrigation treatments, corn roots did not have significant difficulty extracting the soil water necessary for growing a crop relatively free of water stress.

Seasonal ET was rather low, staying below 600 mm in all three years for all irrigation treatments (Table 4, Figure 10). This indicates that the assumption, for the ET calculation, of no runoff or deep percolation was probably not violated, which is consistent with our observations in the field plots. Furthermore, limited evaporation may have kept ET down. Evaporation was likely limited because of the soil surface staying dry when irrigating with these SDI systems, and because of the no-till practices that were used with plenty of corn residue covering the soil surface (Nielsen et al., 2005; Klocke et al., 2009; van Donk et al., 2010; Grassini et al., 2011).

Conclusions

In 2007, there was a clear response of corn yield to total season irrigation amount on SDI1, from a mean yield of 7.8 Mg ha^{-1} for the DL treatment (a season total of 57 mm of irrigation water) to 11.1 Mg ha^{-1} for the 100% ET treatment (253 mm of irrigation water). Corn yield increased steadily with increasing irrigation water in the treatments from B1 (8.7 Mg ha^{-1} with 113 mm of irrigation water) through B5 (10.5 Mg ha^{-1} with 241 mm of irrigation water).

On SDI2, yield increased from 8.9 Mg ha^{-1} with a seasonal irrigation total of 41 mm to 11.5 Mg ha^{-1} with an irrigation total of 264 mm. There was only a slight yield increase for the A treatments going from 10.9 Mg ha^{-1} with 158 mm of irrigation water for the season for A1 to 11.5 Mg ha-1 with 231 mm of irrigation water for A4. Soil water content fell below 0.20 m^3 m^{-3} in the second part of August and in September for the A1 and A2 treatments, but yields for these treatments were not much less than those for the A3 and A4 treatments, suggesting that some drying out of the soil below 0.20 m^3 m^{-3} (below 50% depletion of soil available water) towards the end of the growing season has a minimal impact on corn yield.

Little irrigation was needed before tasseling, so the effect of water stress before tasseling on corn yield could not be tested in this experiment. A strong linear relationship (r^2 = 0.96 for SDI1 and 0.94 for SDI2) of corn yield as a function of total seasonal irrigation water was found. Yield increase per mm of additional irrigation water was 16 kg ha^{-1} for SDI1 and 12 kg ha^{-1} for SDI2.

In 2008, yields were suppressed across the irrigation treatments. Amount or timing of irrigation did not have much of an effect on yields, except for the dryland treatment where yield was substantially less than for the other treatments. Reasons for the low yields included a hailstorm in July, and late planting and emergence caused by wet and cool weather and soil.

In 2009 there were no significant differences in yield among the irrigation treatments. There may have been several reasons for this outcome. First, there was more in-season precipitation in 2009 than in 2007 and 2008, requiring less irrigation water. Second, the cooler weather in 2009, with a lower atmospheric evaporative demand, also contributed to the lower irrigation requirements. Third, much of the irrigation water was applied after mid-August, after the most water-stress sensitive stages of tasseling, silking, and pollination. After mid-August, the soil in the low-irrigation treatments dried out considerably without causing yield losses. Finally, the lower atmospheric demand in 2009 may have been another reason why soil water contents well below 50% depletion, e.g. in the DL and 50% ET treatments, did not cause any yield losses.

Seasonal ET stayed below 600 mm in all three years for all irrigation treatments, which is rather low. Limited evaporation may have kept ET low. Evaporation was likely limited because of the soil surface staying dry when irrigating with these SDI systems, and because of the no-till practices that were used with a nearly 100% cover of corn residue covering the soil surface all the time.

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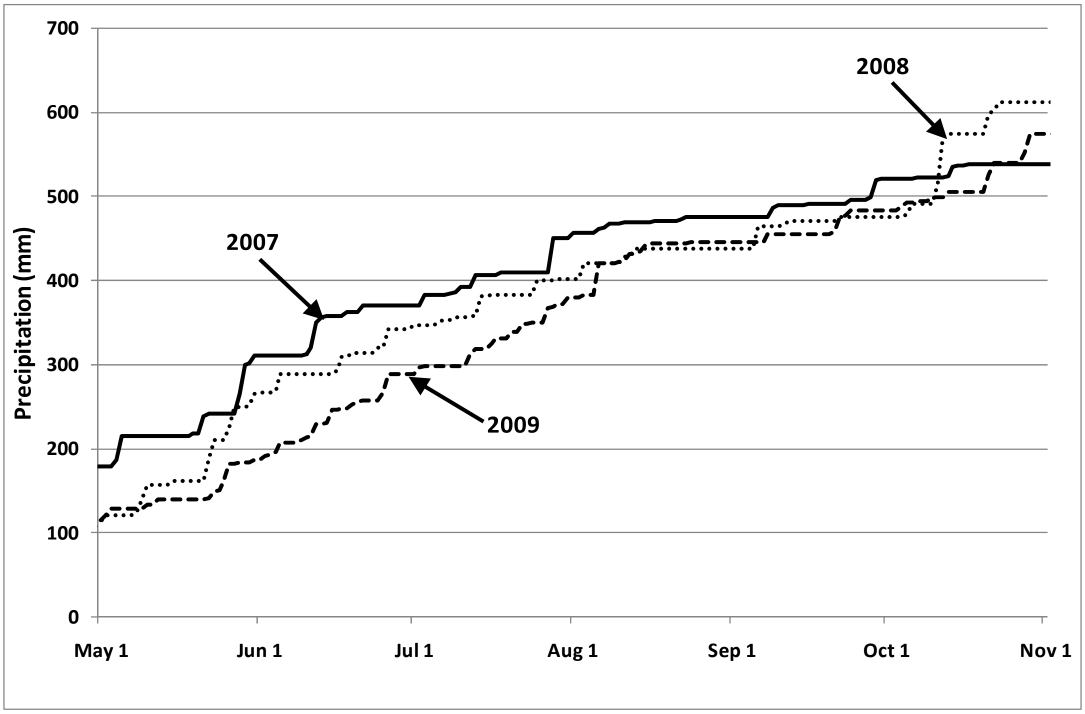

Figure 1. Cumulative precipitation at the experimental site, 2007 - 2009.

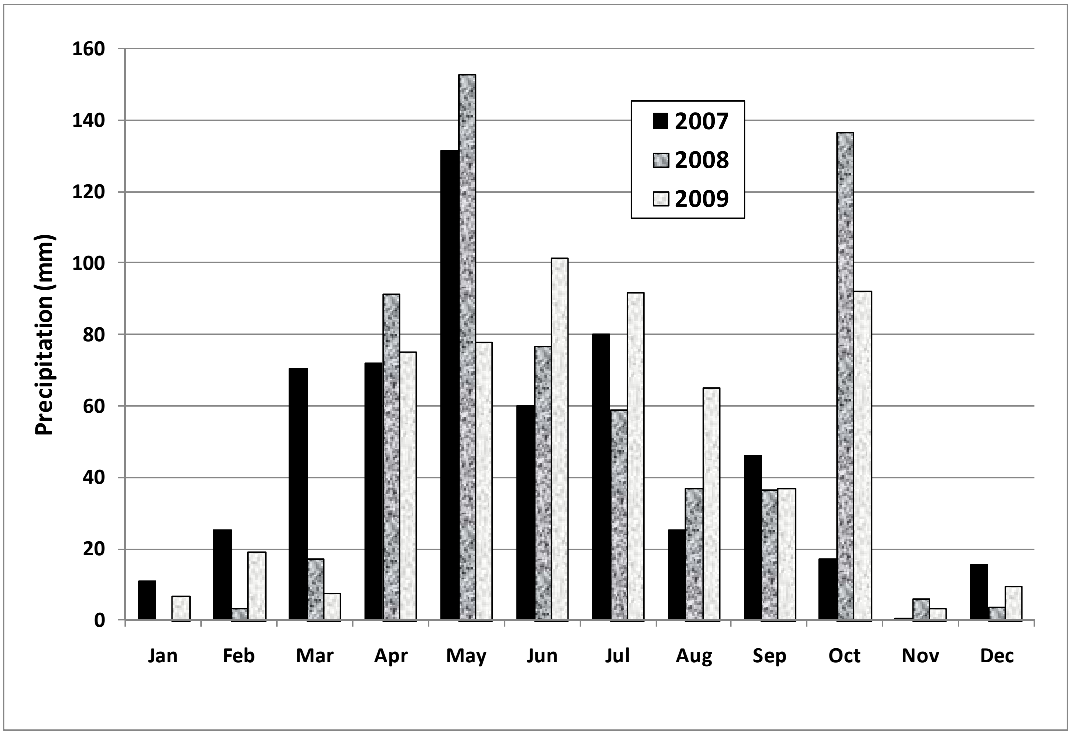

Figure 2. Monthly precipitation at the experimental site, 2007 - 2009.

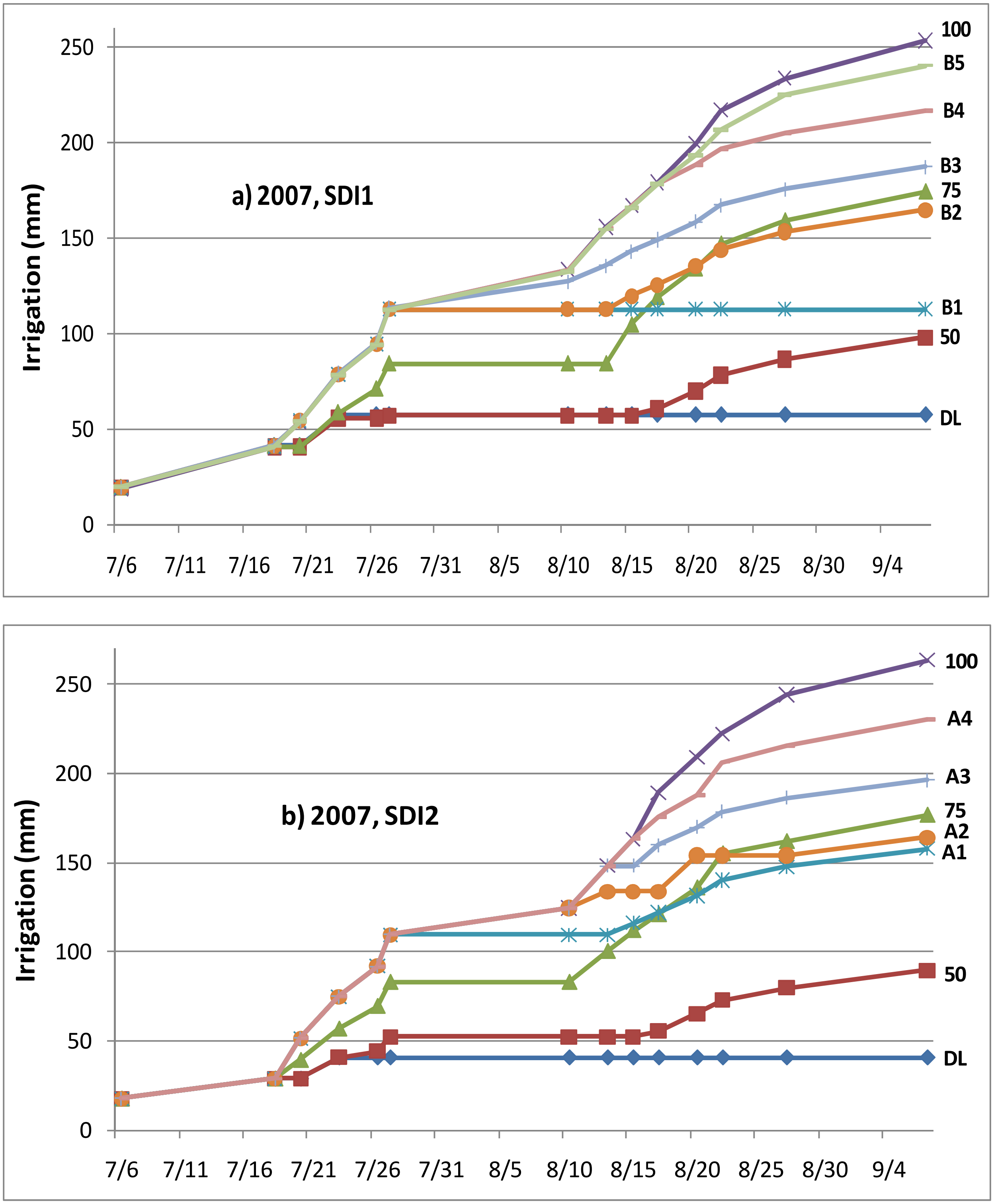

Figure 3. Cumulative irrigation in 2007 for nine irrigation treatments on SDI1 (a) and eight irrigation treatments on SDI2 (b). Descriptions of irrigation treatments are given in Table 1. Dots, squares, etc. indicate irrigation dates.

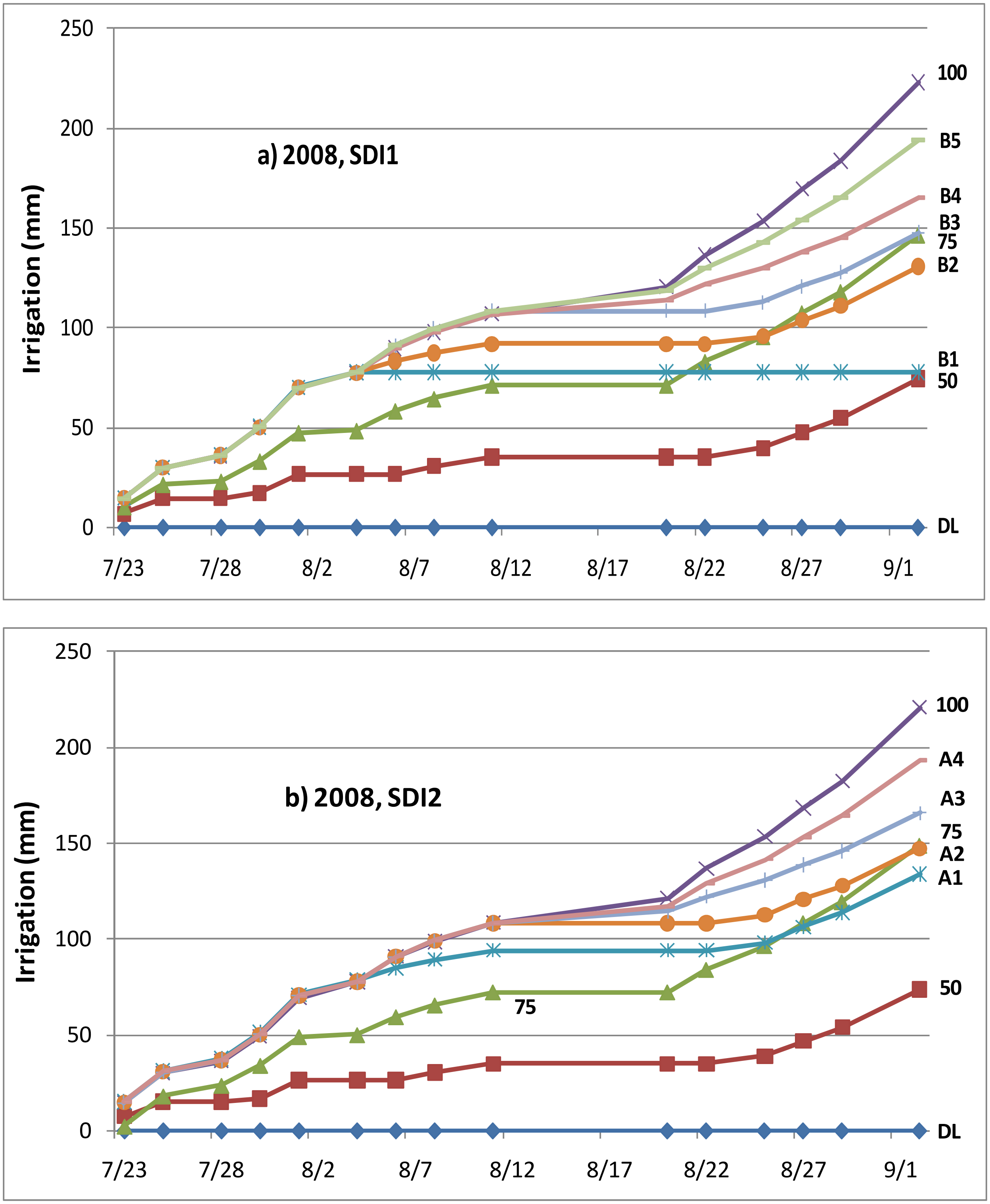

Figure 4. Cumulative irrigation in 2008 for nine irrigation treatments on SDI1 (a) and eight irrigation treatments on SDI2 (b). Descriptions of irrigation treatments are given in Table 1. Dots, squares, etc. indicate irrigation dates.

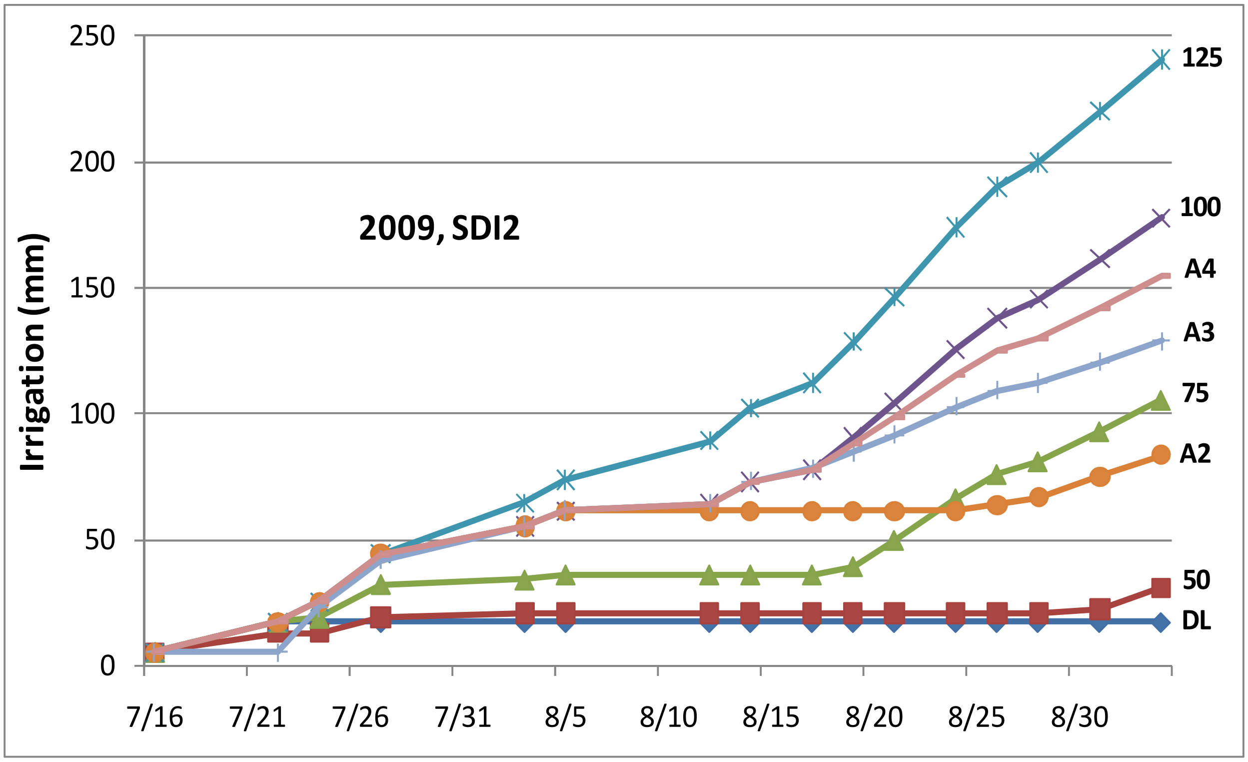

Figure 5. Cumulative irrigation in 2009 for eight irrigation treatments on SDI2. Descriptions of irrigation treatments are given in Table 1. Dots, squares, etc. indicate irrigation dates.

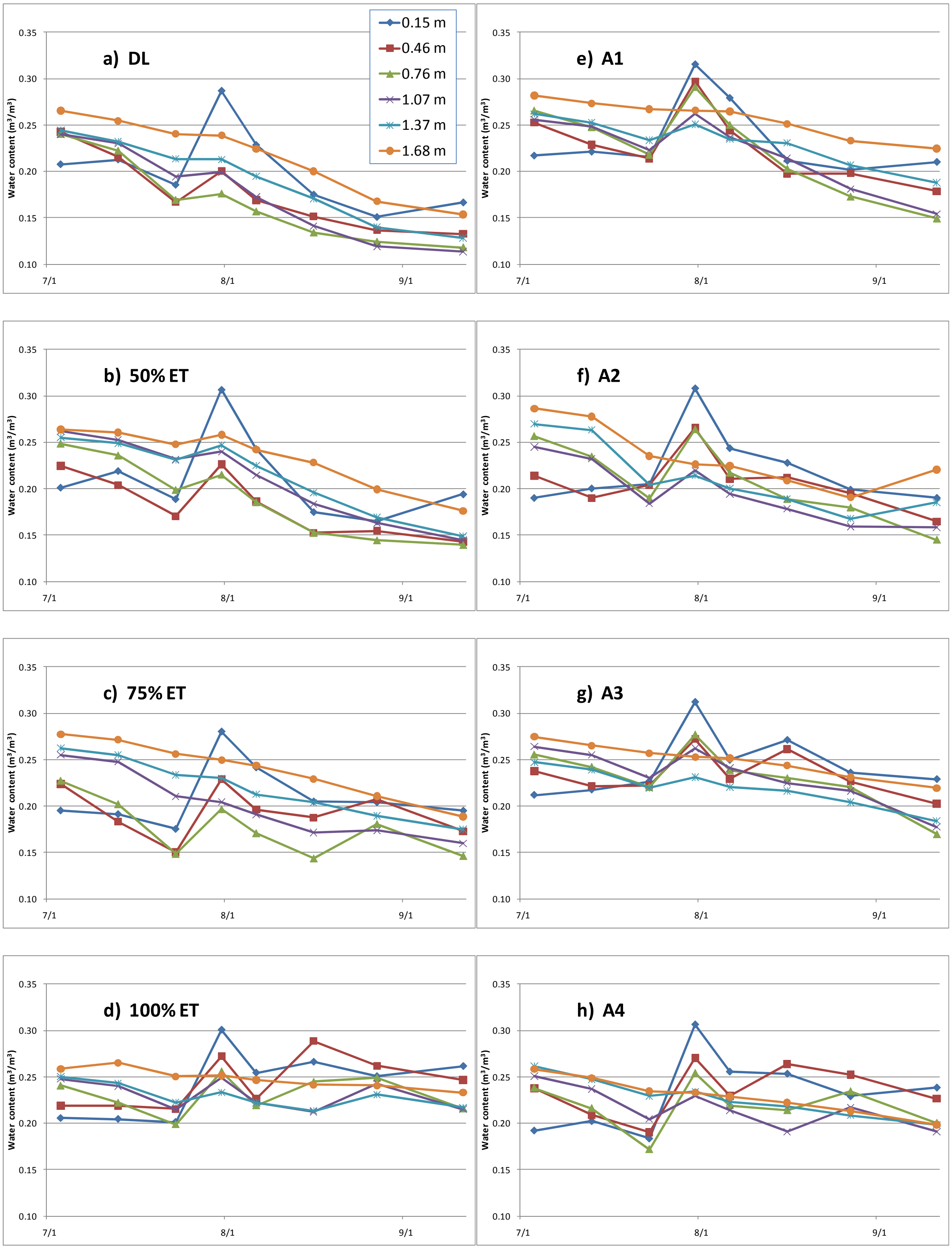

Figure 6. Soil water content (m^3 m^{-3}) in 2007 at six different soil depths for eight irrigation treatments on SDI2. Descriptions of irrigation treatments are given in Table 1.

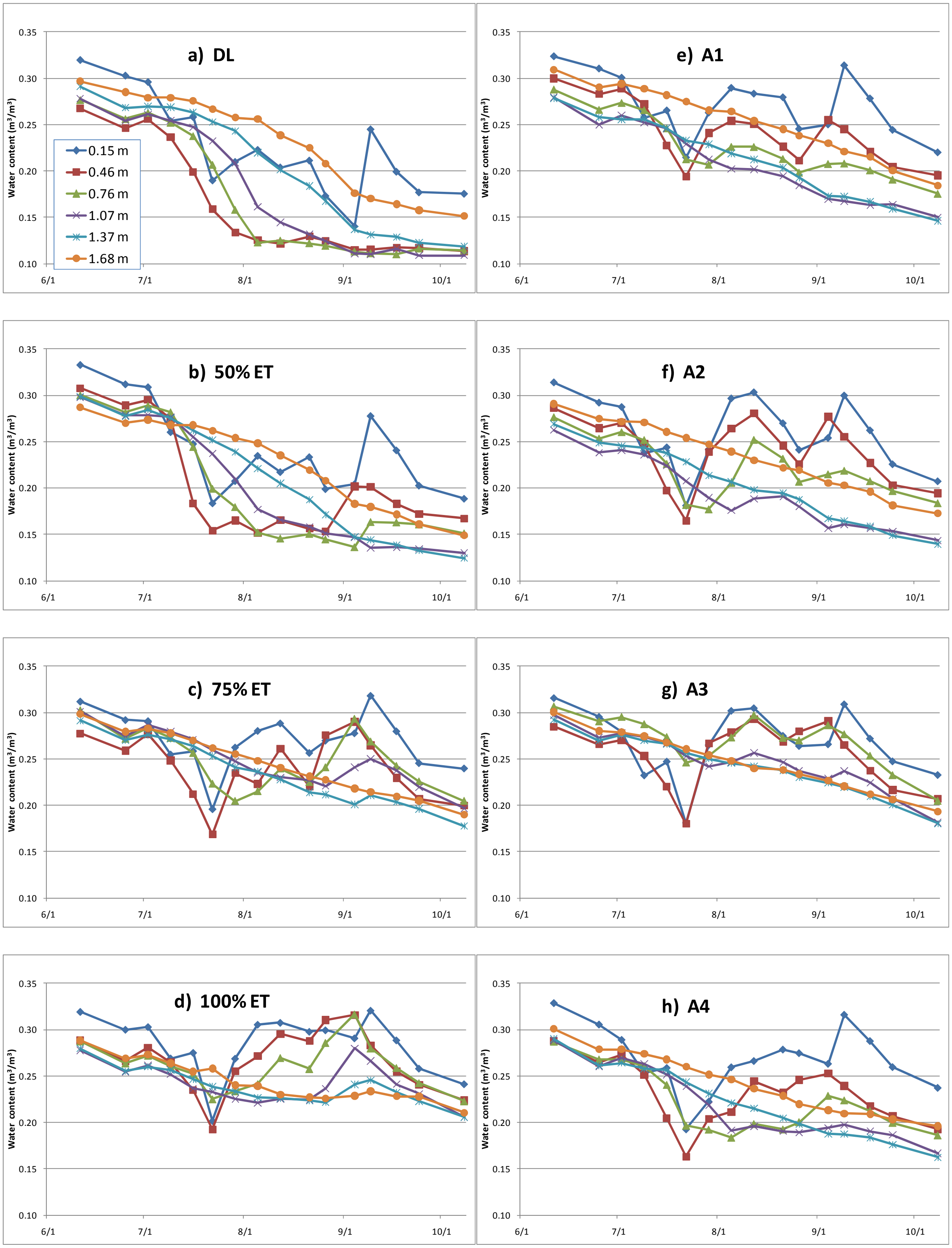

Figure 7. Soil water content ($m^3\ m^{-3}$) in 2008 at six different soil depths for eight irrigation treatments on SDI2. Descriptions of irrigation treatments are given in Table 1.

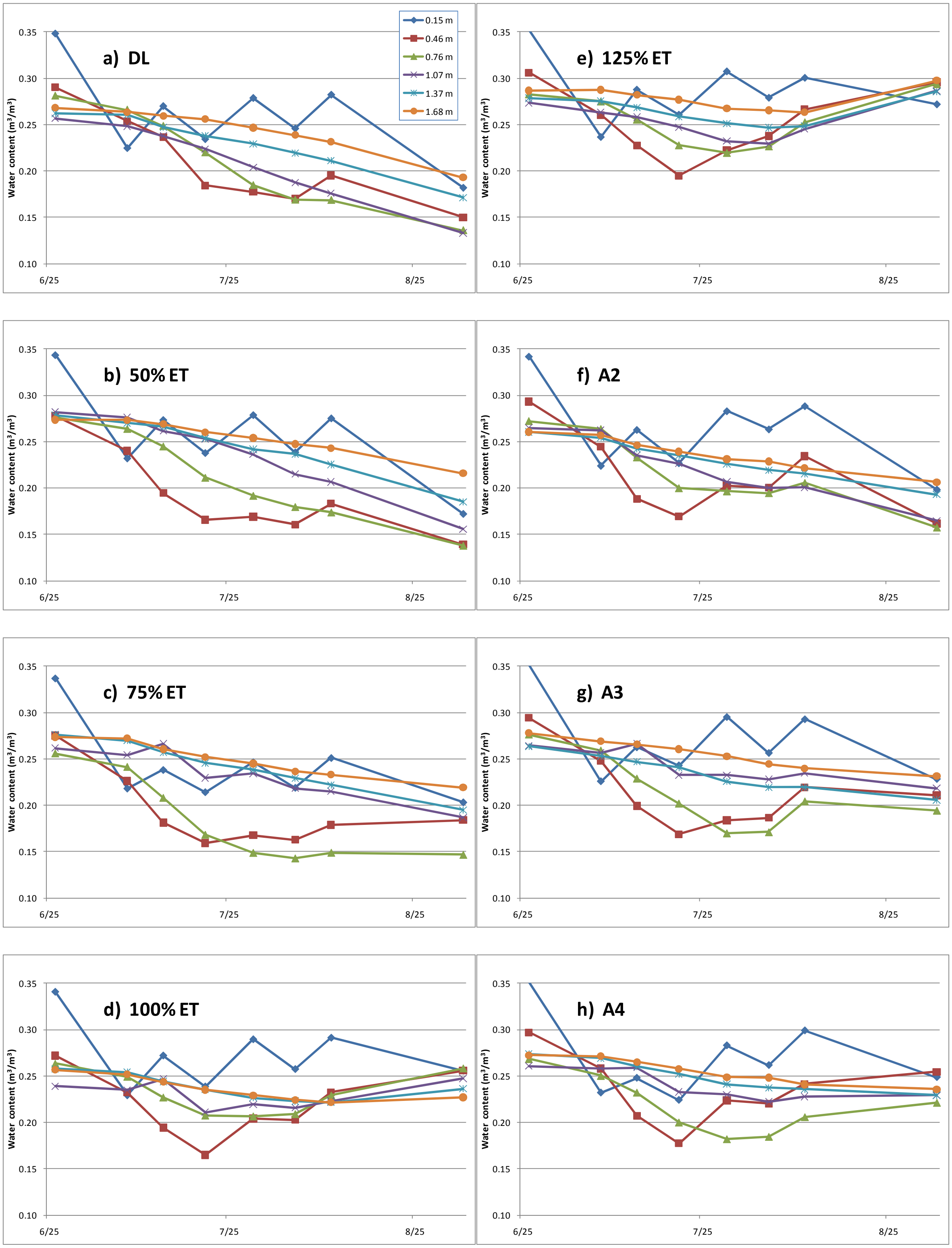

Figure 8. Soil water content (m^3 m^{-3}) in 2009 at six different soil depths for eight irrigation treatments on SDI2. Descriptions of irrigation treatments are given in Table 1.

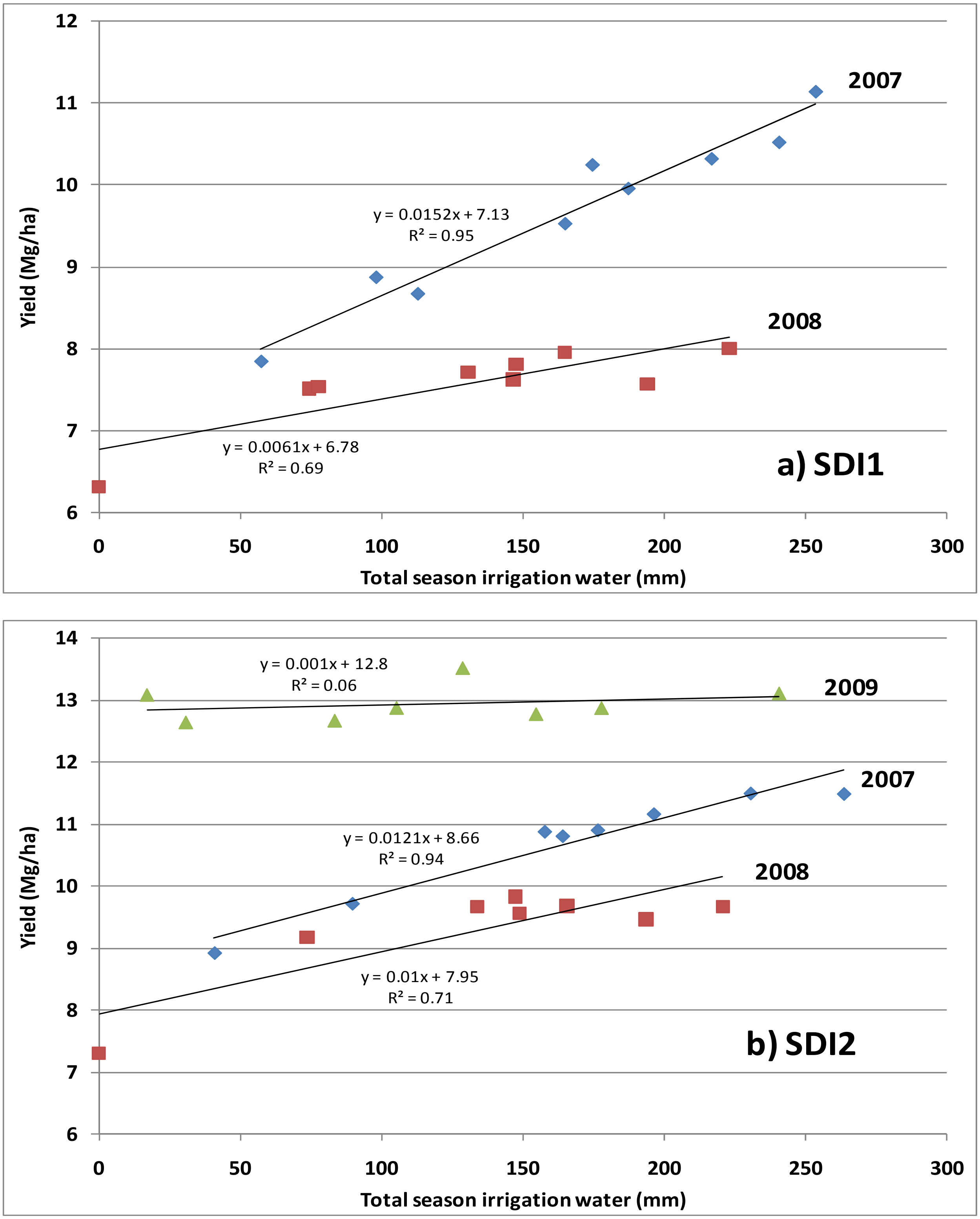

Figure 9. Yield as a function of total season irrigation water for nine irrigation treatments on SDI1 (a) and eight irrigation treatments on SDI2 (b).

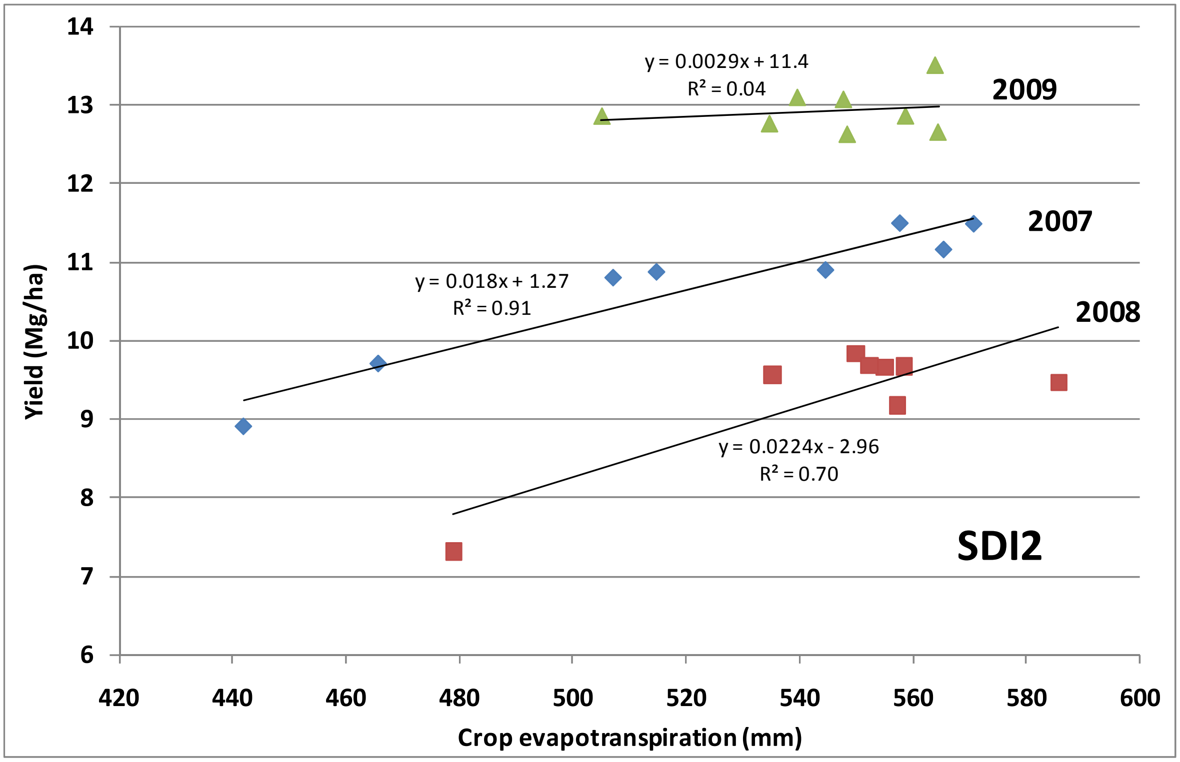

Figure 10. Yield as a function of total season crop evapotranspiration (as calculated in Table 4) for eight irrigation treatments on SDI2.

Table 1. Irrigation treatments on two subsurface drip irrigation systems.

SDI1 treatments

ID	Description of irrigation treatment
DL	Dryland or rainfed (no irrigation)
50	50% ET (meet 50% of evapotranspiration requirements) throughout the growing season
75	As 50, but 75% ET
100	As 50, but 100% ET (full irrigation)
B1	Start with no irrigation, 100% ET during two weeks starting at tasseling, then no more irrigation
B2	Start with 50% ET, 100% ET during two weeks starting at tasseling, then 50% ET
B3	As B2, but three weeks instead of two
B4	As B2, but four weeks instead of two
B5	As B2, but four weeks and 75% ET instead of 50% ET

Nine treatments, eight replications, 72 plots
Plot size: 71.6 m by 9.1 m: 12 rows of corn per plot
Experimental design: Randomized Complete Block
Study conducted in 2007 and 2008
No soil water measurements

SDI2 treatments

ID	Description of irrigation treatment
DL	Dryland or rainfed (no irrigation)
50	50% ET (meet 50% of evapotranspiration requirements) throughout the growing season
75	As 50, but 75% ET
100	As 50, but 100% ET (full irrigation)
125	As 50, but 125% ET (2009 only)
A1	Start with 50% ET, 100% ET during two weeks starting at tasseling, then 50% ET (not in 2009)
A2	As A1, but three weeks instead of two
A3	As A1, but four weeks instead of two
A4	As A1, but four weeks and 75% ET instead of 50% ET

Eight treatments, four replications, 32 plots
Plot size: 38.1 m by 9.1 m: 12 rows of corn per plot
Experimental design: Randomized Complete Block
Study conducted in 2007, 2008, and 2009
Soil water measurements using neutron probe

Table 2. Observed corn growth stages, and planting and harvest dates.

2007	
5/14	Plant corn
5/21	Emergence
7/15	Tasseling
7/31	Fully silked
8/6	Pollination complete, silks brown
8/23	Beginning dent
9/12	Past ¾ milk line, but no black layer yet
10/2	Physiological maturity (black layer)
11/6	Harvest SDI1
11/7	Harvest SDI2
2008	
5/21	Plant corn
6/1	Emergence
7/29	Tasseling
8/6	Pollination starting
8/20	Milk stage (R3)
9/4	Beginning dent
9/24	No black layer yet, close to ½ milk line
10/13	Physiological maturity (black layer)
11/19-20	Harvest SDI2
11/24-25	Harvest SDI1
2009	
5/7	Plant corn
5/20	Emergence
7/24	Tasseling
9/2	Beginning dent
9/28	½ milk line
10/7	No black layer yet
10/10	Physiological maturity (black layer)
12/16-17	Harvest SDI2

Table 3. Corn crop evapotranspiration (ET_c) from High Plains Regional Climate Center station located less than 1 km from the study site.

	2007	2008	2009
Total season ET_c (mm)	617	582	556
Maximum daily ET_c (mm)	10.9	10.7	9.1
# Days ET_c >= 10 mm	6	3	0
# Days ET_c >= 9 mm	10	12	3
# Days ET_c >= 8 mm	28	24	12

Total season ET_c = ET_c between emergence and maturity

Table 4. Water balance components on SDI2 for 2007-2009.

	Trt.	SWC1 mm	SWC2 mm	dSWC mm	Precip. mm	Irr. mm	ET_{begin} mm	ET_{end} mm	ET mm
2007		**July 3**	**Oct. 8**						
	DL	439	297	142	152	41	107	0	442
	50	443	326	117	152	90	107	0	466
	75	439	330	109	152	177	107	0	545
	100	433	385	48	152	264	107	0	571
	A1	468	370	98	152	158	107	0	515
	A2	445	361	84	152	164	107	0	507
	A3	454	344	110	152	196	107	0	565
	A4	438	370	68	152	231	107	0	558
2008		**June 11**	**Oct. 16**						
	DL	527	342	185	286	0	8	0	479
	50	556	366	190	286	74	8	0	557
	75	543	451	92	286	149	8	0	535
	100	530	487	44	286	221	8	0	558
	A1	542	415	127	286	134	8	0	555
	A2	517	409	109	286	147	8	0	550
	A3	548	455	93	286	166	8	0	552
	A4	543	445	98	286	194	8	0	586
2009		**June 26**	**Sept. 2**						
	DL	520	294	225	179	17	60	66	548
	50	528	307	221	179	22	60	66	548
	75	506	346	161	179	93	60	66	559
	100	490	451	39	179	161	60	66	505
	125	542	528	15	179	220	60	66	540
	A2	514	330	185	179	75	60	66	564
	A3	531	393	139	179	120	60	66	564
	A4	520	433	88	179	142	60	66	535

Trt. = irrigation treatment - definitions of irrigation treatments are given in Table 1.
SWC = soil water content in the top 1.83 m
SWC1 = SWC on date indicated (first soil water measurement of the season)
SWC2 = SWC on date indicated (last soil water measurement of the season)
dSWC = SWC1 – SWC2
Precip. = precipitation between first and last soil water measurement of the season
Irr. = irrigation between first and last soil water measurement of the season
ET_{begin} = ET from emergence to date of first soil water measurement of the season, from HPRCC
ET_{end} = ET from last soil water measurement of the season to maturity, from HPRCC
HPRCC = High Plains Regional Climate Center
ET = estimated ET between emergence and maturity: ET = dSWC + Precip. + Irr. + ET_{begin} + ET_{end}
The ET calculation assumes that runoff and deep percolation of water below 1.83 m were insignificant.

Table 5. Mean yields (Mg ha^{-1}) for 2007-2009 on SDI1 and SDI2.

	SDI1			
Trt.	**2007**		**2008**	
DL	7.8	a	6.3	a
50	8.9	b	7.5	b
75	10.2	c	7.6	b
100	11.1	d	8.0	b
B1	8.7	b	7.5	b
B2	9.5	e	7.7	b
B3	10.0	ce	7.8	b
B4	10.3	c	8.0	b
B5	10.5	c	7.6	b

			SDI2			
Trt.	**2007**		**2008**		**2009**	
DL	8.9	a	7.3	a	13.1	a
50	9.7	b	9.2	b	12.6	a
75	10.9	c	9.6	b	12.9	a
100	11.5	d	9.7	b	12.9	a
125	-		-		13.1	a
A1	10.9	c	9.7	b	-	
A2	10.8	c	9.8	b	12.7	a
A3	11.2	cd	9.7	b	13.5	a
A4	11.5	d	9.5	b	12.8	a

Trt. = irrigation treatment - definitions of irrigation treatments are given in Table 1.
The same letters behind yield values indicates no statistically significant difference at the 0.05 level.