Near-surface soil water and temperature for SDI, LEPA, and spray irrigation[1]

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Abstract

Near-surface soil temperatures and volumetric soil water contents were compared for SDI, LEPA, and spray irrigation in a Pullman clay loam soil planted in cotton. Soil temperatures were measured by type-T thermocouples and volumetric water contents were measured by time domain reflectometry (TDR) installed in the center and sides of raised beds at 5-, 10-, and 15-cm depths. Irrigation was applied in alternate furrows, resulting in beds having an irrigated (wet) side and non-irrigated (dry) side. Greater soil temperatures were found in SDI compared with all other irrigation methods. Reduced soil temperatures were found on the wet side of LEPA beds compared with other methods. Volumetric soil water contents were compared following four irrigation events during July. Smaller bed-averaged soil water contents were found in SDI beds compared with other methods. Soil water variability within a bed was greater for SDI than for other methods.

Introduction

Subsurface drip irrigation (SDI) is being increasingly adopted by producers in the Texas High Plains, notably in the cotton producing area around Lubbock. There is a general premise that use of SDI results in greater crop yields, greater water use efficiency, better cotton fiber quality, and enhanced crop earliness compared with typical sprinkler packages used on center pivot irrigation machines (i.e., spray applicators or Low Energy Precision Applicators [LEPA]), which is partially supported by earlier studies of Segarra et al. (1999), Bordovsky and Porter (2003), and Colaizzi et al. (2005). This is thought to be related to reduced evaporative cooling and warmer soil temperatures during crop establishment. For some producers, these factors have justified the much greater cost and management requirements inherent in SDI, as well as the potential difficulties in crop germination for most High Plains soils if precipitation was inadequate prior to planting (Howell et al., 1997; Bordovsky and Porter, 2003; Enciso et al., 2005). New SDI installations in the Texas High Plains have been estimated at around 100,000 ha since 2000 (*J. Bordovsky, pers. communication*) in a region having approximately 1.86 million ha of irrigated area (TWDB, 2001). Continued SDI adoption is anticipated in

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response to intensifying drought, declining water resources, and greater energy costs to pump irrigation water. The northward expansion of cotton into areas where corn was traditionally produced (i.e., the Northern Texas Panhandle and Southwestern Kansas; USDA-NASS, 2005) may also stimulate SDI adoption if: i) warmer soil temperatures do result from use of SDI, ii) warmer temperatures do reduce the greater risk associated with cotton production in thermally limited environments (Esparza et al., 2006), and iii) alternative SDI designs do mitigate difficulties with crop germination (Colaizzi et al., 2006).

The objectives of this study were to compare near-surface soil temperature and volumetric water content under spray, LEPA, and SDI methods applied to raised beds planted with cotton in the thermally-limited climate of the Northern Texas High Plains. The 2006 cotton season was still underway when this report was produced; therefore, final lint yield and fiber quality data have yet to be obtained. Only crop emergence and total reproductive squares will be reported herein, in addition to soil temperatures (in terms of cumulative soil heat units) and volumetric water contents.

Procedure

The experiment was conducted in 2006 at the USDA Agricultural Research Service Conservation and Production Research Laboratory at Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 1070 m elevation above MSL). The climate is semi-arid with evaporative demand of about 2,600 mm per year (Class A pan evaporation) and precipitation averaging 470 mm per year. Most of the evaporative demand and precipitation occur during the growing season (May to October) and average 1,550 mm and 320 mm, respectively. The climate is also characterized by strong regional advection from the south and southwest, with average daily wind runs at 2 m height exceeding 460 km, especially during the early part of the growing season. The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2005), with slow permeability due to a dense B21t horizon that is 0.15- to 0.50-m below the surface. A calcic horizon begins at approximately 1.2 m below the surface.

Agronomic practices were similar to those practiced for high lint yield in the High Plains region of Texas. Cotton (*Gossypium hirsutum* L., Paymaster[3] 2280 BG RR) was planted on 17 May 2006 at 20 plants m^{-2} on east-west oriented raised beds spaced at 0.76 m. Furrow dikes were installed in the irrigated field after crop establishment to control runoff. Preplant fertilizer containing nitrogen (N) and phosphorous (P) (11-52-0) was applied at 18 and 83 kg ha^{-1}, respectively, based on a soil fertility analysis. Additional N (32-0-0) was injected into the irrigation water, resulting in 34 kg ha^{-1} prior to planting, and 45 kg ha^{-1} from first square to early bloom for full irrigation (deficit irrigation rates received proportionately less N in irrigation water). Treflan was applied at one time before planting at 2.3 L ha^{-1} to control broadleaf weeds.

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[3] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

The experimental design consisted of four irrigation methods (MESA, LESA, LEPA, SDI, described in more detail shortly), and five irrigation rates (I_0, I_{25}, I_{50}, I_{75}, and I_{100}). The I_{100} rate was sufficient to prevent yield-limiting soil water deficits from developing, and the subscripts are the percentage of irrigation applied relative to the full (I_{100}) irrigation rate. The I_{100} rate was based on soil water content determined using the neutron probe (NP) to the 2.4-m depth. Early in the season, irrigation water was applied when soil water contents indicated a deficit of 25 mm below field capacity in the I_{100} treatment. From first square to termination of irrigations, the appropriate irrigation amount was applied on a weekly basis. The statistical design was a variant of the split-block design (Little and Hills, 1978), where irrigation methods were in the direction of travel of a three-span lateral move irrigation system, and irrigation rates were perpendicular to the direction of travel. This sacrificed the power of comparing different irrigation rates, but was necessary to facilitate operation of the lateral-move system using applicators common in the Southern High Plains. Each span of the linear move system constituted a complete block (i.e., replicated three times), and irrigation methods were randomized within each block.

Mid-elevation spray application (MESA), low-elevation spray application (LESA), and low energy precision application (LEPA) irrigations were applied with a hose-fed Valmont (Valmont Irrigation, Valley, NE) Model 6000 lateral move irrigation system. Drop hoses were located over every other furrow at 1.52-m spacing. Applicators were manufactured by Senninger (Senninger Irrigation Inc., Orlando, FL) and were equipped with 69-kPa pressure regulators and #17 plastic nozzles, giving a flow rate of 0.41 L s^{-1}. The MESA and LESA spray heads were positioned 1.5 and 0.3 m above the furrow, respectively. A double-ended drag sock (A. E. Quest and Sons, Lubbock, TX) was used for LEPA irrigations. The subsurface drip irrigation (SDI) system consisted of Netafim Typhoon dripline (Netafim USA, Fresno, CA) that was shank injected in 1999 under alternate furrows at a 0.3 m depth below the surface (before bedding). Irrigation treatment levels were controlled by varying the speed of the lateral-move system for the spray and LEPA methods, and by different emitter flow and spacing for the SDI method. Additional details on irrigation equipment are provided in Colaizzi et al. (2004).

Soil temperature and volumetric soil water content were determined in the planted beds under the MESA, LESA, LEPA, and SDI irrigation methods at the I_{50} and I_{100} irrigation rates (eight plots) by arrays of type-T thermocouples and time domain reflectometry (TDR) probes. The thermocouples and TDR probes were placed on each side and in the center of each bed at 5-, 10-, and 15-cm depths (Fig. 1). (The thermocouple at the 15-cm center was omitted due to a limited number of double-ended channels in multiplexers). Each bed array was replicated three times in each plot, for a total of 24 instrumented beds, 192 thermocouples, and 216 TDR probes. The thermocouples were connected to multiplexers (model AM25T, Campbell Scientific, Inc., Logan, UT), which were controlled by two data loggers (model 21x, Campbell Scientific, Inc., Logan, UT) that recorded thermocouple readings every hour. The TDR system consisted of 20-cm long trifilar probes connected to coaxial multiplexers (Evett, 1998), a cable tester (model 1502C, Tektronix, Inc., Redmond, OR), and an embedded computer running the TACQ supervisory TDR system control and data acquisition program (Evett, 2000a; 2000b). The TDR waveforms were recorded every 2 h. The TACQ program determined bulk electrical conductivity and effective frequency from the recorded waveforms and used these data in a water content calibration equation that practically eliminates temperature effects at greater water contents (Evett et al., 2005). The TDR system accuracy (root mean squared error of calibration) is < 0.01 m^3 m^{-3} in all three main horizons of the Pullman soil (Evett et al., 2006).

Soil temperatures were used to compute cumulative soil heat units (CSHU) (measured soil temperature minus the base temperature of 15.6 °C) for each location within a bed (i.e., wet side at 5 cm, etc.). The effect of irrigation method (MESA, LESA, LEPA, or SDI) on CSHU at each bed location was tested for differences using the SAS mixed model (PROC MIXED, Littell et al., 2006). Values of CSHU considered were on June 2 (16 days after planting, when crop emergence was recorded) and on August 20 (95 days after planting). In PROC MIXED, fixed and random effects are specified separately. Fixed effects were irrigation method, bed location, and irrigation method by bed location; the random effect was the bed replicate. The fixed effect "irrigation method by bed location" was tested for differences using least square means ($\alpha \leq 0.05$), with "bed location" as the slice parameter, by each irrigation rate (i.e., I_{50} and I_{100}).

Volumetric water contents from the TDR system were analyzed in a similar manner; however, only measurements following the four irrigation events in July were used in the present analysis, and these were the averages of the three measurements at 2, 4, and 6 h following each irrigation event (Fig. 2). Each measurement average following an irrigation event was specified as a repeated class in PROC MIXED. The TDR waveforms recorded earlier in the season often exhibited weak second reflections possibly due to high bulk densities, leading to errors in computing travel times, and require manual reinterpretation. Future analyses will consider continuous soil water dynamics to investigate relationships with soil temperature. Crop emergence on June 2 and reproductive squares (first and second position) on August 11 were also tested for differences between irrigation methods for irrigation rates (I_{25}, I_{50}, I_{75}, I_{100}) in a similar manner with PROC MIXED (see Colaizzi et al., 2004 for specific details).

Results and Discussion

The period from September 2005 to May 2006 was the driest on record at our location, with only 45 mm of precipitation. In 2006, only three rainfall events were recorded near the experimental site prior to planting (May 17); these were 3 mm, 2 mm, and 12 mm on March 20, April 23, and May 7, respectively. Consequently, 50 mm of preplant irrigation was applied in two 25 mm applications on May 1 and 4 to ensure adequate soil water during peak water use later in the season. A total of 198 mm of rainfall occurred during the 91 days considered in the present study (May 17 to August 16, Fig. 2). Most rainfall occurred during late June, early July, and mid-August, well after crop establishment. A total of 356 mm and 178 mm of in-season irrigation was applied to the I_{100} and I_{50} rates, respectively. These irrigation amounts will be the final seasonal totals because over 200 mm of rainfall occurred August 17-31.

Crop emergence was recorded on June 2 (DOY 153, 16 days after planting), and the effect of irrigation method within an irrigation rate was tested for differences using least squared means ($\alpha \leq 0.05$) in PROC MIXED. There were some significant differences between irrigation methods within an irrigation rate; however, these differences were not consistent from one rate to the next, and irrigation rate was not a significant covariate (Fig. 3). This result was unexpected because, in the absence of sufficient preplant or early season rainfall, SDI is well-known to have serious limitations in germinating a crop in the Pullman soil when laterals are installed in alternate furrows (Colaizzi et al., 2006). For now, we hypothesize that the influences of both irrigation rate and method on crop emergence were masked by preseason irrigation (50 mm) several weeks before planting, and perhaps a 6 mm rainfall event on May 25. This hypothesis will be tested after time domain reflectometry (TDR) waveforms during this period (May 17 to June 2) are reinterpreted. Observed crop emergence patterns may have also been confounded by soil temperatures (as influenced by soil water distribution), which are discussed next.

Cumulative soil heat units (CSHU, 15.6 °C base temperature) were computed beginning at the planting date (17 May) using temperatures determined at each location within a bed, and analyzed when crop emergence was recorded (June 2, 16 days after planting) and analyzed again on August 20, 2006 (95 days after planting). By June 2, CSHU did not vary a great deal for the I_{50} (Fig. 4) or I_{100} (Fig. 5) irrigation rates, with the exception of LEPA, for which CSHU tended to increase from the wet (irrigated) to the dry (non-irrigated) side. This may have resulted from greater conductive and evaporative cooling in and adjacent to the furrow irrigated with LEPA. Another exception was LESA (I_{100} rate only, Fig. 5), for which CSHU was less at all bed positions than it was for other irrigation methods (except for LEPA on the wet side of the bed). This also could have resulted from greater conductive and evaporative cooling distributed uniformly across the bed and furrows. As expected, CSHU decreased with depth for all irrigation methods due to attenuation of diurnal soil temperature amplitude. Crop emergence (Fig. 3) did not appear to be related to CSHU for the I_{50} rate (Fig. 4), but emergence did appear inversely related to CSHU on the wet side of the bed for the I_{100} rate (Fig. 5).

By August 20 (95 days after planting), the crop was past peak bloom and bolls were forming in both the first and second position. For the I_{50} (Fig. 6) and I_{100} (Fig. 7) irrigation rates, SDI resulted in greater CSHU than all other methods at all bed locations, and differences were often significant. Similar to the results of June 2, CSHU by August 20 tended to increase for LEPA (and to a lesser extend SDI) from the wet to the dry side of the bed; and for LESA (I_{100} rate only, Fig. 7) CHSU was less than for other methods at most bed locations.

Volumetric soil water was measured using time domain reflectometry (TDR) at the same bed locations as soil temperature (plus the center of the bed at 15 cm). The effect of irrigation method at each bed location was tested for differences following four irrigation events in July. The greatest variation in soil water content occurred for SDI in both the I_{50} (Fig. 8) and I_{100} (Fig. 9) irrigation rates, ranging from 0.058 $m^3 m^{-3}$ at I_{50}, 5 cm, dry side (Fig. 9a) to 0.351 $m^3 m^{-3}$ at I_{100}, 15 cm, wet side, although MESA and LESA contents were nearly identical at this bed location (Fig. 9c). Water contents for LEPA (and to a lesser extent SDI) generally increased with proximity to the wetted furrow; however, dry side LEPA and SDI water contents were greater than those in the center of the bed at the 10- and 15-cm depths for the I_{100} rate. When soil water contents were averaged for the entire bed, water contents for MESA and LEPA were significantly greater than those for LESA and SDI at the I_{50} rate; but water contents for MESA and LESA were significantly greater than those for LEPA and SDI at the I_{100} rate (Fig. 10). These results were likely related to the method of water application, but could have also been related differences in root water uptake as influenced by soil temperatures. The interaction between wetting patterns, root water uptake, and soil temperatures will be investigated further after TDR waveforms are reinterpreted for the entire season.

On August 11 (DOY 223, 86 days after planting), first and second position squares were slightly greater in number for LEPA and SDI compared with MESA and LESA in both the I_{50} and I_{100} irrigation rates (Fig. 11). For the I_{100} rate, differences in CSHU between MESA and LESA (Fig. 7) did not appear to influence square formation (Fig. 11). It is presently uncertain to what extent the crop will mature because significant rainfall (200 mm) and cool temperatures have persisted during the latter part of August, in stark contrast to the previous eleven months, which were characterized by extreme drought and above average temperatures.

Conclusions

Application of irrigation by SDI resulted in greater soil temperatures than those for all other methods. Soil temperatures associated with LEPA irrigation were less than those for other methods on the irrigated (wet) side of the bed, but similar to or greater than those for MESA or LESA on the non-irrigated (dry) side of the bed. Irrigation using LESA resulted in cooler soil temperatures than all other methods for the I_{100} rate, but was similar to temperatures for MESA at the I_{50} rate. In July, at the I_{50} rate, MESA and LEPA resulted in greater bed-averaged soil water contents than did LESA and SDI, whereas at the I_{100} rate, MESA and LESA resulted in greater soil water contents than did LEPA and SDI. Soil water variability within a bed was greater for SDI than for other methods. Future analyses will include soil water dynamics between wetting events to quantify water uptake and relationships with soil temperatures; and soil water contents early in the season will be analyzed to quantify the effect of irrigation method and irrigation rate on crop emergence.

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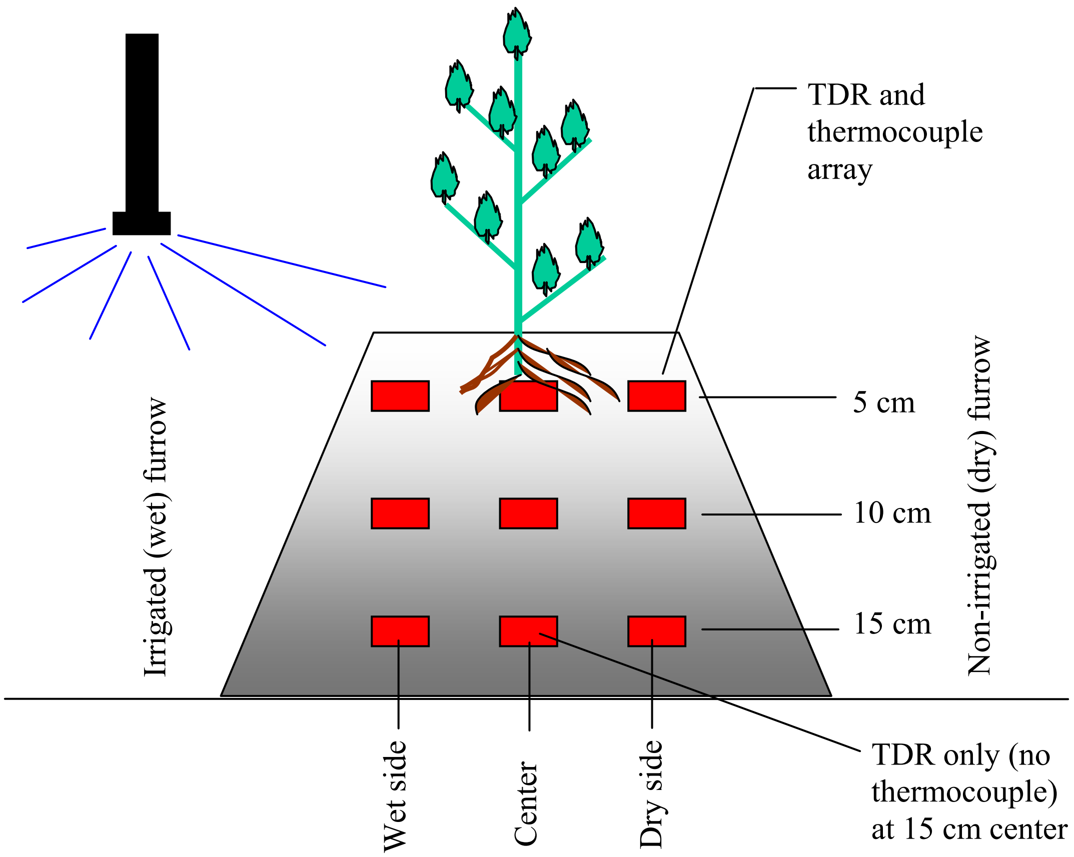


Figure 1. Installation of nine time-domain reflectometry (TDR) probes and eight thermocouples in a raised bed planted in cotton.

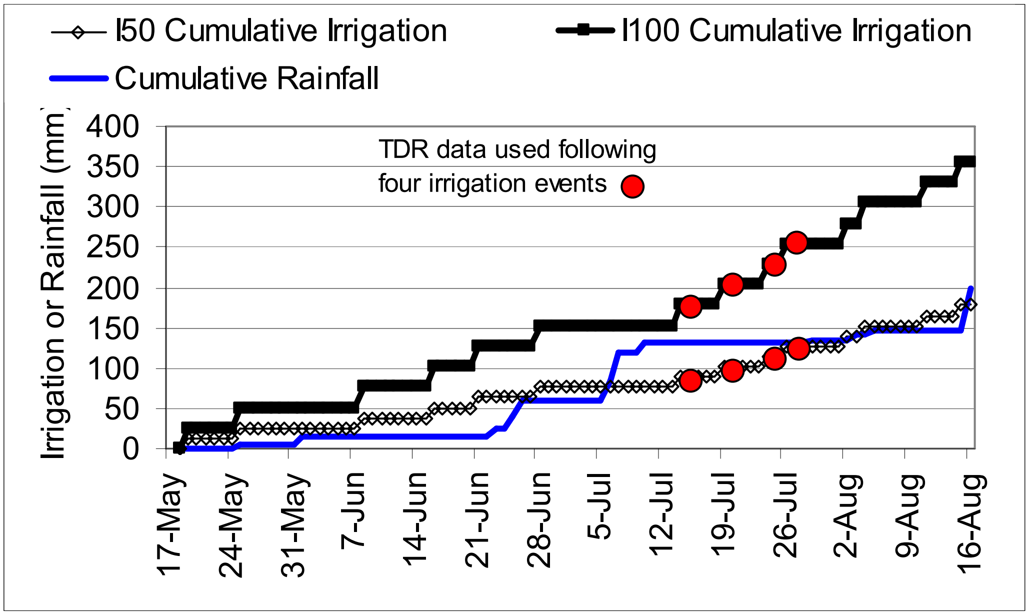


Figure 2. Cumulative irrigation and rainfall through August 16, 2006, and dates of soil water measurement (using TDR) following four irrigation events.

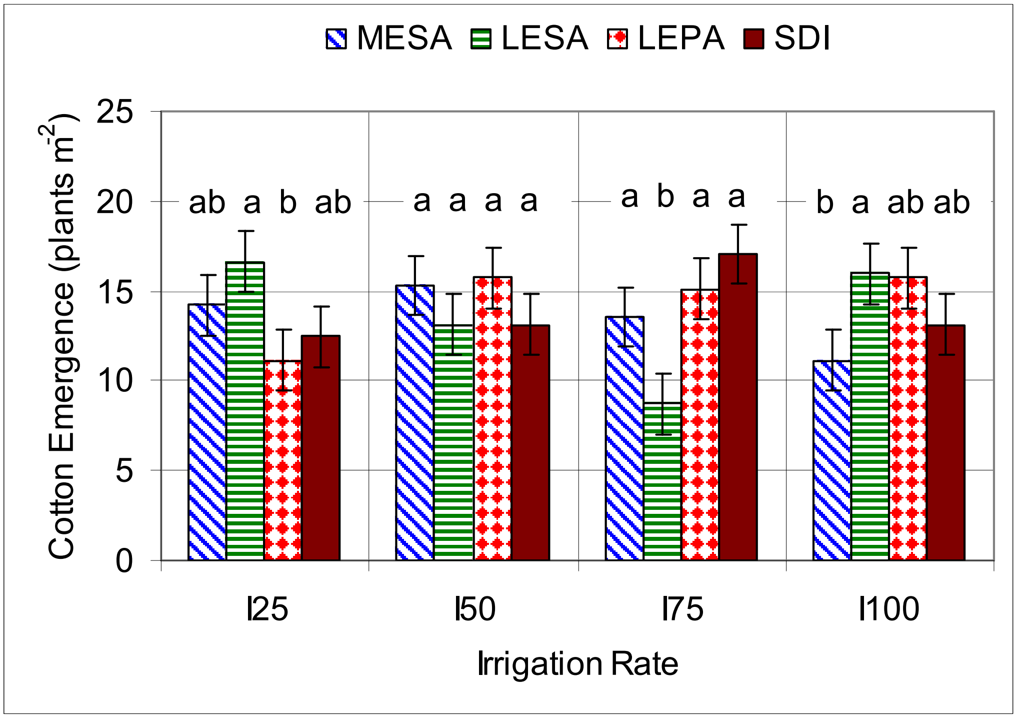
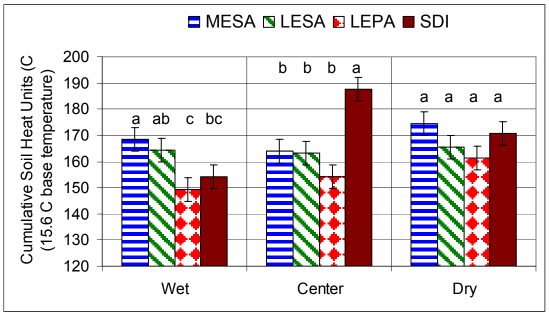
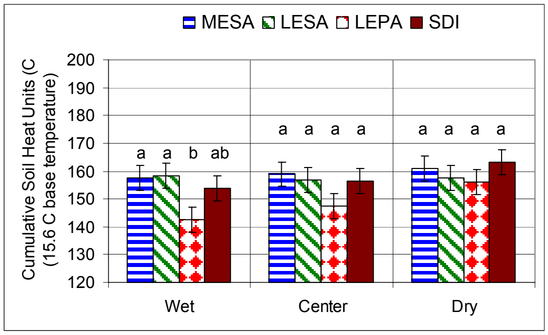


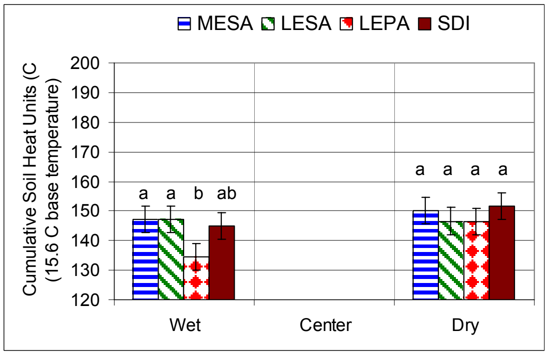
Figure 3. Cotton emergence by June 2, 2006 (DOY 153; 16 days after planting). Columns with the same letter within an irrigation rate are not significantly different ($\alpha \leq 0.05$).



a) 5 cm depth

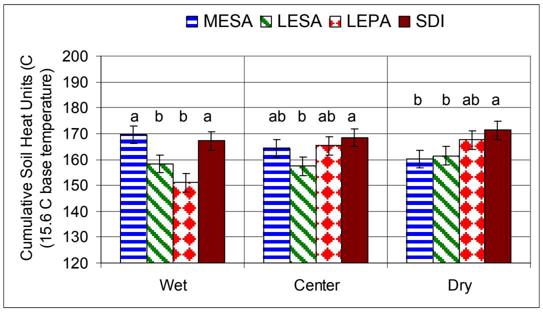


b) 10 cm depth

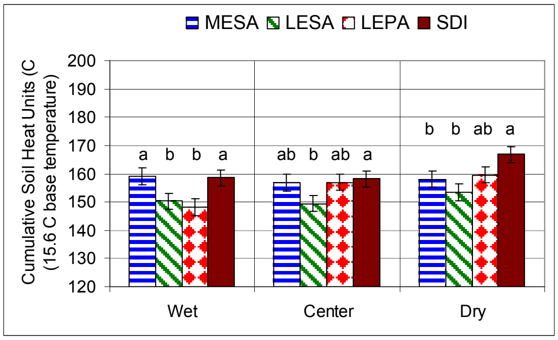


c) 15 cm depth

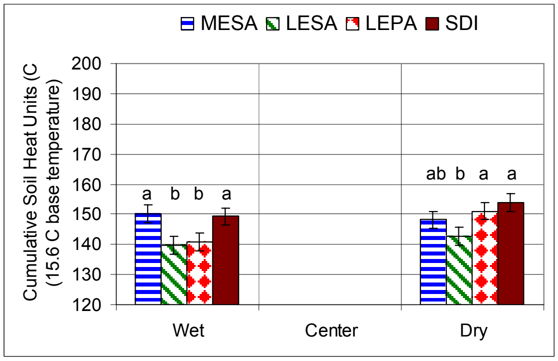
Figure 4. Soil heat units through June 2, 2006 (DOY 153; 16 days after planting) for the I_{50} irrigation rate. Columns with the same letter within a bed position (wet, center, or dry) are not significantly different ($\alpha \leq 0.05$).



a) 5 cm depth

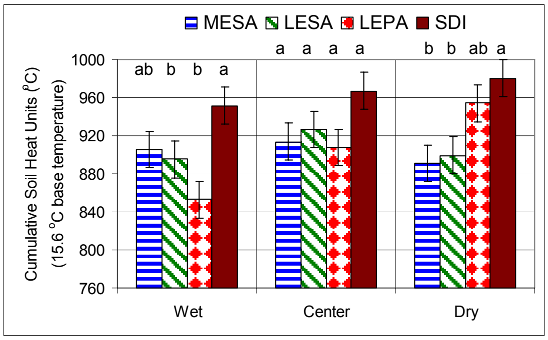


b) 10 cm depth

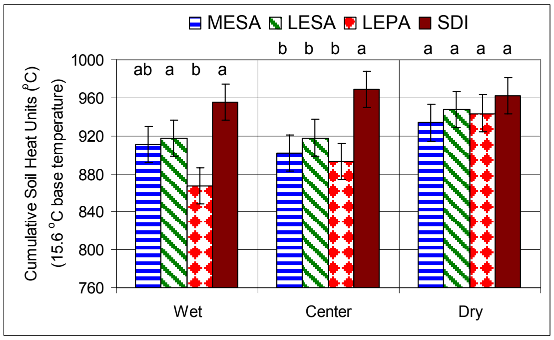


c) 15 cm depth

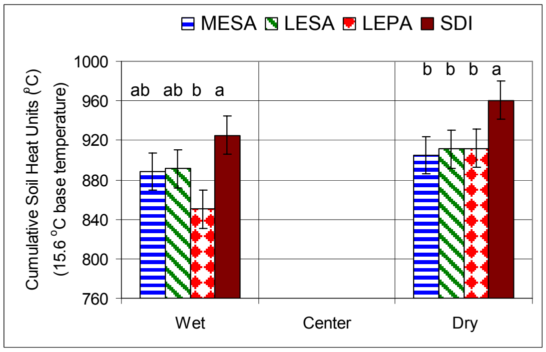
Figure 5. Soil heat units through June 2, 2006 (DOY 153; 16 days after planting) for the I_{100} irrigation rate. Columns with the same letter within a bed position (wet, center, or dry) are not significantly different ($\alpha \leq 0.05$).



a) 5 cm depth

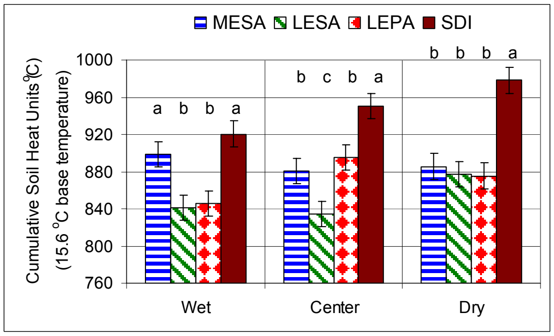


b) 10 cm depth

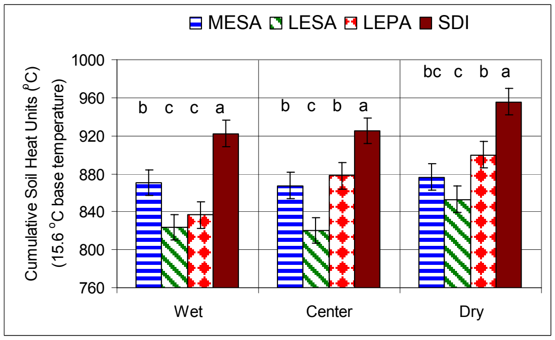


c) 15 cm depth

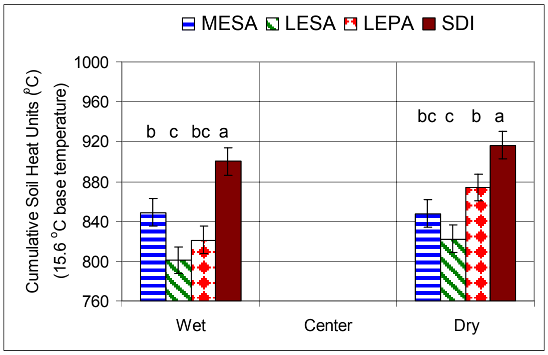
Figure 6. Soil heat units through August 20, 2006 (DOY 232; 95 days after planting) for the I_{50} irrigation rate. Columns with the same letter within a bed position (wet, center, or dry) are not significantly different (α ≤ 0.05).



a) 5 cm depth

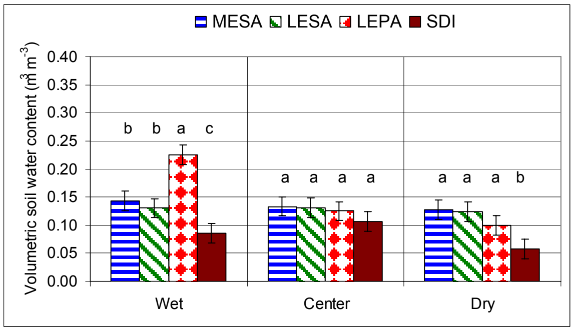


b) 10 cm depth

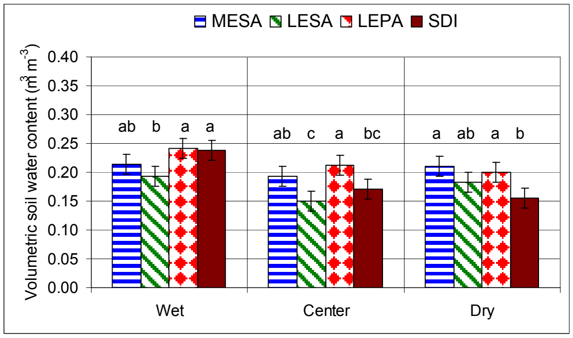


c) 15 cm depth

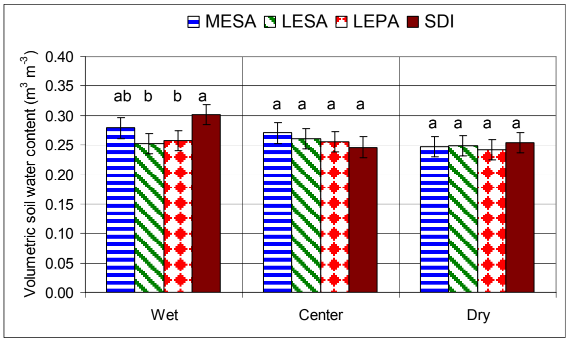
Figure 7. Soil heat units through August 20, 2006 (DOY 232; 95 days after planting) for the I_{100} irrigation rate. Columns with the same letter within a bed position (wet, center, or dry) are not significantly different (α ≤ 0.05).



a) 5 cm depth

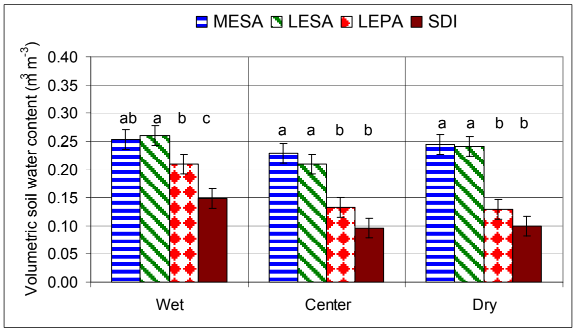


b) 10 cm depth

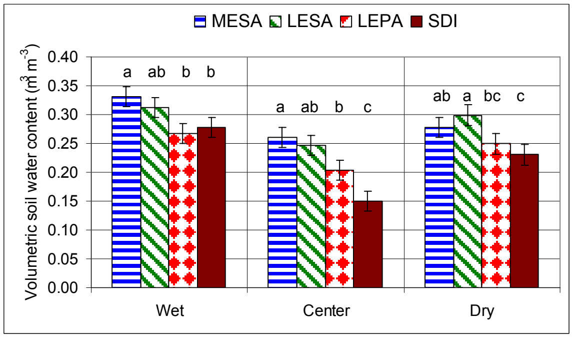


c) 15 cm depth

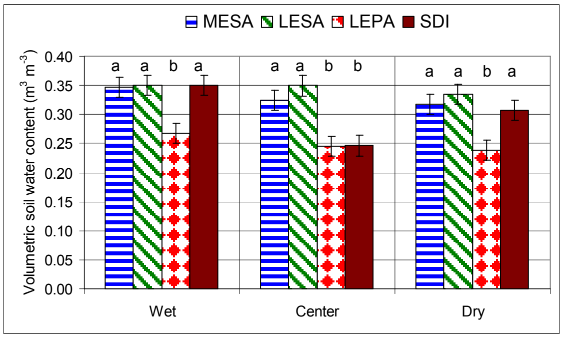
Figure 8. Volumetric water content (using TDR) after four irrigation events in July 2006 for the I_{50} irrigation rate. Columns with the same letter within a bed position (wet, center, or dry) are not significantly different ($\alpha \leq 0.05$).



a) 5 cm depth



b) 10 cm depth



c) 15 cm depth

Figure 9. Volumetric water content (using TDR) after four irrigation events in July 2006 for the I_{100} irrigation rate. Columns with the same letter within a bed position (wet, center, or dry) are not significantly different ($\alpha \leq 0.05$).

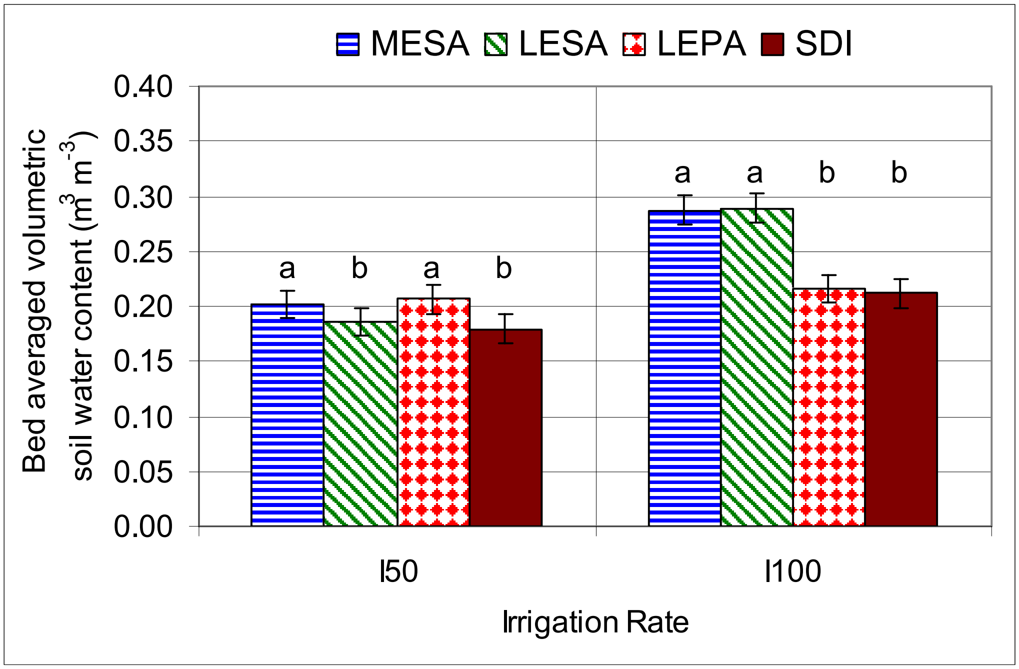


Figure 10. Volumetric water content (using TDR) after four irrigation events in July 2006 averaged for the entire bed.

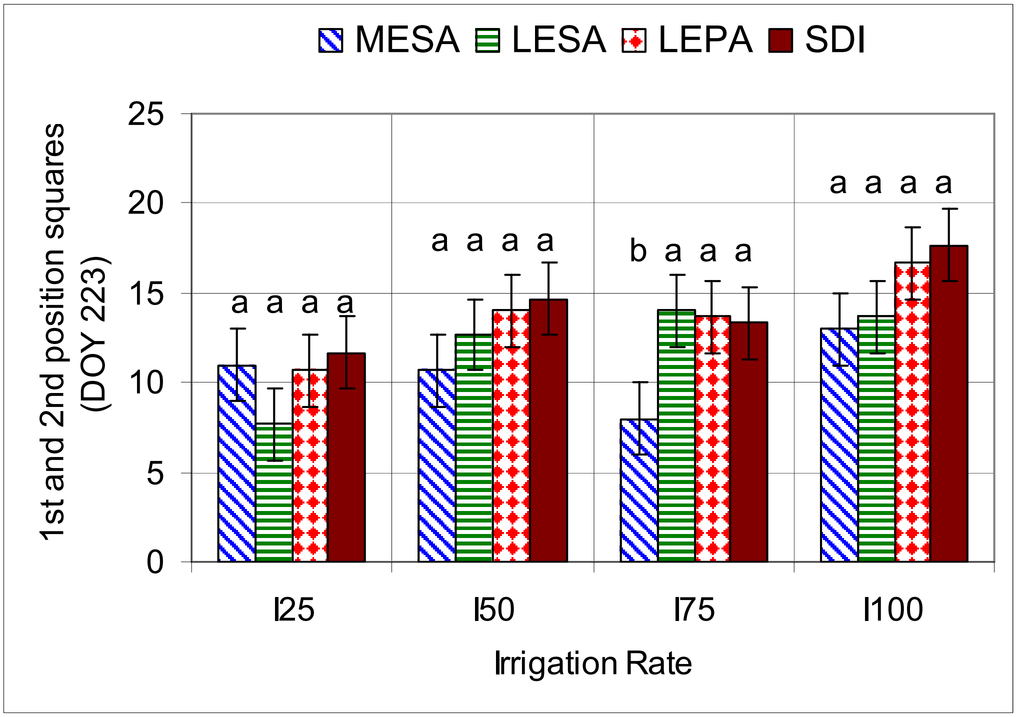


Figure 11. First and second position squares for each irrigation rate and method on August 11, 2006 (DOY 223, 86 days after planting).