Sunflower water productivity in four Great Plains soils

Judy A. Tolk *, Terry A. Howell

USDA Agricultural Research Service, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012, United States

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ABSTRACT

Sunflower (Helianthus annuus L.) is a drought-adapted crop whose short growing season reduces irrigation requirements which makes it ideal for regions with limited irrigation water supplies. Our objectives were to (a) evaluate the yield (Y) potential of sunflower under full and deficit irrigation (IR), (b) determine if water productivity (WP) and irrigation water productivity (IWP) of sunflower were affected by soil textural class differences and (c) compare the WP relationship to a benchmark maximum productivity relationship for consideration of limitations to crop yield in a semiarid environment. Sunflower was grown in 2008 and 2009 in 48 weighing lysimeters under an automated rain shelter containing soil monoliths of four regional soils—clay loam, silt loam, sandy loam or fine sand (12 each)—at Bushland, TX, USA, a semiarid region of the southern Great Plains. Irrigation treatments were 25%, 50%, 75% and 100% replacement of evapotranspiration. The regression of IR:Y for all soil textural classes showed that irrigation increased yield by 0.47 g m⁻² mm⁻¹ in 2008 and 0.51 g m⁻² mm⁻¹ in 2009. Averaged across irrigation treatments, the WP of the crops in the fine sand (0.54 kg m⁻³) was larger than that of the crops in the silt loam (0.46 kg m⁻³) and clay loam (0.44 kg m⁻³). The IWP of the crops in the fine sand (1.0 kg m⁻³) and the silt loam (0.96 kg m⁻³) were significantly larger than the IWP of the crops in the clay loam (0.72 kg m⁻³). Yields were as much as 30% lower at full irrigation levels compared with benchmark maximum yields. Probable limitations to increased yield include high evaporative deficits and soil water evaporation. Although sunflower may be a drought-adapted crop, maximum yields may be difficult to achieve due to the climatic conditions in the southern Great Plains.

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1. Introduction

Irrigation well capacities are declining in the Ogallala Aquifer region of the Great Plains. Sunflower (Helianthus annuus L.) is a deep-rooted crop that has been shown to deplete more available soil water and to greater depths compared with crops such as grain sorghum [Sorghum bicolor Moench (L.)] and soybean (Glycine max L.) (Jones, 1984; Bremmer et al., 1986; Cabelguenne and Debauve, 1998; Stone et al., 2002). This makes sunflower more tolerant of short periods of water stress. The relatively shorter growing season compared with other crops grown in the region also reduces its irrigation needs which makes it a potential crop for regions with limited irrigation water supplies (Lamm et al., 2011). Sunflower is one of the most important oil crops in the world (Škorič, 1992), with the major production in the US located in the northern Great Plains where sunflower is grown under rainfed conditions (Schneider, 1992). Of the more than 600,000 ha harvested in the USA in 2010, about 480,200 ha were harvested in Kansas, North Dakota, and South Dakota with an average seed yield of 1635 kg ha⁻¹ (NASS, 2011). Irrigation of sunflower in semiarid areas has been shown to increase seed yields by 78% in Turkey (Göksoy et al., 2004), 33% in Lebanon (Karam et al., 2007), 47% in Kansas, USA (Stone et al., 1996), and 92% in Texas, USA (Unger, 1982) compared with non-irrigated sunflower crops. Irrigation of sunflower in the USA is not a common practice, however, with only about 2200 ha of irrigated oil sunflower reported harvested each year in 2002 and 2007 in Texas (NASS, 2011).

Deficit irrigation (DI), defined as the application of water below full crop-water requirements (evapotranspiration, or ET), is an important tool for reducing irrigation water use (Fereres and Soriano, 2007). With limited water supplies, a common practice is for the producer to irrigate continuously. Based on many factors such as well capacities, atmospheric demand, precipitation, and stored soil water, water stress can occur at any growth stage. The ratios of economic yield:ET (Y:ET), or water productivity (WP), and Y:applied irrigation water (Y:IR), or irrigation water productivity (IWP), help evaluate the productivity of water in agricultural systems which can be useful in evaluating DI strategies. One difficulty with DI, especially in semiarid climates, is that there can be insufficient stored soil water to substitute for reduced irrigation, and yields are reduced. Soil hydraulic properties can further reduce sunflower water productivity. Katerji and Mastrorilli (2009)
reported a 37% reduction in sunflower seed yield and a 25% reduction in WP for crops grown in a clay soil compared with those grown in a loamy soil.

Few studies (Katerji and Mastrorilli, 2009) have compared sunflower water productivity grown with a range of irrigation levels in multiple soil textural classes in a uniform environment so that the impact of irrigation and soil hydraulic characteristics on water productivity could be examined. Our objectives were to (a) evaluate the yield potential of sunflower under full and deficit irrigation, (b) determine if WP and IWP of sunflower were affected by soil textural class differences and (c) compare the WP relationship to a benchmark maximum productivity relationship for consideration of limitations to crop yield in a semiarid environment.

2. Materials and methods

2.1. Site

The experiment was conducted at the Soil–Plant–Environment Research (SPER) facility, USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX, USA (35° 11’N, 102° 06’W, 1170 m elevation above mean sea level). The SPER facility was located in a 0.25–ha field with a rain shelter facility in which there were 48 weighing lysimeters containing four different soil series. The lysimeters were 1.0 m by 0.75 m, and 2.4–m deep and contained monolithic cores to about a 2.3–m depth with a vacuum drainage system in the bottom. The lysimeters were arranged in two pits, with each pit containing two side-by-side rows of 12 lysimeters each. Soil series were randomly located within each pit. There were 12 lysimeters of each soil series. The lysimeters were surrounded by a similarly cropped area. The rain shelter was a metal building 13 by 18 m by 3.7-m high, with a control system that automatically initiated building movement over the lysimeters when about 1 mm of rain was detected. Complete details concerning the monolithic core collection techniques and SPER facility can be found in Schneider et al. (1993) and Tolk et al. (2005).

The lysimeter mass was measured using deck scales (DS3040-10K, Weigh-Tronix,1 Fairmont, MN). The deck scales were excited and measured by a data acquisition system (CR-7X, Campbell Scientific, Inc., Logan, UT). Lysimeter scale mass data were acquired on a 0.1-Hz sampling interval and composited into 30-min means for output. The deck scales were calibrated after installation, and the calibration checked yearly prior to the cropping season. Calibration results were reported in water depth equivalency (mm), with 0.75 kg of mass representing 1 mm water depth equivalence based on a water density of 1.0 Mg m⁻³. A typical root mean squared error (RMSE) of the calibration was 0.09 mm. Complete calibration procedures can be found in Tolk et al. (2005). The 30-min output of the deck scales was used to measure any gain in mass due to water infiltration such as irrigation or precipitation and loss of mass due to drainage or ET. The lysimeters were drained periodically using a vacuum pump attached to the drainage system on each lysimeter. Daily ET was calculated as the change in soil water storage calculated from the difference in lysimeter mass recorded at midnight of consecutive days, plus any water added as precipitation and irrigation and minus any drainage during that period.

During the experiments, the lysimeter area was surrounded by similarly cropped sunflower for about 30–35 m in the prevailing S-SW wind direction. About 450 m of dryland cotton in 2008 and a fallow field in 2009 was south of the SPER facility. In the upwind

fetch, there was a heterogeneous landscape of grassland and irrigated and dryland cropland.

2.2. Climate

The climate at Bushland is typical of the semiarid High Plains, which has a high annual evaporative demand of ~2600 mm (based on Class A pan evaporation) and precipitation averaging about 470 mm. About 70% (350 mm) of the precipitation occurs from May to September when evaporative potential averages ~1520 mm. Wind direction is predominately from the south-southwest. Meteorological measurements at 2-m of air temperature, relative humidity, wind speed, and solar radiation were collected at a weather station with irrigated, cool season grass located about 500 m to the SE of the SPER facility. The type of weather instrumentation was described fully in Dusek et al. (1987). Calculation of Penman–Monteith grass reference ET (ET₀) followed procedures outlined in Allen et al. (2005). Vapor pressure deficit was calculated as the difference between actual and saturation vapor pressure, with saturation vapor pressure calculated using Allen et al. (2005). Dew point temperature was calculated from Murray’s (1967) dew point temperature equation which used measured air temperature and relative humidity.

2.3. Agronomy

The lysimeters were planted with sunflower (“845HO”, Triumph Seed Co., Ralls, TX) in 2008 and 2009 at a density of 5.3 plants m⁻² in a single row down the center of each lysimeter, which maintained a 0.75-m row spacing with the adjacent lysimeters and surrounding similarly cropped area of the SPER facility. The crop was planted on Day of Year (DOY) 178 (26 June) and harvested on DOY 282 (8 October) in 2008. It was planted on DOY 167 (16 June) and harvested on DOY 251 (8 September) in 2009. The lysimeters were fertilized according to recommendations based on soil analyses prior to planting for each soil. Plant nutrients were applied in broad bands on either side of the plant row. Tillage was done by hand to a depth of about 0.2 m. The sunflower in the lysimeters was hand-harvested, and the heads threshed. Seeds were dried at 60°C, and yields reported at 0% moisture.

The irrigation treatments were 100% (T-100), 75% (T-75), 50% (T-50), and 25% (T-25) replacement of the ET of the full irrigation (100%) treatment averaged across soil types, with the T-50 and T-25 treatments simulating deficit irrigation. There were three replicates of each irrigation treatment in each soil type. Irrigation applications were applied twice weekly using pressure-compensating point source drip irrigation emitters. The lysimeters were uniformly irrigated with about 60 mm in 2008 and 50 mm in 2009 after planting to ensure crop emergence and development, after which differential irrigation treatments began.

2.4. Soils

Soil types were Pullman clay loam (fine, mixed, superactive, thermic Torreric Paleustolls) from Bushland, TX; Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls) from Garden City, KS; Amarillo sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustolls) from Big Spring, TX; and Vingo fine sand (coarse-loamy, mixed, superactive, mesic Aridic Paleustolls) from Dalhart, TX. The soils were selected to provide a range of textural classes of agricultural soils. The Amarillo, Pullman, and Ulysses soil series each are found on about 1,340,000 ha and the Vingo on about 50,000 ha of the southern and central Great Plains.

The Amarillo soil series is a deep, well drained, moderately permeable soil that formed in calcareous loamy materials that has a moderate water-holding capacity, calcium carbonate horizons

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1 Mention of trade names or commercial products in this manuscript is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.
beginning at about 1 m, and relatively high bulk densities. The Pullman soil series is a deep, well drained, slowly permeable soil that formed in calcareous clayey materials. It has a moderate to high water-holding capacity depending on the depth to the calcium carbonate horizons, which begin at about 1–1.5 m, and it has a dense Bt layer at about 0.8 m. The Ullyses soil series is a deep, well drained, moderately permeable upland soil that formed in calcareous loess and has a high water-holding capacity. The Vingo soil series is deep, well drained, moderately rapidly permeable soil formed in sandy materials of eolian origin. Estimated total plant available water holding capacities to 2.2 m are 290 mm for the Amarillo sandy loam, 275 mm for the Pullman clay loam, 315 mm for the Ullyses silt loam, and 176 mm for the Vingo fine sand (Ratliff et al., 1983).

### 2.5. Soil water content measurements

Volumetric soil water contents were measured by neutron scattering (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) in a centrally located tube in each lysimeter. The measurements were taken at 0.2-m increments starting at 0.1 m and ending at 2.1 m for a total measurement depth of 2.2 m. The gauge was calibrated in situ at the Garden City, KS; Big Spring, TX; Dalhart, TX; and Bushland, TX, monolith collection sites using techniques described by Evett and Steiner (1995) and Evett (2008). To estimate plant available water (PAW), the lower limit of water availability was estimated from the lowest soil water contents observed at harvest. Soil water content measurements taken at harvest were considered to be indicative of the maximum drying potential of the profile (Cabelguenne and Debaeke, 1998; Lehane and Staple, 1960). The PAW used in these analyses was the water content of the soil above that lowest water content.

### 2.6. Statistical procedures

Linear regression analysis was performed using a general linear regression model (SigmaPlot for Windows, v. 10, Systat Software, Inc., San Jose, CA). To determine whether the linear relationship differed among years, the regressions of the ET:Y and IR:Y relationships were analyzed using the procedures outlined by Zarnoch (2009). Measurements of seed yield, seed mass, seed number m⁻², WP, and IWP were analyzed for differences among soil types and irrigation treatment using the General Linear Model procedures of PROC GLM (SAS Institute, 1985). Mean separations were computed using the Ryan–Einot–Gabriel–Welsch multiple range test which controls Type 1 experimental error. The measurements comparing years were analyzed using a mixed linear model PROC Mixed (Littell et al., 1996) with years as the main effect.

### 3. Results

The meteorological conditions during July and August of the growing season tended to produce larger ET₀, VPD, and maximum temperature in 2009 compared with 2008 (Table 1). The dwarf, high oleic sunflower variety used in the studies was predicted to mature in about 100 days. Sunflower was physiologically mature at about 100 days in 2008, and at about 84 days in 2009.

#### 3.1. Comparison between years

When comparing years averaged across soil type and irrigation treatment, there were significant differences between years in ET (p = 0.005), WP (p = 0.03), IWP (p = 0.0002), seed mass (p < 0.0001), and seed number m⁻² (p < 0.0001) and a significant interaction between year and soil textural class for IWP (Table 2). The ET was 70 mm larger in 2009 compared with 2008 (Table 3), the WP was 0.50 kg m⁻³ in 2008 and 0.46 kg m⁻³ in 2009, and IWP was 0.76 kg m⁻³ in 2008 and 0.63 kg m⁻³ in 2009. Although seed yield was not significantly different between years (240.5 g m⁻² in 2008 and 255 g m⁻² in 2009), seed mass in 2008 (60 mg seed⁻¹) was significantly larger compared with seed mass in 2009 (50 mg seed⁻¹), and seed number m⁻² in 2008 (3938 seed m⁻²) was significantly smaller compared with seed number m⁻² in 2009 (4970 seed m⁻²). The regression of all IR:Y data by year showed that irrigation increased yield by 0.47 g m⁻² mm⁻¹ in 2008 and 0.51 g m⁻² mm⁻¹ in 2009 (Fig. 1).

#### 3.2. Soil textural class differences

When comparing results among soil textural classes averaged across years and irrigation treatment, there were significant

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>ET₀ (mm)</th>
<th>Tmn (°C)</th>
<th>Tmx (°C)</th>
<th>Tavm (°C)</th>
<th>RH (%)</th>
<th>VPD (kPa)</th>
<th>U (m s⁻¹)</th>
<th>Rₑ (MJ m⁻² day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>9.3</td>
<td>14.3</td>
<td>33.4</td>
<td>9.3</td>
<td>47.1</td>
<td>1.98</td>
<td>5.4</td>
<td>28.9</td>
</tr>
<tr>
<td>July</td>
<td>6.7</td>
<td>17.0</td>
<td>31.1</td>
<td>14.5</td>
<td>60.8</td>
<td>1.40</td>
<td>4.1</td>
<td>24.6</td>
</tr>
<tr>
<td>August</td>
<td>5.6</td>
<td>16.3</td>
<td>29.6</td>
<td>14.6</td>
<td>66.1</td>
<td>1.19</td>
<td>3.4</td>
<td>22.3</td>
</tr>
<tr>
<td>September</td>
<td>4.5</td>
<td>11.1</td>
<td>26.1</td>
<td>10.7</td>
<td>66.5</td>
<td>0.87</td>
<td>3.5</td>
<td>19.8</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>7.1</td>
<td>15.4</td>
<td>31.3</td>
<td>11.7</td>
<td>56.9</td>
<td>1.46</td>
<td>4.0</td>
<td>24.4</td>
</tr>
<tr>
<td>July</td>
<td>7.3</td>
<td>16.7</td>
<td>32.2</td>
<td>13.5</td>
<td>57.4</td>
<td>1.62</td>
<td>3.7</td>
<td>26.0</td>
</tr>
<tr>
<td>August</td>
<td>6.7</td>
<td>16.2</td>
<td>31.4</td>
<td>13.5</td>
<td>57.7</td>
<td>1.45</td>
<td>3.8</td>
<td>24.9</td>
</tr>
</tbody>
</table>
| September | 4.9   | 10.9     | 26.5     | 9.0       | 59.4   | 1.09      | 3.3       | 19.5             

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>ET</th>
<th>WP</th>
<th>IWP</th>
<th>Seed mass</th>
<th>Seed number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>n.s.*</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Soil</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Year X Soil</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
</tbody>
</table>
Table 3
Seed yield, evapotranspiration, water productivity (WP), irrigation water productivity (IWP), seed mass, and seed number m$^{-2}$ averaged across irrigation treatments for crops grown in the Amarillo sandy loam, Pullman clay loam, Ulysses silt loam, and Vingo fine sand soils.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Yield (g m$^{-2}$)</th>
<th>ET (mm)</th>
<th>WP (kg m$^{-3}$)</th>
<th>IWP (kg m$^{-3}$)</th>
<th>Seed mass (mg seed$^{-1}$)</th>
<th>Seed number (seed m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td>278.2a, 4.54</td>
<td>512.3a</td>
<td>0.54ab</td>
<td>0.91a</td>
<td>63a</td>
<td>4401a</td>
</tr>
<tr>
<td>Clay loam</td>
<td>195.5c, 250.0</td>
<td>434.1b</td>
<td>0.43c</td>
<td>0.57c</td>
<td>53b</td>
<td>3517b</td>
</tr>
<tr>
<td>Silt loam</td>
<td>217.3b, 245.4</td>
<td>487.1a</td>
<td>0.47bc</td>
<td>0.72b</td>
<td>57b</td>
<td>4033b</td>
</tr>
<tr>
<td>Fine sand</td>
<td>250.4ab, 270.3</td>
<td>452.1b</td>
<td>0.56a</td>
<td>0.72a</td>
<td>67a</td>
<td>3802b</td>
</tr>
<tr>
<td>Mean</td>
<td>240.5, 255.0</td>
<td>471.68b</td>
<td>0.50A</td>
<td>0.76A</td>
<td>60A</td>
<td>3938b</td>
</tr>
</tbody>
</table>

* Mean separations (represented by a, b, c) compare differences among soil types within a column (excluding the mean).
* Mean separations (represented by A, B) compare differences between years within a row.

The regressions of the ETY relationship, with slopes ranging from 0.44 kg m$^{-3}$ for the crops in the fine sand (0.48 kg m$^{-3}$) to 0.67 kg m$^{-3}$ for the crops in the clays into the sandy loam (0.58 kg m$^{-3}$), were both significantly larger than the IWP of the crops in the clay loam (0.46 kg m$^{-3}$), and sandy loam (0.48 kg m$^{-3})$, which was also larger than the WP of the crops in the fine sand (0.46 kg m$^{-3}$) and clay loam (0.49 kg m$^{-3}$) and the WP of the crops in the sandy loam (0.49 kg m$^{-3}$), which was larger than the WP of the crops in the fine sand (0.46 kg m$^{-3}$) and clays into the sandy loam (0.48 kg m$^{-3}$).
In 2009, there were significant differences among soil textural classes in ET (p = 0.02), WP (p = 0.002), and IWP (p = 0.004) (Table 3). The mean ET of the crops in the silt loam and clay loam was larger than that of the crops in the sandy loam and fine sand, but the difference in crop ET in 2009 among soil textural classes was <30 mm compared with ET differences of 79 mm in 2008. Significantly larger ET but not significantly larger yield of the crops in the clay loam and silt loam produced significantly smaller WP compared with the crops in the sandy loam and fine sand. The crops in the fine sand produced a significantly larger IWP of 0.71 kg m⁻³ compared with crops in the other three soil textural classes. The difference in crop IWP in 2009 among soil textural classes was 0.12 kg m⁻³ compared with 0.34 kg m⁻³ in 2008.

3.3. Irrigation treatments

When comparing results from irrigation treatments averaged across soils (Table 4), increasing irrigation significantly increased yield, ET, and seed mass in both 2008 and 2009, and additionally WP and seed number m⁻² in 2009. The increase in irrigation from the T-25 to the T-100 treatment in 2008 by 315 mm increased yield by 87% and seed mass by 54%, and the same increase in irrigation treatment in 2009 by 390 mm increased yield by 130% and seed mass by 38%. The increase in irrigation from the T-25 to the T-100 treatment in 2009 increased seed number m⁻² by 68%, but in 2008, the seed number m⁻² of the T-75 treatment (4451 seed m⁻²) was larger than that of the T-100 treatment (4268 seed m⁻²). While the largest yield of 351.1 g m⁻² was produced in the T-100 treatment in 2009, the largest WP of 0.55 kg m⁻³ of all irrigation treatments and years occurred in the T-75 treatment in 2008. Comparing the T-100 and T-75 treatments in 2008, the additional 95 mm of irrigation of the T-100 treatment increased yield by 13 g m⁻² and increased ET by 56 mm which resulted in a smaller WP for the T-100 treatment. The IWP significantly declined from the T-25 to the T-100 treatment by 34% in 2008 and by 16% in 2009.

3.4. Irrigation treatment and soil textural class

The yields and WP from the crops in the T-25 irrigation treatments were significantly different among soil textural classes in both years, with the yields from the crops in the clay loam and silt loam tending to be smaller (<150 g m⁻²) than the crops in the fine sand and sandy loam (>150 g m⁻²) (Table 5). The crops in the fine sand had the largest WP in 2008 (0.62 kg m⁻³) and 2009 (0.54 kg m⁻³) and the crops in the clay loam the smallest WP in 2008 (0.29 kg m⁻³) and 2009 (0.32 kg m⁻³). In the T-50 irrigation treatment, the ET of the crops in the clay loam (384 mm) in 2008 was significantly smaller than the ET of crops in the other soil textural classes (~450 mm) with yield, WP, and IWP similar among soil textural classes in both years (Table 5). In the T-75 treatment, the crops in the fine sand in 2009 had significantly larger yield (334 g m⁻²), WP (0.55 kg m⁻³), and IWP (0.73 g m⁻³) compared with the crops in the sandy loam and silt loam. The crops in the fine sand in the 2008 T-75 irrigation treatment produced the largest WP (0.59 kg m⁻³) of all soil/irrigation/year treatment combinations. The yields from the T-100 treatments were significantly different among soil textural classes only in 2008, with the yield from the crop in the fine sand 32% smaller than that from the crop in the sandy loam.

4. Discussion

4.1. Water productivities

Averaged across soil textural class, the slope of the IR:Y relationship showed that irrigation increased yield by 0.47 g m⁻² mm⁻¹ in 2008 and by 0.51 g m⁻² mm⁻¹ in 2009. Among soil textural classes, the largest response to irrigation was by crops grown in the clay loam (0.63 g m⁻² mm⁻¹) and silt loam (0.58 g m⁻² mm⁻¹) soils (Fig. 3). Data reported by Demir et al. (2006) for crops grown in a clay soil produced a slope of 0.46 g m⁻² mm⁻¹, and data reported
Table 4
Irrigation treatment (Tt.), amount of applied irrigation (Irr. Amt.), seed yield, evapotranspiration (ET), water productivity (WP), irrigation water productivity (IWP), seed mass, and seed number m$^{-2}$ averaged across soil textural classes for the T-25, T-50, T-75, and T-100 irrigation treatments in 2008 and 2009.

<table>
<thead>
<tr>
<th>Trt.</th>
<th>Irr. Amt. (mm)</th>
<th>Yield (g m$^{-2}$)</th>
<th>ET (mm)</th>
<th>WP (kg m$^{-3}$)</th>
<th>IWP (kg m$^{-3}$)</th>
<th>Seed mass (mg seed$^{-1}$)</th>
<th>Seed number (seed m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>180</td>
<td>215</td>
<td>151.6a</td>
<td>152.8d</td>
<td>346.9d</td>
<td>369.2d</td>
<td>0.45b</td>
</tr>
<tr>
<td>50</td>
<td>275</td>
<td>355</td>
<td>207.7b</td>
<td>233.1c</td>
<td>433.2c</td>
<td>491.3c</td>
<td>0.48b</td>
</tr>
<tr>
<td>75</td>
<td>400</td>
<td>465</td>
<td>290.1a</td>
<td>283.1b</td>
<td>525.3b</td>
<td>605.7b</td>
<td>0.55a</td>
</tr>
<tr>
<td>100</td>
<td>495</td>
<td>605</td>
<td>302.6a</td>
<td>351.1a</td>
<td>581.2a</td>
<td>697.8a</td>
<td>0.52ab</td>
</tr>
</tbody>
</table>

* Mean separations (represented by a, b, c) compare differences among irrigation treatments within a column.

Table 5
Seed yield, evapotranspiration (ET), water productivity (WP), irrigation water productivity (IWP) averaged across irrigation treatment for the soil textural classes of Amarillo sandy loam, Pullman clay loam, Ulysses silt loam, and Vingo fine sand for 2008 and 2009 experimental seasons.

<table>
<thead>
<tr>
<th></th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield (g m$^{-2}$)</td>
<td>ET (mm) (kg m$^{-3}$)</td>
<td>WP (kg m$^{-3}$)</td>
<td>IWP (kg m$^{-3}$)</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>209.3a</td>
<td>0.53ab</td>
<td>1.24a</td>
<td>233.8</td>
</tr>
<tr>
<td>Clay loam</td>
<td>91.1b</td>
<td>0.29c</td>
<td>0.47b</td>
<td>169.8</td>
</tr>
<tr>
<td>Silt loam</td>
<td>124.9b</td>
<td>0.38bc</td>
<td>0.73b</td>
<td>189.8</td>
</tr>
<tr>
<td>Fine sand</td>
<td>220.5a</td>
<td>0.62a</td>
<td>1.30a</td>
<td>237.3</td>
</tr>
</tbody>
</table>

* Mean separations (represented by a, b, c) compare differences among soil textural classes within a column and within a year.
for crops grown in the Ulysses silt loam soil by Stone et al. (1996) produced a slope of 0.41 g m⁻² mm⁻¹. In these experiments, the IR:Y slope for the crops grown in the Ulysses silt loam indicated a greater response to irrigation by crops grown in Texas compared with crops grown in Kansas. The limited yield response to the T-100 treatment by crops grown in the fine sand may be the result of loss of soil nutrients at larger water application levels.

Irrigation WP significantly declined as irrigation amount increased (Table 4), but IWP did tend to increase with increasing yield within an irrigation treatment as affected by soil textural class (Fig. 4). Crops in different soil textural classes and irrigation treatments produced yields in ranges that overlapped. In 2008, the crops in the sandy loam and fine sand T-25 and T-50 treatments, the crops in the clay loam T-75 treatment, and the crops in the fine sand T-100 irrigation treatment produced average yields that ranged from 209 to 240 g m⁻² (Table 5). In 2009, the crops in the clay loam, silt loam, and fine sand T-50 treatment and the silt loam and sandy loam T-75 treatments produced average yields that ranged from 238 to 258 g m⁻². Although the differences were often not significant among soil textural classes, the soil textural classes produced similar rankings in crop WP and IWP averaged across years and irrigation treatment which were fine sand > sandy loam > silt loam > clay loam. The large productivities of the crops in the fine sand were primarily due to the tendency to have large yields at less than full irrigation levels, especially in the T-25 treatment (Table 5, Fig. 4). However, at full irrigation, the yields of the crops in the fine sand declined compared with yields of the crops in the other soil textural classes. These differences among productivities for the crops in the soil textural classes within irrigation treatments caused the yields to overlap.

Yield increased linearly with ET. Averaged across soil textural class, the slope of the ET:Y relationship of 2008, the year with lower ET, was 0.68 g m⁻² mm⁻¹ and for 2009, the year with higher ET, was 0.59 g m⁻² mm⁻¹. Demir et al. (2006) also reported a difference in slope due to differences in seasonal ET, with a slope of 0.56 g m⁻² mm⁻¹ in a year with lower ET compared with a slope of 0.46 g m⁻² mm⁻¹ in a year with higher ET. Other slopes include 0.39 g m⁻² mm⁻¹ (Browne, 1977), and 0.35 g m⁻² mm⁻¹ produced from data presented in Unger (1982), Nielsen et al. (2010) reported an ET:Y slope for sunflower grown on a silt loam soil in Colorado of 0.66 g m⁻² mm⁻¹. Aboudrare et al. (2006) reported an ET:Y relationship that was linear only in an ET range of 220 to 270 mm with a decline in yield at larger values of ET although the total range in ET was only about 220–340 mm. According to Stewart and Hagan (1973), non-linear relationships such as that reported by Aboudrare et al. (2006) were explicable only if the harvest index (ratio of grain yield to total biomass) changed.

Water productivity significantly increased in 2009 from 0.41 kg m⁻³ for the crops in the T-25 treatment to 0.50 kg m⁻³ for the crops in the T-100 treatment (Table 4). In 2008, WP significantly increased with increasing irrigation but reached a maximum for all year/irrigation treatment combinations of 0.55 kg m⁻³ in the T-75 treatment. Demir et al. (2006) determined that WP, which averaged 0.64 kg m⁻³, did not significantly change as irrigation amount increased. Stone et al. (1996) reported a reduction in WP from a pre-plant irrigation treatment WP of 0.60 kg m⁻³ to a four-in-season irrigation treatment WP of 0.54 kg m⁻³. Karam et al. (2007) found that the WP of a deficit irrigation treatment (0.83 kg m⁻³) was significantly higher than the WP of the fully irrigated control (0.74 kg m⁻³).

### 4.2. Maximum productivity

Reported maximum irrigated seed yields include 395 g m⁻² with 652 mm of ET (0.61 kg m⁻³) from Turkey (Demir et al., 2006), 450 g m⁻² with 634 mm of ET (0.71 kg m⁻³) from Australia (Connor et al., 1985), 559 g m⁻² with 629 mm of ET (0.89 kg m⁻³) from Lebanon (Karam et al., 2007), and 308 g m⁻² with 576 mm of ET (0.53 kg m⁻³) in Kansas, USA (Stone et al., 1996). Using four years of farm yields from the Western Pampas of Argentina, Grassini et al. (2009) established an upper boundary for seed yield with a slope of 0.8 g m⁻² mm⁻¹ and an x-intercept of 75 mm for water productivity of sunflower (Fig. 5). A similar slope was reported in Connor et al. (1985). The maximum ET in these experiments was 738 mm from the T-100 treatment in the Ulysses soil in 2009, which resulted in a yield of 374 g m⁻² (Table 5), which is about 30% less than the 530 g m⁻² predicted by the benchmark proposed by Grassini et al. (2009) for that ET. This indicates that there was a reduction in potential yield as ET increased (Fig. 5). Musick et al. (1994) emphasized the need for attaining relatively high yields of wheat (Triticum aestivum L.) for attaining high WP. Water productivity did increase as yield increased (Fig. 6), but the maximum WP values tended to stabilize at ~0.6 kg m⁻³. The curvilinear regression between yield and WP in these experiments indicates a diminishing return response of yield to ET beginning at a yield of about 200 g m⁻² and a WP of 0.49 kg m⁻³. Beyond that point, the increase in estimated yield to 420 g m⁻² only increased estimated WP to 0.58 kg m⁻³.

The 70 mm difference in average ET between 2008 and 2009 (Table 3) did not significantly increase yields in 2009 compared with 2008, but it was the difference in the average irrigation application amount of 340 mm in 2008 and 410 mm in 2009. The 70 mm may have been lost in soil water evaporation due to the higher
evaporative demand in 2009 compared with 2008. Grassini et al. (2009) showed yield data reported from other semiarid environments that fell at or below this upper boundary, and determined that the differences from the ET:Y upper boundary relationship were associated with the fraction of ET lost in soil water evaporation, evaporative demand, and seasonal water use distribution. Yields in this experiment were limited to <400 g m\(^{-2}\) in the four textural classes even in the full irrigation treatments of 2008 and 2009.

![Fig. 5](image_url)  
**Fig. 5.** The relationship between evapotranspiration and seed yield and the upper boundary of water productivity.

![Fig. 6](image_url)  
**Fig. 6.** The relationship between seed yield and water productivity for the four soil textural classes.

![Fig. 7](image_url)  
**Fig. 7.** The relationship between plant available water measured at pollination and seed mass (SM) at harvest.

### 4.3. Deficit irrigation treatments

Yields of the T-25 treatment in 2008 of crops grown in the clay loam and silt loam soils were significantly lower by as much as 59% compared with yields of crops grown in the sandy loam and fine sand (Table 5) although they received the same amount of irrigation. The difference in the response to irrigation among the soil textural classes may have been affected by the amount of beginning PAW. In 2008, beginning 2.2-m PAW in the T-25 treatment averaged about 180 mm in the sandy loam, 150 mm in the fine sand, 125 mm in the silt loam, and 85 mm in the clay loam. The significantly larger yield of the crops in the fine sand (220.0 g m\(^{-2}\)) produced the significantly largest WP (0.62 kg m\(^{-3}\)) and IWP (1.3 kg m\(^{-3}\)) compared with the significantly smaller yield of the crop in the clay loam (91.1 g m\(^{-2}\)), which produced the significantly smallest WP (0.29 kg m\(^{-3}\)) and IWP (0.47 kg m\(^{-3}\)). In 2009, beginning 2.2-m PAW in the T-25 treatment was about 105 mm in the clay loam, about 130 mm in the silt and sandy loam soils, and 160 mm in the fine sand. As in 2008, both WP and IWP increased with increasing PAW in that irrigation treatment, demonstrating the impact of beginning soil water content on the productivity of water in deficit irrigation treatments.

### 4.4. Yield and yield components

Grain yield is a function of both seed mass and seed number. The yields were similar in 2008 and 2009. Comparing the two years, seed mass was significantly larger and seed number m\(^{-2}\) was significantly smaller in 2008, and seed mass was significantly smaller and seed number m\(^{-2}\) was significantly larger in 2009 (Table 3). Differences in plant density were not a factor, since density was held constant at 5.3 plants m\(^{-2}\) in each year. Seed number m\(^{-2}\) is partially determined by capitulum size and floret production and survival, all of which can be affected by many factors such as nutritional deficiencies, temperature, and radiation level prior to anthesis (Connor and Sadras, 1992). The proportion of florets that set seed is greatly reduced by water stress during and after...
anthesis (Connor and Sadras, 1992). The significantly larger number of seeds in 2009 compared with 2008 suggests that the crop in 2009 benefited from the additional 10–60 mm of irrigation prior to anthesis compared with 2008. Adequate water during seed development is needed to obtain large, well-developed seed (Unger, 1982). The relationship between PAW measured during anthesis and seed mass at harvest for 2008 and 2009 is shown in Fig. 7. After anthesis, the crops received an average (across irrigation treatments) of 138 mm of irrigation in 2008 and 183 mm in 2009. The increase in seed mass in response to increasing PAW was greater in 2008 compared with 2009. The assimilates available for seed fill which continues from late anthesis through physiological maturity (Connor and Sadras, 1992) were distributed among a larger number of seeds in 2009 compared with 2008 resulting in a smaller seed size.

5. Conclusions
Irrigation increased yield as expected, but the amount of increase varied among soil textural classes, ranging from slopes of 0.22 g m\(^{-2}\) mm\(^{-1}\) for crops grown in the fine sand to 0.63 g m\(^{-2}\) mm\(^{-1}\) for crops grown in the clay loam. Crops grown in fine sand and sandy loam tended to produce larger yields in the T-25 irrigation treatment compared with those grown in the clay loam and silt loam, but, in the T-100 irrigation treatment, crops grown in the fine sand produced the lowest yields. Beginning PAW was especially important for producing yield of crops grown in the clay loam soil under deficit irrigation.

Averaged across irrigation treatment, soil textural class resulted in significant differences in WP and IWP, with crops in the fine sand having the largest IWP and WP and crops in the clay loam the lowest. The magnitude of these differences in WP and IWP among soil textural classes was affected by the meteorological conditions, with the year with the smaller evaporative deficits having significantly larger WP and IWP compared with the WP and IWP of the year with the larger evaporative amounts.

Differences in water productivities among soil textural classes within an irrigation treatment resulted in yields from different irrigation treatments to overlap. Crops grown in the fine sand and sandy loam under deficit irrigation produced yields comparable to yields of crops grown in the clay loam and silt loam which received larger irrigation amounts.

Water productivity increased with yield, but there were diminishing returns in yield with increased ET beginning at yields of about 200 g m\(^{-2}\). Maximum WP tended to reach about 0.6 g m\(^{-2}\) mm\(^{-1}\) with yields that were up to 30% less than benchmark yields.

Acknowledgments
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References