

Evapotranspiration of Corn and Forage Sorghum for Silage

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Abstract

In the U.S. Southern High Plains, dairies have expanded and have increased the regional demand for forage and silage. The objectives were to measure water use and determine crop coefficients for corn (*Zea mays* L.) and forage sorghum (*Sorghum bicolor* (L.) Moench) produced for silage on the Southern High Plains. Water use was measured with large, precision weighing lysimeters in 2006 and 2007. Both growing seasons had normal to above normal rainfall. The 2006 season was more advective with greater mean daily reference evapotranspiration (*ET*) rates. Seasonal *ET* was 671 mm for forage sorghum with a yield of 1.48 kg m^{-2} in 2006 and 489 mm in 2007 with a yield of 1.70 kg m^{-2}; water productivity was 2.21 kg m^{-3} in 2006 and 3.47 kg m^{-3} in 2007. Seasonal *ET* was 418 mm for corn for silage with a yield of 1.52 kg m^{-2} in 2006 and 671 mm in 2007 with a yield of 2.44 kg m^{-2}; water productivity was 3.63 kg m^{-3} in 2006 and 3.64 kg m^{-3} in 2007. Using the 2007 season as a better species comparison, forage sorghum can achieve comparable water productivity as corn with less *ET* (~73% of corn *ET*) and irrigation requirement although with a reduced yield (~62% of corn dry matter).

Introduction

The U.S. Southern High Plains is the center of large regional beef cattle and swine feeding industries with about 35% of all the U.S. feed beef cattle within a 250 km radius from Amarillo, Tex. Recently, dairies have expanded within the region with two nearby large cheese processing plants. The beef feedyards have utilized limited amounts of silages, primarily from corn in past years, but the dairies impose a much greater demand for forages and silages. Corn (*Zea mays* L.) has a large water use, yet it produces high grain yields and digestible nutrients. Forage sorghum (*Sorghum bicolor* (L.) Moench) can produce similar silage quality and uses less water, but forage sorghum also yields less biomass than corn.

Howell et al. (2006) presented a summary of crop coefficient and evapotranspiration (*ET*) data from Bushland, Tex. for irrigated corn, wheat (*Triticum aestivum* L.), sorghum, soybean (*Glycine max* (L.) Merr.), cotton (*Gossypium hirsutum* L.), and alfalfa (*Medicago sativa* L.). Limited literature exists on *ET* of corn and forage sorghum grown for silage in the Southern High Plains.

The purpose of this paper is to present a preliminary summary of water use and crop coefficient data for corn and forage sorghum produced for silage in the Southern High Plains having a semi-arid, advective environment for the 2006 and 2007 seasons.

Procedures

These studies were conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Tex. (35º 11' N lat.; 102º 06' W long.; 1,170 m elev. above MSL) in 2006 and 2007. Crop *ET* was measured with two weighing lysimeters (Marek et al. 1988) each located in the center of 4.4-ha 210 m E-W by 210 m N-S fields (two fields arranged in a rectangular pattern). The soil at this site is classified as Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll) (Unger and Pringle 1981; Taylor et al. 1963) which is described as slowly permeable because of a dense B22 horizon about 0.3 to 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 (Tolk and Howell 2001) ~200 mm to 1.5-m) depth). A calcareous layer at about the 1.4-m depth limits significant rooting and water extraction below this depth. Variations of this soil series are 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). Weighing lysimeters offer one of the most accurate means to measure *ET* (Hatfield 1990). Predominate wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeds 1 km. The field slope is less than 0.3 percent. More descriptive information is provided in Howell et al. (1995b), Howell et al. (1997), Evett et al. (2000), and Howell et al. (2004).

Lysimeter Procedures

Lysimeter mass was determined using a Campbell Scientific[1] CR-7X data logger (Campbell Scientific, Inc., Logan, Utah) to measure and record the lysimeter load cell (Interface SM-50, Scottsdale, Ariz.) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 5 min and composited to 30-min means (reported on the mid point of the 30 min interval, i.e. data were averaged from 0-30 minutes and reported at 15 min). The lysimeter mass resolution was 0.01 mm, and its accuracy exceeded 0.05 mm (Howell et al. 1995a). Daily *ET* was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). A pump regulated to -10 kPa provided vacuum drainage, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here). Lysimeter *ET* data included days with irrigations and rainfall.

Weather Data

Solar irradiance, wind speed, air temperature, dew point temperature, relative humidity, precipitation, and barometric pressure were measured at an adjacent weather station (Howell et al. 1995b) operated by the Texas High Plains *ET* Network (Porter et al. 2005) placed over an irrigated grass surface (cool-season lawn mixture containing bluegrass, perennial rye-grass, etc.).

Crop Coefficients

Reference *ET* (ET_{os} and ET_{rs}) was computed with the ASCE/EWRI standardized equations (Allen et al. 2005) using the Texas High Plains ET Network (Porter et al. 2005). These calculations were verified using REF-ET© v2 (Allen 2001). Crop coefficients were computed as

$$K_c = \frac{ET_c}{ET_*} \qquad [1]$$

where ET_c is the crop water use expressed in mm d^{-1} and ET_* represents a reference crop water use expressed in the same units (Doorenbos and Pruitt 1977; Jensen et al. 1990; Allen et al. 1998). The symbols of ET_o and K_{co} are used for clipped grass (0.12-m tall), and the symbols of ET_r and K_{cr} were used for alfalfa (0.5-m tall) in this paper. The K_c values are presented and discussed qualitatively, here, only on a time scale (day of year). They will be reported in more detail with appropriate statistical analyses in future papers in both scales for time (both as days after planting and percent of time until full cover) and growing degree formats.

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Agronomic Procedures

Corn (NC+7373RB, NC+ Hybrids, Lincoln, Neb.) was planted on 11 May in 2006 (DOY 126) and 17 May in 2007 (DOY 137). Forage sorghum (Dairymaster, Richardson Seeds, Ltd., Vega, Tex.) was planted on 5 June in 2006 (DOY 156) and 30 May in 2007 (DOY 150). The forage sorghum hybrid was a "brown mid rib" variety that reportedly has a higher digestibility (Bean et al. 2007). The previous crop in 2005 was irrigated grain sorghum. In 2006, corn was grown on the NE lysimeter field, and the forage sorghum was grown on the SE lysimeter field. In 2007, forage sorghum was grown on the NE lysimeter field, and the corn was grown on the SE lysimeter field. Cultural practices were typical for high yielding irrigated silage crops in this region. The 2006 corn crop was damaged by an unknown plant virus or herbicide and was replanted to a short-season hybrid (NC+3723RB) on 3 July (DOY 184). Thus, the 2006 inter-crop comparison is invalid, but the crop *ET* data remains useful.

Irrigation

The lysimeter fields were irrigated with a lateral-move sprinkler system to meet the crop water use. The sprinkler system was a 10-span lateral-move system (Lindsay Manufacturing, Omaha, Neb.) with an end-feed hose and aboveground, end guidance cable. The sprinkler system was aligned N-S, and irrigated E-W or W-E. The system was equipped with gooseneck fittings and spray heads (Nelson Irrigation Corp., Walla Walla, Wash.) with concave spray plates on drops located about 1.5 m above the ground and 1.5 m apart. Each spray head was equipped with a 100-kPa pressure regulator and a 1-kg polyethylene drop weight. Irrigations were scheduled to meet the crop *ET* water use rate (by daily plotting the lysimeter masses in terms of water depth) and were typically applied in one to two 25-mm applications per week.

Soil Water Measurements

Soil water contents were measured periodically using a neutron probe (model 503DR Hydroprobe, CPN International, Inc., Martinez, Calif.) at 0.2-m depth increments beginning with the 0.10-m depth using 30-s counts and methods described in Hignett and Evett (2002). Two access tubes were located in each lysimeter (read to 1.9-m depth), and four tubes were located in the field surrounding each lysimeter (read to 2.3-m depth). The probe was field calibrated for the Pullman soil using a method similar to that described by Evett and Steiner (1995).

Plant and Yield Sampling

In each field for the two crop species, plant samples from three separate 1.5-m^2 areas were obtained periodically to measure crop development. These field samples were taken at sites about 10 to 20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. Leaf area index (LAI), crop height (CH), and aboveground dry matter (DM) were measured from three samples. Final yield was measured by harvesting the lysimeter grain and aboveground plant matter from each lysimeter (9 m^2), and dry matter and yield at harvest were measured from three adjacent 1.5-m^2 plant samples. Forage quality samples were obtained and sent to a testing laboratory for nutritive and digestibility analyses (results not presented here). Field harvest was on 28 October in 2006 (DOY 301) and on 15 October in 2007 (DOY 288).

Results

The 2006 year had 354 mm of rainfall and 2007 received 411 mm of rainfall. While both years were below the long-term Bushland, Tex. annual precipitation of 480 mm, the growing season rainfall in each crop season was typical or exceeded the long-term growing season rainfall. Figure 1 illustrates the growing season rainfall and irrigation in 2007 along with the cumulative ET_c from the two crops. Table 1 presents the crop water use, dry matter yield, and water productivity for each crop in the two years. Both crops are C_4 species and should be expected to have similar water productivities. In 2006, the forage sorghum had lower water productivity than expected possibly due to the greater advection during the interval when the first corn crop was being replanted with a shorter-season corn hybrid. In both seasons, corn

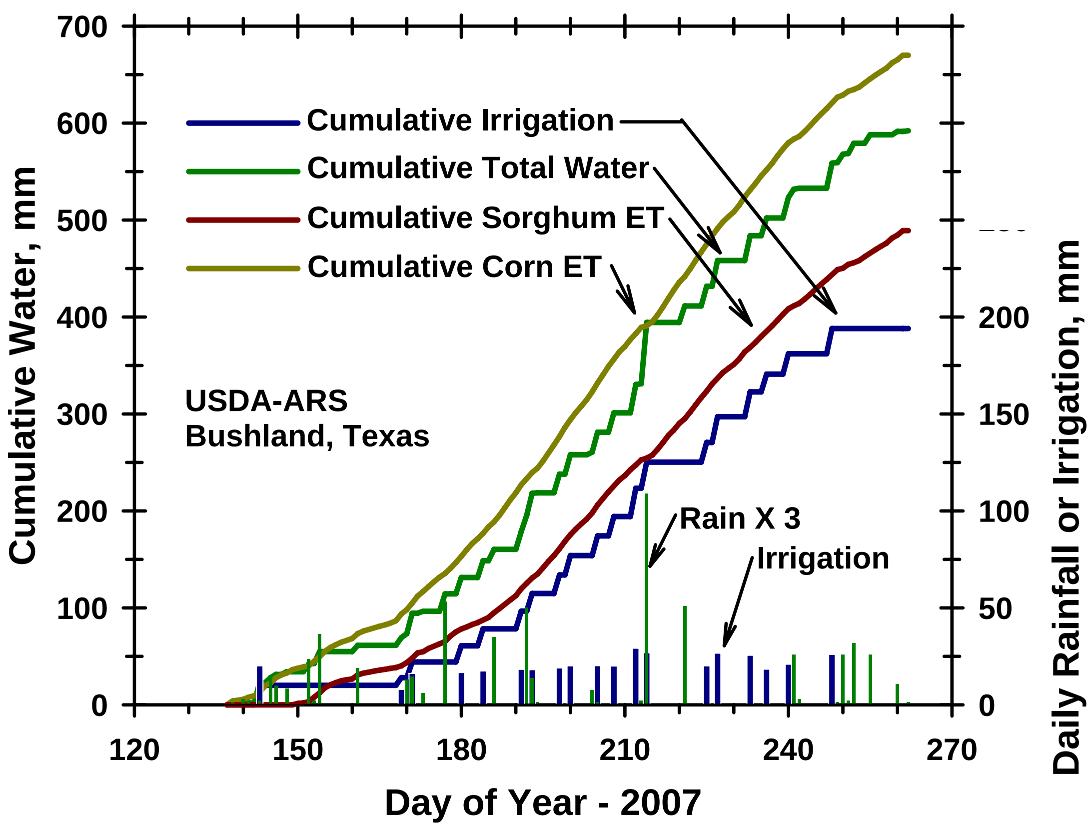

Figure 1. Cumulative irrigation, rainfall, and ET_c for the forage sorghum and corn (left axis scale) and daily rainfall received (note, daily rainfall was multiplied by 3 to be visible on the right-hand scale) and irrigation applied (right axis scale) to the fields in 2007 at Bushland, Tex.

produced nearly identical water productivity (~3.6 kg m^{-3}) as noted previously with differing corn hybrids (Howell et al. 1998). The forage sorghum had less *ET* and irrigation requirement in 2007 but with comparable water productivity (~3.5 kg m^{-3}) with corn (~3.6 kg m^{-3}) when a more direct species comparison was valid although the forage sorghum had less yield (~38%).

Table 1. Water use, yield, and water productivity of forage sorghum and corn produced for silage at Bushland, Tex.

Season	Species	ET_c mm	Dry Matter g m^{-2}	Water Productivity kg m^{-3}
2006	Forage Sorghum	671	1,484	2.21
	Corn	418	1,519	3.63
2007	Forage Sorghum	489	1,699	3.47
	Corn	671	2,444	3.64

The 2007 year was less advective with an annual mean ET_o and ET_r of 4.28 and 5.95 mm d^{-1}, respectively, while 2006 had an annual mean ET_o and ET_r of 5.04 and 7.28 mm d^{-1} (Table 2). The annual mean dew point temperature was also lower in 2006 indicating a larger vapor pressure deficit.

The greater advection in the 2006 season is illustrated in Figure 2 by the larger

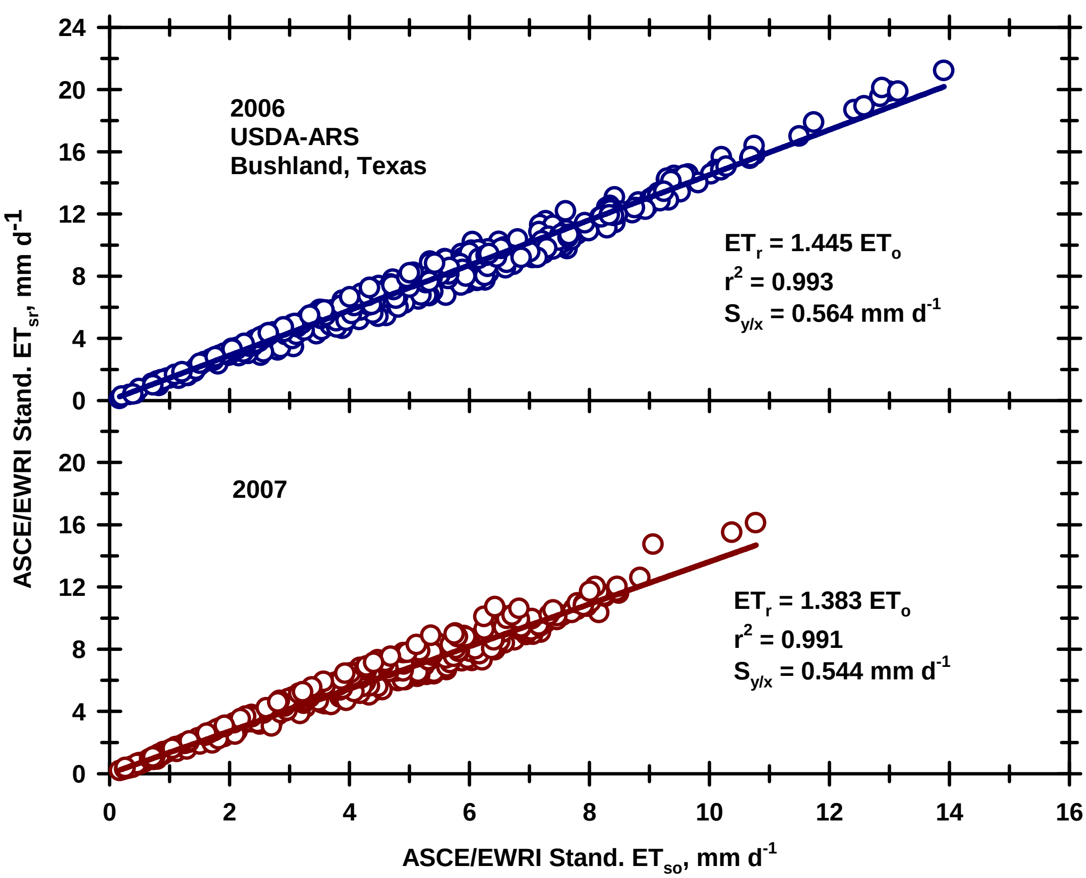

Figure 2. Reference *ET* relations in 2006 and 2007 at Bushland, Tex.

slope between ET_r and ET_o and the larger reference ET_* rates in 2006. Several reference *ET* equations were compared with the ASCE-EWRI Standardized Penman-Monteith equation (ASCE PM ET_{so}) for a short crop reference *ET* (ET_{so}) (Allen et al. 2005) at Bushland, Tex. in Table 3. Of interest is the close agreement between the ET_{so} (Allen et al. 2005) and the ASCE PM ET_o, (Jensen et al. 1990) 1948 Penman ET_o (48 Pen ET_o), and the 1996 Kimberly Penman ET_o (96 Kpen ET_o) equations. The tall crop reference *ET* (ET_r) was consistently about 1.4 times ET_{so}. The two temperature-radiation reference *ET* equations [1985 Hargreaves (85 Harg ET_o) and 1972 Priestley-Taylor (72 P-T ET_o)] consistently underestimated ET_{so} at Bushland, Tex. and had the lowest coefficients of determination (r^2). These relationships are important in translating crop coefficients (K_c) from location to location.

Table 2. Climate summary at Bushland, Tex.

Mon	Tair °C	Tmax °C	Tmin °C	Tdew °C	Rs MJ m^{-2} d^{-1}	U2 m s^{-1}	Prec. mm mo^{-1}	ET_o[1/] mm d^{-1}	ET_r[1/] mm d^{-1}	ET_o(hr[2/]) mm d^{-1}	ET_r(hr[2/]) mm d^{-1}
2006											
Jan	-1.3	5.0	-6.5	-5.7	10.8	3.5	5	1.3	2.0	1.3	1.7
Feb	2.8	11.4	-4.5	-4.8	14.0	4.2	2	2.7	4.1	2.5	3.5
Mar	10.5	18.3	3.4	2.0	17.6	4.1	101	3.6	5.1	3.4	4.7
Apr	10.1	17.5	3.2	3.6	21.7	4.6	32	4.0	5.4	4.0	5.3
May	17.0	24.5	10.1	10.0	24.3	3.7	40	5.2	6.8	5.1	6.7
Jun	21.6	29.5	14.5	13.3	25.9	3.8	56	6.5	8.6	6.2	8.2
Jul	24.0	31.8	16.5	15.3	26.7	3.2	37	6.7	8.7	6.5	8.5
Aug	24.5	32.7	17.6	16.1	23.3	3.7	64	6.5	8.7	6.2	8.3
Sep	20.7	28.8	13.9	13.8	19.8	3.8	43	5.0	6.9	4.7	6.2
Oct	15.5	24.7	7.0	3.7	17.8	4.3	10	4.8	7.2	4.5	6.4
Nov	7.8	16.8	-0.8	-4.2	12.8	4.0	0	3.1	5.0	2.9	4.4
Dec	1.8	9.0	-4.4	-4.6	9.5	3.9	22	1.8	2.8	1.6	2.3
2007											
Jan	5.6	15.7	-3.6	-8.4	12.1	4.5	2	3.3	5.4	3.0	4.6
Feb	4.2	14.1	-4.8	-9.7	16.2	4.7	1	3.6	5.6	3.3	4.8
Mar	8.6	16.8	1.1	-3.8	17.4	5.4	22	4.5	6.7	4.1	6.0
Apr	16.0	25.4	5.9	-0.2	24.7	5.3	6	6.9	10.0	6.5	9.4
May	20.6	29.3	11.8	4.9	25.9	4.3	18	7.5	10.7	7.1	9.9
Jun	25.0	33.7	16.1	9.9	27.0	4.9	30	9.1	13.0	8.6	12.2
Jul	25.9	33.8	18.3	13.3	24.9	3.6	62	7.4	10.2	7.0	9.6
Aug	23.4	30.5	17.7	16.3	21.8	3.4	99	5.7	7.5	5.5	7.3
Sep	17.6	25.0	11.3	10.0	18.8	3.3	32	4.2	5.7	4.1	5.4
Oct	13.3	21.2	6.5	5.5	15.4	4.0	44	3.6	5.3	3.4	4.8
Nov	7.9	17.1	-0.1	-2.2	13.1	4.0	0	2.9	4.6	2.7	4.0
Dec	1.6	9.1	-4.6	-4.5	10.3	3.1	39	1.5	2.4	1.5	2.1

[1/] Daily data
[2/] Sum of hourly reference *ET*

Table 3. Regression relations between various reference *ET* equations for the 2006 and 2007 years at Bushland, Tex. based on Ref-ET (Allen 2001). Regression parameters are based on the Standardized Penman-Monteith Equation (Allen et al. 2005) as the independent variable (i.e., X of Y = a + b X).

2006 & 2007 n=730 Equation	Mean mm d^{-1}	Mean Ratio ---	r^2 ---	Intercept mm d^{-1}	Slope ---	Sy/x[1/] mm d^{-1}
ASCE PM ET_{so}	4.772					
ASCE PM ET_{sr}	6.855	1.437	0.977	-0.067	1.451	0.584
ASCE PM ET_r	6.954	1.457	0.976	-0.104	1.479	0.608
ASCE PM ET_o	4.840	1.014	1.000	-0.021	1.019	0.027
82 Kpen ET_r	6.006	1.259	0.957	-0.098	1.279	0.717
96 Kpen ET_o	4.714	0.988	0.875	-0.099	1.009	1.008
72 Kpen ET_r	6.941	1.455	0.951	0.434	1.364	0.951
48 Pen ET_o	4.724	0.990	0.957	0.060	0.977	0.547
85 Harg ET_o	3.718	0.779	0.790	0.368	0.702	0.956
72 P-T ET_o	3.113	0.652	0.626	0.183	0.614	1.253

[1/] Standard error of the estimate

Crop Development

Despite the late replanting of corn in 2006 and the consequent hybrid change, it reached a crop height of 2.8 m, a leaf area index (LAI) of 5.7, and a final harvest dry matter of 1.52 kg m^{-2}. The forage sorghum had a maximum crop height of 2.6 m, a LAI of 5.6, and a final harvest dry matter of 1.48 kg m^{-2}. Both crops reached a maximum crop height of nearly 3 m in 2007 (Figure 3). The forage sorghum had a maximum LAI of 5.4 while the corn LAI maximum was slightly greater than 7. The final harvest dry matter was 1.70 kg m^{-2} for the forage sorghum and 2.44 kg m^{-2} for the corn.

Soil Water

The 2006 season began with a relatively dry upper soil water content profile and frequent irrigations were required to replenish the soil profile and maintain the crops. The 2007 season had a larger initial soil water content. Figure 4 shows the mean and standard deviation of soil water content of the upper 1.5-m profile at four neutron tube sites nearby each weighing lysimeter in 2007. Because the spray heads were not renozzled for the different crop fields, the irrigation amounts applied to each crop during a growing season were approximately the same. This slightly over-irrigated the forage sorghum while slightly deficit irrigating the corn. The corn field and lysimeter, especially in 2007, had ample soil water in the soil profile to likely meet full crop needs. But any deficit irrigation of corn may have slightly reduced the evaporation from the soil. The mean soil water content for the forage sorghum illustrates this “recharge” of the profile (Figure 3) until the crop *ET* met or exceeded irrigation plus rainfall (Figure 1). The mean 1.5-m profile soil water content didn’t exceed the “field capacity” of the Pullman soil, except once at one neutron tube site

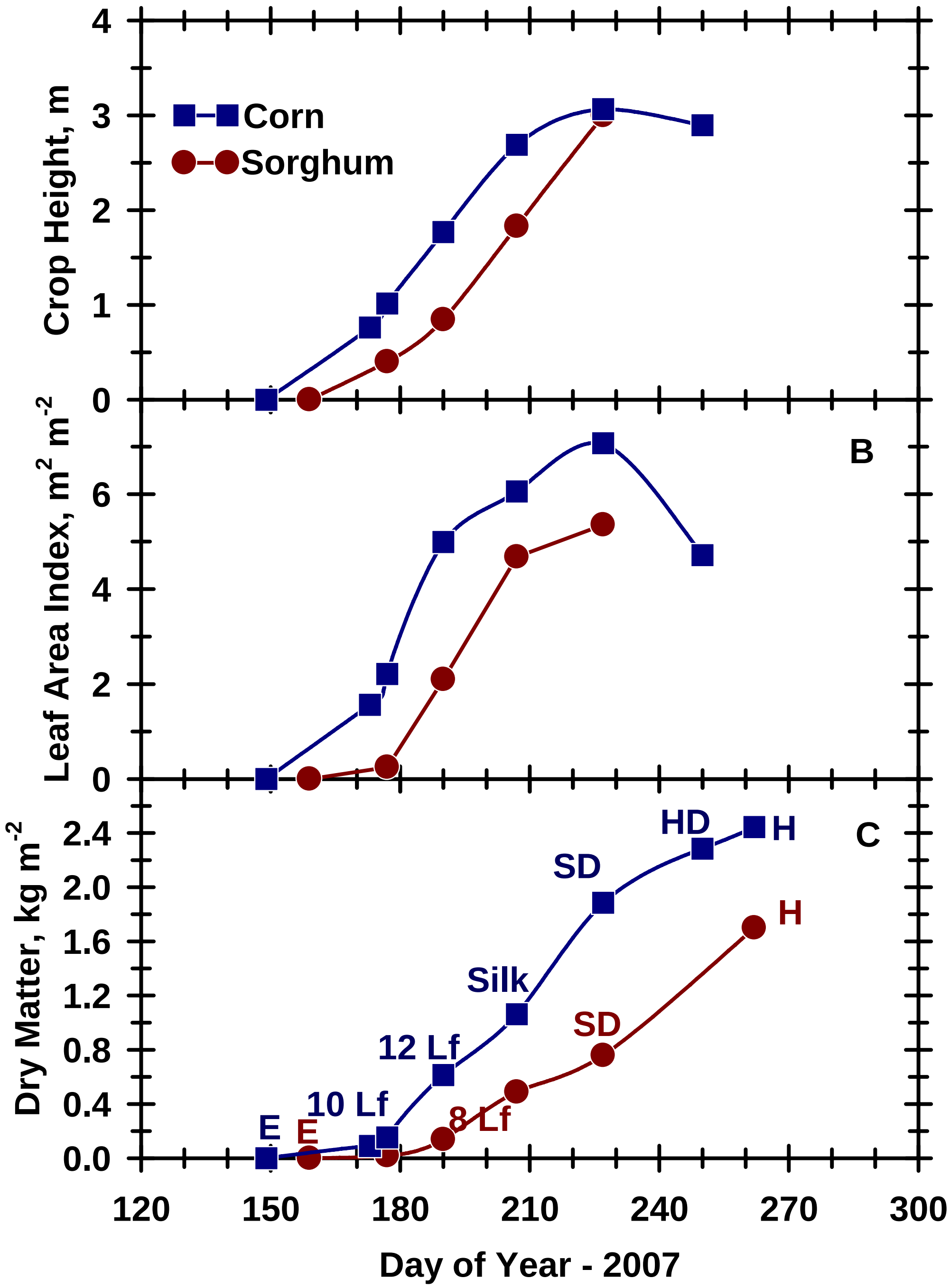

Figure 3. Crop development of forage sorghum and corn in 2007 at Bushland, Tex. Top (A) is crop height; middle (B) is leaf area index; and bottom (C) is dry matter. The symbols on C represent emergence (E), leaf number (# Lf); silking (Silk); soft dough (SD); hard dough (HD); and harvest (H).

for the forage sorghum. The corn utilized the available profile soil water when irrigation and rainfall were less than the crop *ET*.

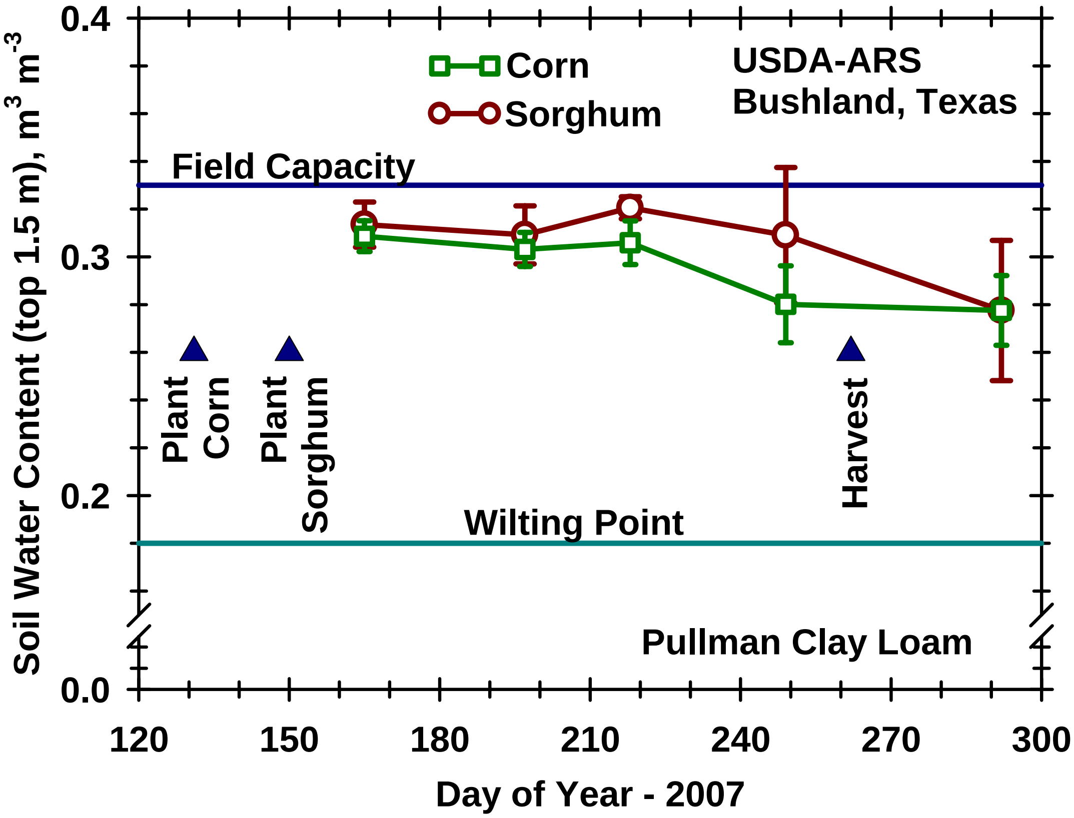

Figure 4. Mean and standard deviation of the 1.5-m profile soil water content for the forage sorghum and corn fields (4 neutron tube sites near each weighing lysimeter) in 2007 at Bushland, Tex. Shown are the field capacity and wilting point values for the Pullman clay loam soil (0.33 m^3 m^{-3} and 0.18 m^3 m^{-3}, respectively).

Crop Coefficients

Crop coefficients for both species in Figures 5 and 6 for the short-crop reference *ET* (ET_o) and the tall-crop reference *ET* (ET_r) for the 2006 and 2007 seasons, respectively. Although with sprinkler irrigation it is difficult to achieve “basal” conditions (Wright 1982), we drew straight line segments like FAO-56 (Allen et al. 1998) to estimate our approximation of the “basal” crop coefficients. The K_{c_ini} was estimated at 0.1 for both species in 2006. The initial “basal” K_c for sorghum at Davis, Calif. was 0.12 (Jensen et al. 1990). Wright (1982) determined the corn “basal” K_c at Kimberly, Idaho as 0.15. The 2006 estimated initial period “basal” K_c for forage sorghum with nearly bare soil appeared to even be less than 0.1 for either reference *ET* equation, probably due to the drier initial soil profile in that year. The maximum “basal’ K_c for forage sorghum was estimated as 1.00 in 2006 and 0.90 in 2007 for ET_o and 0.75 in 2006 and 0.70 in 2007 for ET_r. The maximum “basal’ K_c for corn was estimated as 1.10 in 2006 and 2007 for ET_o and 0.85 in 2006 and 2007 for ET_r. The maximum “basal” K_c at Davis, Calif. for grain sorghum was 1.08 for ET_o (Jensen et al. 1990) and 0.93 for field corn for ET_r at Kimberly, Idaho (Wright 1982).

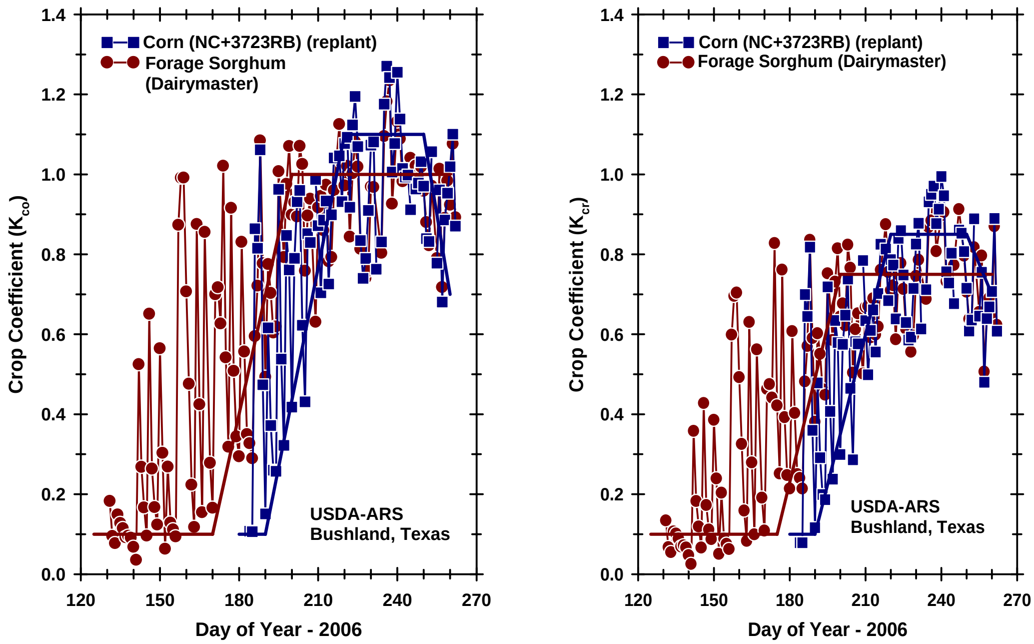

Figure 5. Corn and forage sorghum crop coefficients in 2006 at Bushland, Tex. for short-crop reference ET_o (K_{co}) [left] and tall-crop reference ET_r (K_{cr}) [right].

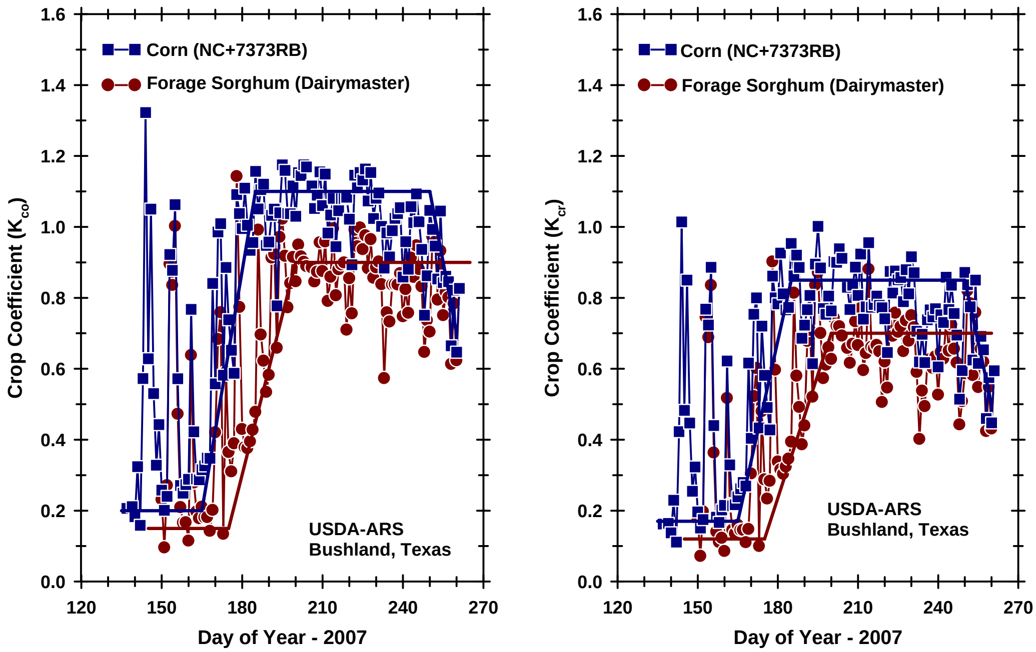

Figure 6. Corn and forage sorghum crop coefficients in 2007 at Bushland, Tex. for short-crop reference ET_o (K_{co}) [left] and tall-crop reference ET_r (K_{cr}) [right].

The Bushland forage sorghum "basal" K_c was slightly lower than the reported Davis, Calif. data for grain sorghum for the ET_o reference ET (1.00 and 0.90 at Bushland in 2006 and 2007, respectively compared with 1.08 at Davis, Calif.), but the Calif. data were usually based on "real" mowed, irrigated grass reference ET. The Idaho field corn K_c data were computed using the 1982 Kpen reference ET_r (Wright 1982). When the maximum field corn K_c at Kimberly, Idaho of 0.93 (Wright 1982) was converted using the 1982 Kpen mean ET_r (Table 3) and the ASCE-EWRI ET_{sr} (Table 3) ratio, the adjusted Kimberly, Idaho corn maximum K_c is about 0.81 for ET_r at Bushland, Tex., which is slightly lower than the Bushland corn K_c values (0.85) for ET_r. In 2007, the forage sorghum initial "basal" K_c was estimated as 0.15 for ET_o and 0.12 for ET_r while the corn initial "basal" K_c was estimated as 0.20 for ET_o and 0.17 for ET_r (Figure 6). The maximum forage sorghum "basal" K_c was estimated as 0.90 for ET_o and 0.70 for ET_r in 2007 (Figure 6) while the corn maximum "basal" K_c was estimated as 1.1 for ET_o and 0.85 for ET_r in 2007 (Figure 6). The estimated Bushland "basal" K_c values generally agree with the "basal" K_c values from both Davis, Calif. and Kimberly, Idaho when the uncertainties in measuring ET_c estimating reference ET_* are considered together with weather data uncertainties (Allen et al. 2005).

Summary

Forage sorghum offers an attractive alternative to corn for silage in the Southern High Plains to conserve water while achieving nearly equal water productivity as corn. However, the yield of forage sorghum will be less than corn for silage. In 2007 when a valid comparison between forage sorghum and corn was feasible, the forage sorghum was about the same height as the corn with LAI being lower (~5.4 compared with ~7.1) and having less dry matter (~1,700 g m^{-2} compared with ~2,400 g m^{-2} for corn). However, the forage sorghum ET was significantly less (by ~180 mm in 2007 or ~27%). The reduced irrigation demand of forage sorghum makes it more compatible with declining well yields as forage demands from dairies increase on the Southern High Plains. Forage sorghum should be examined as an alternative to corn for silage in the regional water planning to meet future water requirements with reduced water availability in the Southern High Plains from the Ogallala Aquifer.

Acknowledgements

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