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Evapotranspiration, water productivity and crop coefficients for irrigated sunflower in the U.S. Southern High Plains

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ABSTRACT

Sunflower is a diverse crop grown for oil or confectionary uses in the U.S. Southern High Plains, often under irrigation, but its water use, water productivity (water use efficiency) and crop coefficients for irrigation scheduling are not well known for the Texas High Plains. Crop water use (evapotranspiration or ET) was measured in 2009 and 2011 in two 4.4-ha fields using two precision 9 m^2 weighing lysimeters containing 2.3-m deep monoliths of Pullman clay loam soil. The fields were irrigated with a lateral move sprinkler system with nozzles about 1.7–1.8 m above the ground and 1.5-m apart. The sunflower ET averaged 638 mm; seed yields averaged 308 g m^{-2}; and the lysimeter crop water productivity averaged 0.49 kg (dry seed + hull) m^{-3}. Even in the 2011 record drought season with limited soil water reserves, seed yield and oil content appeared similar to those for the 2009 season with greater precipitation and less irrigation requirement. Also, a month later sowing date in 2011, which might occur following an early cotton crop failure, did not appear to greatly affect ET, crop coefficients, or sunflower seed yields. The basal crop coefficients were 0.15 for the initial period after planting (K_{cbini}) and 1.22 for the peak water use rate at full cover (K_{cbmid}) based on the daily ASCE short “grass” reference ET (ET_{os}) and FAO 56 climate adjustment. The K_{cbmid} based on the ASCE taller, rougher “alfalfa” Reference ET (ET_{rs}) was 0.80. Using a thermal-time base (growing degree day) for the crop coefficient did not greatly improve the representation of the crop coefficient. Comparisons of ASCE reference ET computed using hourly versus daily summary data, and for short and tall reference crops, to each other and to FAO 56 reference ET showed that the relationships between reference ET methods varied significantly from one year to the next. This climate effect means that conversions of crop coefficients from one standard ET formulation to another will not be straightforward.

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1. Introduction

Diverse varieties of sunflower (*Helianthus annuus* L.) are grown for oil or confectionary uses in the Southern High Plains, often under irrigation or more commonly dryland culture. In the Texas High Plains, where cotton is grown, sunflower is often cultivated following early cotton (*Gossypium hirsutum* L.) crop failure due to hail. USDA NASS (NASS, 2012) showed harvested U.S. area exceeding 590,000 ha in 2011. The NASS data for the 2010 season reported these harvested areas for the major production states: 348,988 ha in N.D.; 200,405 ha in S.D.; 53,846 in Kans.; 37,247 ha in Colo.; and 28,745 ha in Tex. As well capacities decline in the Ogallala Aquifer region, sunflower becomes an attractive alternative crop due to its drought tolerance and deep root system compared with traditional crops such as grain sorghum [*Sorghum bicolor* Moench (L.)] and soybean (*Glycine max* L.) (Jones, 1984; Bremmer et al., 1986; Cabelguenne and Debaeke, 1998; Stone et al., 2002). Sunflower is considered more tolerant for short periods of water stress. Tolk and Howell (2012) reported fully irrigated sunflower seed yields between 290 and 350 g m^{-2} with a water productivity of 0.49 kg m^{-3} averaged for the 2008 and 2009 seasons at Bushland for the Pullman clay loam soil. Lamm et al. (2011) suggested that the shorter growing season for sunflower, compared with other crops grown regionally, should reduce the irrigation requirement, offering an option for areas with limited irrigation water supplies and well capacities that decline during the summer growing season.

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Sunflower is one of the most important oil crops in the world (Škorić, 1992). In the U.S., sunflower is more commonly produced under dryland or rainfed cultures in northern parts of Kan., Colo., S.D. and N.D. (Schneiter, 1992). Irrigation, typically applied in semi-arid areas, has increased seed yields (Göksoy et al., 2004; Karam et al., 2007a; Stone et al., 1996; Unger, 1982) compared with non-irrigated sunflower crops. Yet, few studies Tyagi et al. (2000) and Tolk and Howell (2012) reported sunflower evapotranspiration (ET) measured by weighing lysimetry. Tyagi et al. (2000) reported a peak daily ET rate of 14.1 mm d^{-1} in India with seasonal ET totals varying from 646 to 664 mm for 1994 and 1995, respectively, at Karnal. Tolk and Howell (2012) reported mean seasonal crop ET averaged for four soil types ranging from 581 to 698 mm in 2008 and 2009, respectively, at Bushland for full irrigation. Although they did not develop crop coefficients, they did note important soil type effects on seasonal ET, yield and crop water productivity (WP = kg dry seed per m^3 of water consumed in ET, also known as water use efficiency, WUE).

The FAO-56 (Allen et al., 1998) procedures for determining and using crop coefficients are currently the most widely used. The procedure relies on a version of the Penman–Monteith reference ET equation for a short, smooth "grass" crop (Allen et al., 2005) that represents a standardized reference ET (ET_o) method, and which is calculated from weather data, namely wind speed, air temperature and humidity, and solar irradiance. Crop ET (ETc) is estimated as

$$ET_c = (K_s K_{cb} + K_e) ET_o \quad (1)$$

using three coefficients: K_s is a soil water deficit coefficient (0–1); K_{cb} is the "basal crop coefficient" (Wright, 1982) defined for a non-water-deficit condition with a "dry" soil surface; and K_e is a coefficient to account for soil or soil/crop surface evaporation from wetting by irrigation or precipitation. This is termed the dual ($K_s K_{cb}$ and K_e) crop coefficient approach. A simpler version with only a single crop coefficient, K_c, is also used in cases where data are not available for calculation of the three coefficients in Eq. (1).

Procedures for computing crop coefficients are based on inverting Eq. (1) for days when there is no soil water deficit but the soil is dry, in which case $K_s = 1$ and $K_e = 0$, to find $K_{cb} = ET_c/ET_o$. Then, the inverted equation is applied to data from days when the soil is dry and there is a soil water deficit to find $K_s = ET_c/(ET_o K_{cb})$ using the known K_{cb}. Finally, with known values of K_{cb} and K_s, the equation is inverted using data for days when the soil is wet to find K_e. Tolk and Howell (2001) showed how to find values for K_{cb}, K_s, and K_e for the Pullman soil using guides in the FAO-56 manual. Howell et al. (2004) also used the spreadsheet they developed, which was patterned after Appendix 8 in the FAO-56 manual.

Few studies besides Allen (1999, 2000), Hunsaker (1999), Tolk and Howell (2001), and Howell et al. (2004) present independent validations for the FAO-56 methods. Tolk and Howell (2001) and Howell et al. (2004) found the dual K_c approach for sorghum and cotton, respectively, superior compared with the single K_c approach using the FAO-56 methodology.The objectives of this research were to determine irrigated sunflower ET, water productivity and crop coefficients for estimating ET in the Southern High Plains, specifically for the Pullman soil series. A sub objective, motivated by the influence of choice of reference ET method on crop coefficient values, was to investigate how ASCE 2005 "short" and "tall" reference ET values differed according to whether daily summary or hourly data were used to compute them and how they compared with FAO 56 reference ET. This information is critical for irrigation scheduling models and for regional water planning.

2. Materials and methods

2.1. Agronomic methods

The study was conducted at the USDA-ARS Laboratory at Bushland, Tex. (35° 118′N, 102° 068′W, 1170 m elevation above mean sea level). ET was measured during the 2009 and 2011 seasons with two weighing lysimeters (Marek et al., 1988) each located in the center of a 4.4-ha, 210 m E–W by 210 m N–S, field, with the two fields arranged in a rectangular pattern. The site is very thoroughly described by Evett et al. (2012a). Weighing lysimeters offer one of the most accurate means to measure ET (Hatfield, 1990). Dominant wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeded 1 km.

The soil at this site is classified as Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll) (Taylor et al., 1963; Unger and Pringle, 1981), which is described as slowly permeable because of a dense Bt horizon about 0.3–0.5 m below the surface. The plant available water holding capacity within the top 2.0 m of the profile is approximately 240 mm; 200 mm to 1.5 m depth. This soil is common to more than 1.2 million ha of land in this region and about 1/3 of the sprinkler-irrigated area in the Texas High Plains (Musick et al., 1988). The field slope was less than 0.3%. A calcareous Btka soil horizon occurs at the 1.4 to 1.5-m depth and inhibits deeper water flux due to the capillary barrier it presents (the Btka is considerably more porous than the overlying Bt). In some years, this limits both water flux and significant rooting and water extraction below this depth. Tolk and Evett (2012) reported that the lower limit of water content for maize (*Zea mays* L.) root water extraction was larger (0.236 $m^3 m^{-3}$) than water content values measured in the laboratory at −1.5 MPa soil water potential, but the lower limit values for cotton (*Gossypium Hirsutum* L.) (0.204 $m^3 m^{-3}$) and grain sorghum [*Sorghum bicolor* (L.) Moench] (0.215 $m^3 m^{-3}$) were similar to the laboratory measured value (0.199 $m^3 m^{-3}$). Sunflower has often been used as a crop for the greatest soil water extraction from soils (Ratliff et al., 1983).

The two adjacent lysimeter fields, designated northeast (NE) and southeast (SE), were planted to sunflower cultivar S 672 NuSu[1]; Triumph Dwarf, in 2009 and to S 668 Nu Sun; Triumph Dwarf in 2011. The lysimeter fields were managed similarly for irrigation and fertilization, and for weed and insect control. The row spacing was 0.76 m, and rows had an E–W row orientation, with four rows on each lysimeter. The planting rate was approximately 5.6 seeds m^{-2} (56,800 plants ha^{-1}) on June 4, 2009 (day of year, DOY, 155) and the crop emerged on DOY 164. In 2011, the seeding rate was 5.4 plants m^{-2} (54,300 plants ha^{-1}) on June 16, 2011, but the field was re-planted due to poor emergence on June 29, 2011 (DOY 180) at the same seeding rate. Emergence from the 2011 re-planting was on DOY 187. The 2009 crop was fertilized at the recommended rate, based on soil tests, of 8.9 g (N) m^{-2} and 5.3 g (P) m^{-2}. The 2011 crop was fertilized at the same rate as 2009. Both crops followed irrigated cotton in 2008 and 2010. The furrows were diked to store irrigation and rainfall, simulating the detention due to the lysimeter rim and minimizing runoff. All cultural practices were by conventional six-row machinery, except for the approximately 28 m^2 immediately surrounding and including the lysimeter that was hand cultivated. Areas outside the lysimeter were bedded like the field. The lysimeter soil surface was flat. Fertility and pest control were applied uniformly.

[1] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.