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Evapotranspiration of Corn and Forage Sorghum for Silage

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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, TX. 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, TX 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. Since the 2006 corn was replanted with a short-season hybrid, we'll focus this report just on the 2007 season's results.

Figure 1. SE weighing lysimeter (silage corn) on 15 June 2007 at Bushland, Texas

Weighing lysimeters offer one of the most accurate means to measure ET

Procedures

These studies were conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX (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, UT) to measure and record the lysimeter load cell (Interface SM-50, Scottsdale, AZ) 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

$$K_c = \frac{ET_c}{ET_*}$$

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).

Agronomic Procedures

Corn (NC+7373RB, NC+ Hybrids, Lincoln, NB) was planted on 17 May in 2007 (DOY 137). Forage sorghum (Dairymaster, Richardson Seeds, Ltd., Vega, TX) was planted on 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 corn was grown on the SE lysimeter field. Cultural practices were typical for high yielding irrigated silage crops in this region.

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, NB) with an end-feed hose and aboveground, end guidance cable. The sprinkler system was aligned N-S, and irrigated E-W or W-E.

[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.

The system was equipped with gooseneck fittings and spray heads (Nelson Irrigation Corp., Walla Walla, WA) 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, CA) 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 15 October in 2007 (DOY 288).

Results

Figure 1 (page 3) shows a photograph

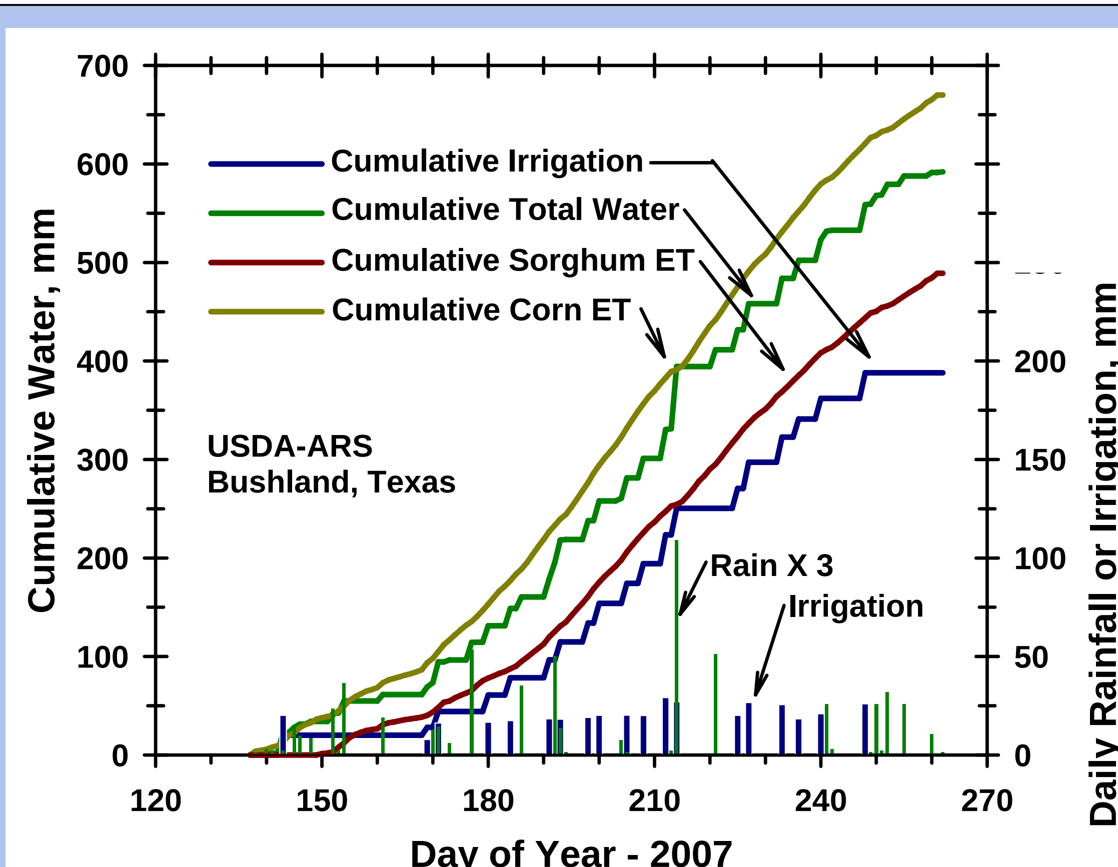

Figure 2. Cumulative irrigation, rainfall, and ET_c for the forage sorghum and corn (left axis scale) and daily rainfall received (note, daily rainfall was multiplied by 3 to be visible on the right-hand scale) and irrigation applied (right axis scale) to the fields in 2007 at Bushland, Tex.

Table 1. Water use, yield, and water productivity of forage sorghum and corn produced for silage at Bushland, Tex. in 2007.

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

of the SE weighing lysimeter on 15 June 2007 with silage corn. The 2007 year received 411 mm of rainfall (Fig. 2), which is below the long-term Bushland, TX annual precipitation of 480 mm. The growing season rainfall was typical or exceeded the long-term growing season rainfall, however. Figure 2 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 2007. Both crops are C_4 species and should be expected to have similar water productivities. The corn produced nearly identical water productivity (~3.6 kg m^{-3}) to previous corn crops (see Howell et al., 1998 for crop water productivities for corn hybrids with differing maturity). 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}) although the forage sorghum had less yield (~38%). Figure 3 shows photographs of the fields (Fig. 3A) in 2007 and the forage sorghum lysimeter (Fig. 3B). Figure 4 shows a photograph of the forage sorghum silage harvest 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, TX in Table 2. 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, TX and had the lowest coefficients of determi-

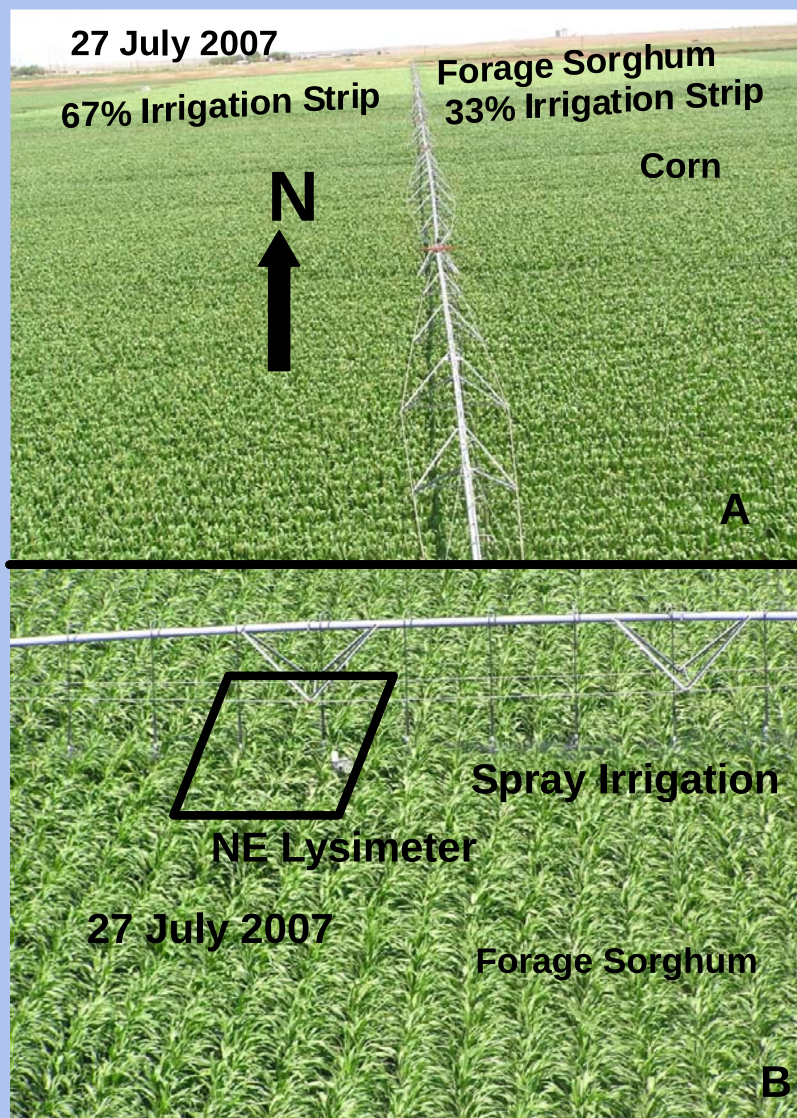

Figure 3. Photograph of lysimeter fields (A) and NE lysimeter (B) with forage sorghum on 27 July 2007 at Bushland, Tex.

Figure 4. Photograph of forage sorghum harvest on 6 Oct. 2006 at Bushland, Tex.

Table 2. Regression relations between various reference *ET* equations for the 2006 and 2007 years (1 March through 31 October) 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=609 Equation	Mean mm d^{-1}	Mean Ratio ---	r^2 ---	Intercept mm d^{-1}	Slope ---	Sy/x[1/] mm d^{-1}
ASCE PM ET_{so}	5.095					
ASCE PM ET_{sr}	7.223	1.418	0.980	-0.232	1.463	0.562
ASCE PM ET_r	7.325	1.438	0.979	-0.279	1.493	0.586
ASCE PM ET_o	5.165	1.014	1.000	-0.029	1.019	0.027
82 Kpen ET_r	6.502	1.276	0.962	-0.023	1.281	0.679
96 Kpen ET_o	5.196	1.020	0.888	0.092	1.002	0.952
72 Kpen ET_r	7.321	1.437	0.951	0.336	1.371	0.832
48 Pen ET_o	5.112	1.003	0.963	0.135	0.977	0.510
85 Harg ET_o	4.114	0.807	0.799	0.647	0.680	0.914
72 P-T ET_o	3.550	0.697	0.645	0.559	0.587	1.166

[1/] Standard error of the estimate

nation (r^2). These relationships are important in translating crop coefficients (K_c) from location to location.

Crop Development

Both crops reached a maximum crop height of nearly 3 m in 2007 (Fig. 5). 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 2007 season had a larger initial soil water content than in 2006. Figure 6 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 re-nozzled 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 (Fig. 6) until the crop *ET* met or exceeded irrigation plus rainfall (Fig. 2). 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 for the forage sorghum. The corn utilized the available profile soil water when irrigation and rainfall were less than the crop *ET*.

Crop Coefficients

Crop coefficients for both species in Figures 7 and 8 for the short-crop reference *ET* (ET_o) and the tall-crop reference *ET* (ET_r), respectively, for the 2007 season. Although with sprinkler irrigation it is difficult to

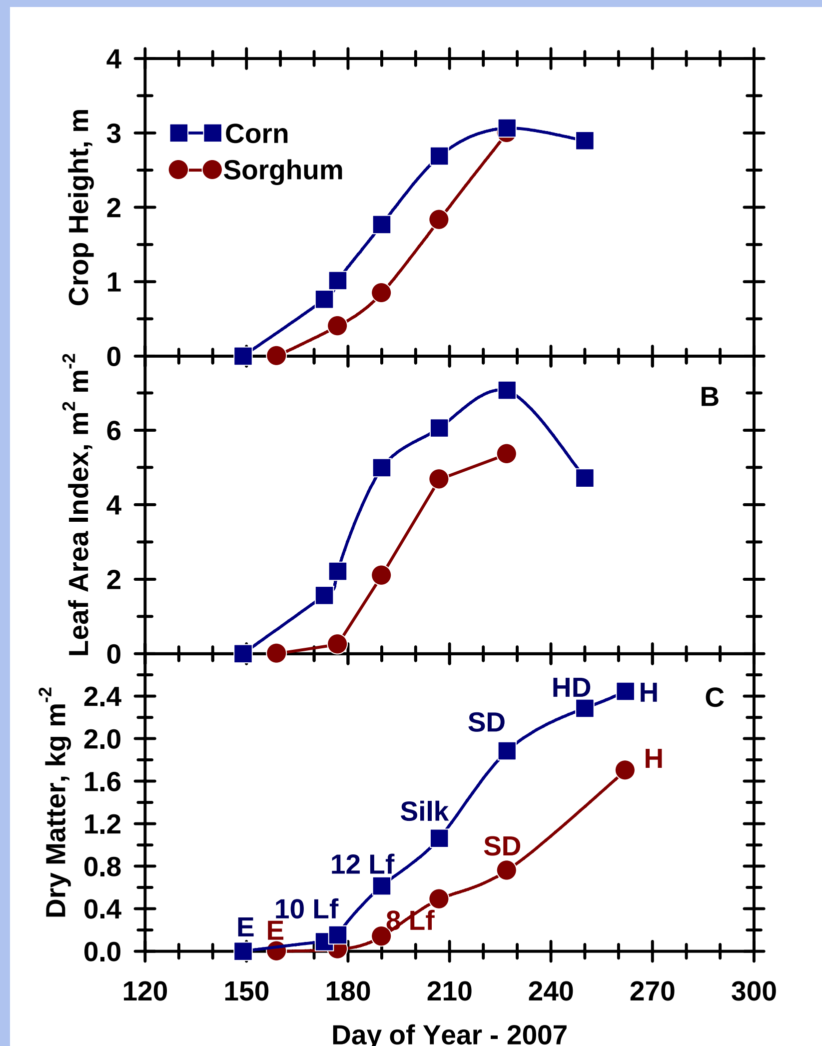

Figure 5. Crop development of forage sorghum and corn in 2007 at Bushland, Tex. Top (A) is crop height; middle (B) is leaf area index; and bottom (C) is dry matter. The symbols on C represent emergence (E), leaf number (# Lf); silking (Silk); soft dough (SD); hard dough (HD); and harvest (H).

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. In 2007, the forage sorghum initial "basal" K_c was estimated as 0.15 for ET_o (Fig. 7) and 0.12 for ET_r (Fig. 8) while the corn initial "basal" K_c was estimated as 0.20 for ET_o (Fig. 7) and 0.17 for ET_r (Fig. 8). The maximum forage sorghum "basal" K_c was estimated as 0.90 for ET_o (Fig. 7) and 0.70 for ET_r (Fig. 8) in 2007 while the corn maximum "basal" K_c was estimated as 1.1 for ET_o (Fig. 7) and 0.85 for ET_r (Fig. 8) in 2007. The initial "basal" K_c for sorghum at Davis, CA was 0.12 (Jensen et al., 1990) for *ETso*. Wright (1982) determined the initial corn "basal" K_c at Kimberly, ID as 0.15 for *ETsr*. The maximum "basal" K_c at Davis, CA for grain sorghum was 1.08 for ET_o (Jensen et al., 1990) and 0.93 for field corn for ET_r at Kimberly, ID (Wright 1982). The Bushland forage sorghum "basal" K_c was slightly lower than the reported for Davis, CA data for grain sorghum for the ET_o reference *ET* (0.90 at Bushland in 2007 compared with 1.08 at

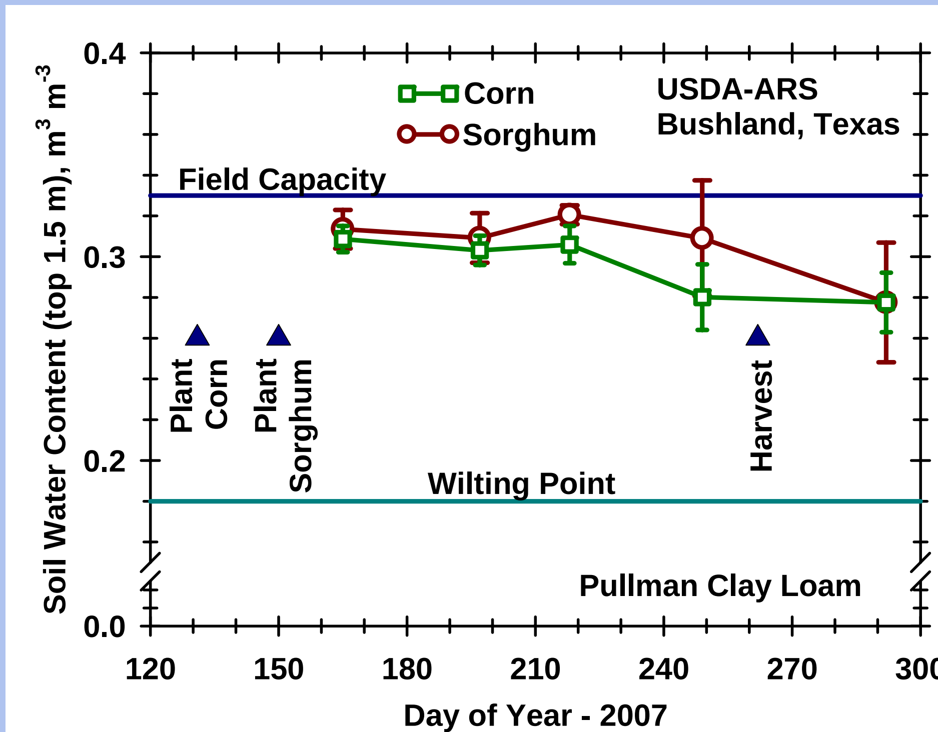

Figure 6. Mean and standard deviation of the 1.5-m profile soil water content for the forage sorghum and corn fields (4 neutron tube sites near each weighing lysimeter) in 2007 at Bushland, Tex. Shown are the field capacity and wilting point values for the Pullman clay loam soil (0.33 m^3 m^{-3} and 0.18 m^3 m^{-3}, respectively).

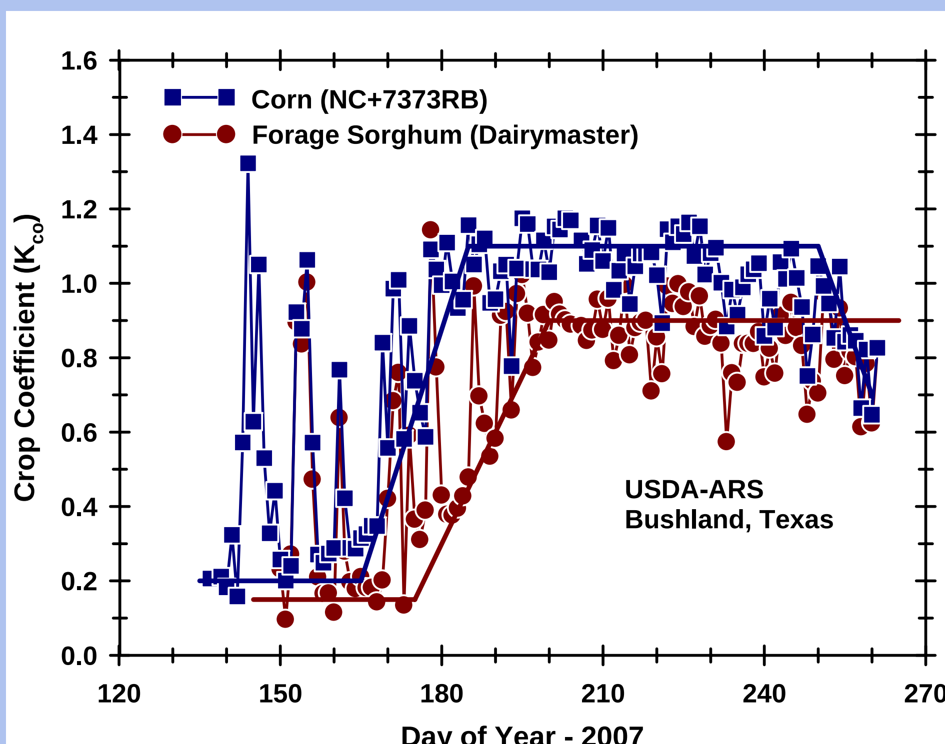

Figure 7. Corn and forage sorghum crop coefficients in 2007 at Bushland, Tex. for short-crop reference ET_o (K_{co}).

Davis, CA), but the California 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, ID of 0.96 (Jensen et al., 1990) was converted using the 1982 Kpen mean ET_r (Table 2) and the mean ASCE-EWRI ET_{sr} (Table 2) [means for 1 March to 31 October], the adjusted Kimberly, ID corn maximum K_c is about 0.85 for ET_r at Bushland, TX., which exactly matches the Bushland corn K_c value (0.85) for ET_r. The estimated Bushland "basal" K_c values generally agree with the "basal" K_c values from both Davis, CA and Kimberly, ID when the uncertainties in measuring ET_c and in 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

These data were obtained through the dedicated and meticulous work of numerous technicians in the USDA-ARS Soil and Water Research Unit at Bushland, TX. Their tireless efforts were required to obtain these data, and we sincerely recognize their dedication.

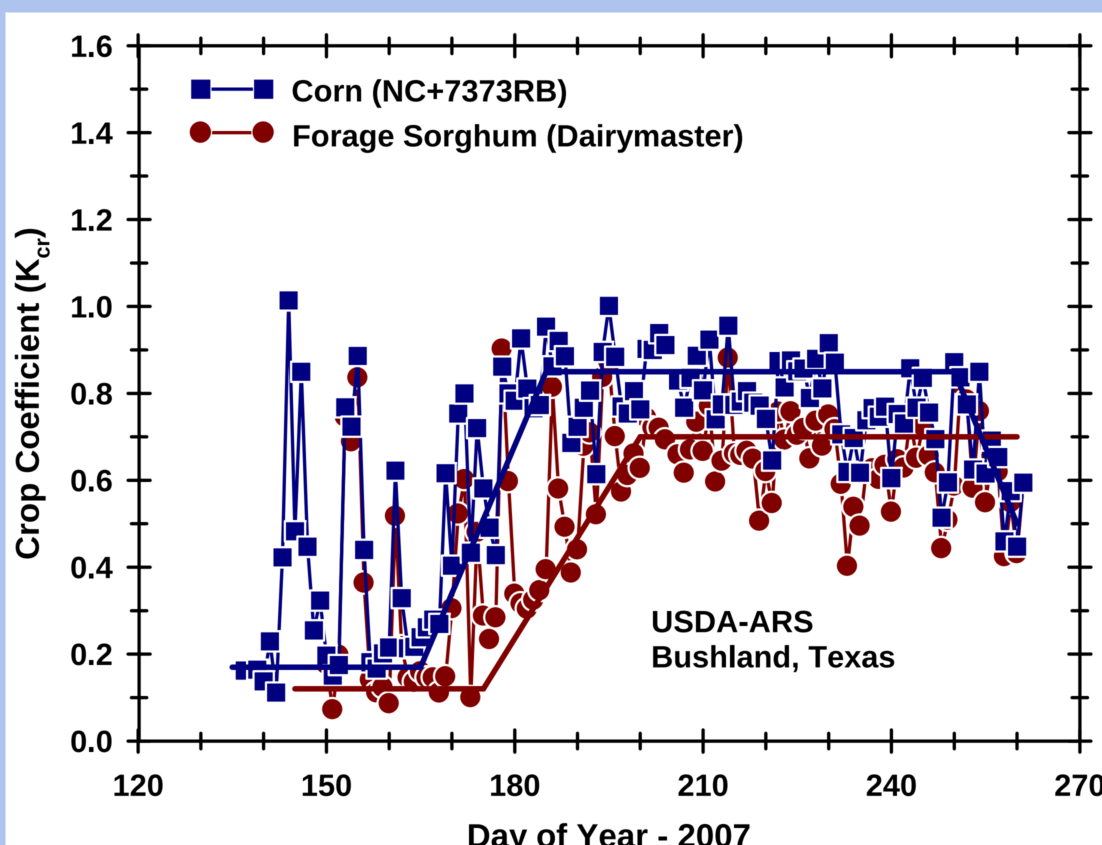

Figure 8. Corn and forage sorghum crop coefficients in 2007 at Bushland, Tex. for tall-crop reference ET_r (K_{cr}).

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Radiation Partitioning Model for Row Crops: Refinement of the Campbell and Norman 1998 Approach

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Introduction

Radiative transfer models for the soil-plant-atmosphere continuum are the basic drivers for models that describe crop growth and development, evapotranspiration (ET), and gas exchange. Effective water resource management in irrigated regions, for example, require accurate estimates of ET, which can be accomplished with two-source energy balance models, where the energy balance of the soil and canopy layers are computed separately (Kustas and Norman, 1999; Kustas et al., 2004). Colaizzi et al. (2006) evaluated a two-source energy balance model against ET measurements of various crops grown in large weighing lysimeters at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX. Overall model agreement with measured ET was acceptable; however, they observed significant errors for some energy components, such as net radiation partitioning between the soil and canopy layers for row crops with partial canopy cover. This pointed to the need to investigate and refine radiative transfer models designed for these conditions.

Campbell and Norman (1998; hereafter referred to as CN98) described a radiative transfer model for vegetation and soil that only required incident global radiation and basic knowledge of canopy characteristics. The CN98 model separates the visible and near-infrared portions of the shortwave spectrum, and further separates these into their direct beam and diffuse components, all of which have very different transmittance and reflectance properties. We refined the CN98 model by including several new parameters that account for the "clumping" nature of row crops for any row orientation (e.g., circular rows typically found under center-pivot irrigation systems). Briefly, these parameters were the fraction of canopy cover normal to the solar beam (fcs), the path length fraction (PLF) of a solar beam propagating through a canopy relative to nadir, and the multiple row function (MRF) to account for a solar beam propagating through more than one crop row at low zenith angles. These parameters were analogous to the "clumping factor" described by Chen and Cihlar (1995), Anderson et al. (2005), and others. We evaluated the CN98 model with these refinements for grain corn, grain sorghum, and upland cotton, which are important row crops for the Texas High Plains economy.

Procedure

The present study was conducted at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, USA (35º 11' N lat., 102º 06' W long., 1,170 m elevation M.S.L.). The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. Strong advection of heat energy from the South and Southwest is typical. The soil was a Pullman clay loam (fine, mixed, super active, thermic torrertic Paleustolls) with slow permeability (Unger and Pringle, 1981).

Instrumentation and measured

radiation parameters are summarized in Table 1. All measurements were sampled every 6 s and reported as 0.5 h averages (0.25 h in 2007). Only days with clear skies were used, which would be of primary interest for remote sensing applications, and to reduce data sets to a manageable size. Incoming shortwave solar radiation (Rs), incoming photosynthetic active radiation (IPAR), transmitted shortwave radiation (TRs), and transmitted PAR (TPAR) were measured for grain corn (*Zea mays* L.; 1989 and 2007 seasons), grain sorghum (*Sorghum bicolor* L.; 1988 and 2007 seasons), and upland cotton (*Gossypium hirsutum* L.; 2000, 2001, and 2007 seasons) (Howell et al., 1997; 2004). Reflected shortwave (RRs), reflected PAR (RPAR), and total net radiation (Rn) were measured for corn (1989 only) and grain sorghum (RPAR measured in 1988 only). (Note that components commonly reported as PAR are actually the photosynthetic photon flux density in units of µmol m^{-2} s^{-1}). In 1992, measurements of RRs and RPAR were used over bare soil at two lysimeter sites to determine soil albedo and reflectance in the visible and near infrared spectrums. The RRs and RPAR measurements over bare soil used the same instrumentation as 1988 grain sorghum and 1989 corn (Table 1; Tunick et al., 1994).

Agreement between observed and predicted (i.e., modeled) radiation parameters (TRs, TPAR, RRs, RPAR, and Rn) was assessed using standard statistical parameters (observed and predicted mean; slope; intercept; coefficient of determination, r^2; root mean square error, RMSE; and bias), as well as, non-squared parameters described by Legates and McCabe (1999) (modified index of agreement, D; modified coefficient of efficiency, ε; and mean absolute error, MAE). D is similar to r^2 in that $0 \leq D \leq 1$, with greater values of D indicating better agreement between observed and predicted values. Values of ε range from $-\infty$ to 1, and ε = 0 indicates that the mean of all observed values is as good a predictor as the model (if ε < 0, then the mean of observed values is actually a better predictor than the model). MAE should be used in conjunction with RMSE, where the extent that RMSE > MAE indicates outliers in the data. We also computed RMSE divided by the observed mean expressed as a percentage (RMSE/$\bar{O}_{obs}$).

Results & Discussion

Statistical parameters of model agreement were tabulated for grain corn (Table 1), grain sorghum (Table 2), and upland cotton (Table 3) for each radiation parameter, consisting of transmitted shortwave radiation (TRs), transmitted photosynthetically active radiation (TPAR), reflected shortwave radiation (RRs), reflected photosynthetically active radiation (RPAR), and total net radiation (Rn). Modeled vs. observed radiation parameters were plot for each crop (Figure 1). Overall, most data clustered about the 1:1 line with significant linearity (two-tailed Student t test, α = 0.05). All root mean square error (RMSE) values were no greater than 1.4 times the corresponding mean absolute error (MAE) values, indicating reasonably low presence of outliers. The modified index of agreement (D) ranged from 0.664 for cotton Rn (Table 3) to 0.899 for corn TPAR (Table 1). All modified coefficient of efficiency (ε) values were greater than zero, meaning that all models contributed additional information beyond the means of observed values ($\bar{O}_{obs}$). The RMSE/$\bar{O}_{obs}$ values were 30% or less, the largest resulting for corn RPAR (Table 1). These results were encouraging given the inherent difficulty in measuring radiation in plant canopy environments.

Transmitted radiation (i.e., TRs and TPAR) tended to cluster at relatively low values for corn and grain sorghum, because most measurements were obtained after canopy closure (Figure 1). Most of the greater values of TRs and TPAR were observed early in the season before full canopy, with very few occurring late in the season after leaf senescence. However, TRs and TPAR were more uniformly distributed across the range of values for cotton. These measurements were obtained in a deficit-irrigated crop (i.e., 50% of full irrigation requirement), with only about 40% of the soil surface covered. Therefore, a portion of the tube solarimeters (used to measure TRs) and line quantum sensors (used to measure TPAR) received direct sunlight during most of the day since the rows of the cotton crop were oriented east-west. A similar experiment is presently underway with cotton rows oriented north-south, which will test the robustness of CN98 model refinements.

Reflected shortwave radiation (RRs) tended to be distributed somewhat uniformly in the observed range, whereas reflected photosynthetically active radiation (RPAR) tended to cluster at lower values of the observed range (Figure 1). This was expected because green leaves have much greater absorption (~0.85) of photosynthetically active radiation (i.e., visible spectrum around 400 to 700 nm) compared with near-infrared radiation (~0.15). The energy of visible and near-infrared radiation is distributed approximately equally in incoming shortwave radiation (Campbell and Norman, 1998). The modeled underestimates of RPAR for corn (first column, fourth plot in Figure 1) occurred late in the season, and were likely the result of tassels and senesced leaves not accounted for in the model. This was also observed for cotton, when leaf senescence may have exposed a greater amount of soil background (which has greater reflection in the visible spectrum). However, cotton RPAR was also overestimated early in the season when canopy cover was low, possibly due to reduced (underestimated) soil reflectance from wetting that was not accounted for. These errors could be easily addressed through actual measurements of surface reflectance, which are routinely obtained by ground-based, airborne, or satellite remote sensing platforms (Gowda et al., 2008).

Total net radiation (Rn) had systematic bias, with overestimates for corn and grain sorghum but underestimates for cotton, possibly the result of instrument calibration errors. The net radiometer deployed over the 2007 grain sorghum had the closest agreement with modeled values, which can be discerned as the cluster of points closest to the 1:1 line (second column, fifth plot in Figure 1).

"The Campbell and Norman (1998) radiative transfer model (CN98) was evaluated with new refinements that accounted for the clumping nature of row crops for grain corn, grain sorghum, and upland cotton."

Conclusion

The Campbell and Norman (1998) radiative transfer model (CN98) was evaluated with new refinements that accounted for the clumping nature of row crops for grain corn, grain sorghum, and upland cotton. Acceptable model agreement was obtained for transmitted and reflected radiation, which is an important result for improving crop water use models used in water resource management. Some error observed in reflected radiation parameters may have been due to leaf senescence later in the season that was not accounted for in the present version of the model, and underestimates of soil reflectance due to wetting events. These errors could be easily addressed by using routine measurements of surface reflectance from remote sensing. Systematic bias was observed for net radiation in all but one season, but this may have been due to instrument calibration errors. The CN98 model will continue to be validated and refined with different crop row orientations, as part of the Bushland Agricultural and Evapotranspiration Experiment of 2008 BEAREX08).

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Table 1. Instrumentation used in radiation measurements. The mention of trade names of commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Grain Corn		1989		2007	
Parameter		Instrument	Qty.	Instrument	Qty.
Rs	Incident solar radiation [1]	Eppley [2] PSP	2	Eppley [2] PSP	2
IPAR	Incident PAR [1]	Licor [3] LI-190 SA	1	Licor [3] LI-190 SA	1
TRs	Transmitted solar radiation	Decagon [4] tube solarimeter	4	Delta-T [5] TSL	2
TPAR	Transmitted PAR	Licor [3] LQ	4	Licor [3] LI-191	3
RRs	Reflected solar radiation	Eppley [2] B&W 8-48	2	---	---
RPAR	Reflected PAR	Licor [3] LI-190 SA	2	---	---
Rn	Total net radiation	REBS [6] Q*4	2	---	---
Ts	Surface temperature	Everest [7] IRT (nadir)	2	Exergen [8] IRT/c (soil)	6
		Everest [7] IRT (oblique)	2	Exergen [8] IRT/c (canopy)	6

Grain Sorghum		1988		2007	
Parameter		Instrument	Qty.	Instrument	Qty.
Rs	Incident solar radiation [1]	Eppley [2] PSP	2	Eppley [2] PSP	2
IPAR	Incident PAR [1]	Licor [3] LI-190 SA	1	Licor [3] LI-190 SA	1
TRs	Transmitted solar radiation	Decagon [4] tube solarimeter	4	Delta-T [5] TSL	2
TPAR	Transmitted PAR	Licor [3] LQ	4	Licor [3] LI-191	3
RRs	Reflected solar radiation	Eppley [2] B&W 8-48	2	Kipp & Zonen[10] CM14	1
RPAR	Reflected PAR	Licor [3] LI-190 SA	2	---	---
Rn	Total net radiation	Frichen [9] net radiometer	2	REBS [6] Q 7*1	2
Ts	Surface temperature	Everest [7] IRT (nadir)	2	Exergen [8] IRT/c (soil)	6
		Everest [7] IRT (oblique)	2	Exergen [8] IRT/c (canopy)	6

Upland Cotton		2000 & 2001		2007	
Parameter		Instrument	Qty.	Instrument	Qty.
Rs	Incident solar radiation [1]	Eppley [2] PSP	2	Eppley [2] PSP	2
IPAR	Incident PAR [1]	Licor [3] LI-190 SA	1	Licor [3] LI-190 SA	1
TRs	Transmitted solar radiation	---	---	Delta-T [5] TSL	3
TPAR	Transmitted PAR	---	---	Licor [3] LI-191	3
RRs	Reflected solar radiation	Kipp & Zonen[10] C14	2	---	---
RPAR	Reflected PAR	Licor [3] LI-190 SA	2	---	---
Rn	Total net radiation	REBS [6] Q 7*1	2	---	---
Ts	Surface temperature	Exergen [8] IRT/c (oblique)	2	Exergen [8] IRT/c (soil)	6
				Exergen [8] IRT/c (canopy)	6

[1] Incident measurements were taken at a nearby grass reference site.
[2] Eppley Laboratory, Inc., Newport, RI, USA.
[3] Licor, Inc., Lincoln, NE, USA.
[4] Decagon Devices, Inc. Pullman, WA, USA.
[5] Delta T Devices, Ltd., Cambridge, U.K.
[6] Radiation and Energy Balance Systems, Inc., Seattle, WA, USA.
[7] Everest Interscience, Inc., Tucson, AZ, USA.
[8] Exergen Corp., Watertown, MA, USA.
[9] Frichen
[10] Kipp & Zonen USA, Inc., Bohemia, NY, USA.

Table 2. Statistical parameters of agreement between observed and modeled transmitted shortwave radiation (TRs), transmitted photosynthetically active radiation (TPAR), reflected shortwave radiation (RRs), reflected photosynthetically active radiation (RPAR), and total net radiation (Rn) for grain corn.

	TRs $W\ m^{-2}$	TPAR $\mu mol\ m^{-2}\ s^{-1}$	RRs $W\ m^{-2}$	RPAR $\mu mol\ m^{-2}\ s^{-1}$	Rn $W\ m^{-2}$
n	545	545	392	392	476
mean Obs	285.1	382.6	147.3	90.6	519.2
mean Pred	268.4	382.5	152.1	71.0	568.9
Slope	0.905	1.006[a]	0.774	1.036[a]	1.063
Intercept	10.5	-2.4[a]	38.2	-22.9	17.3
r^2	0.916	0.958	0.789	0.878	0.956
RMSE	64.2	89.5	9.9	26.8	55.2
Bias	-16.7	0.0	4.9	-19.6	49.8
D	0.863	0.899	0.709	0.730	0.729
ε	0.736	0.797	0.418	0.327	0.389
MAE	46.2	67.4	8.5	21.9	49.8
RMSE/$\bar{O}_{obs}$	23%	23%	7%	30%	11%

[a] Slope or intercept is not significantly different from one or zero, respectively (two-tailed Student t test, α = 0.05).

Table 3. Statistical parameters of agreement between observed and modeled transmitted shortwave radiation (TRs), transmitted photosynthetically active radiation (TPAR), reflected shortwave radiation (RRs), reflected photosynthetically active radiation (RPAR), and total net radiation (Rn) for grain sorghum.

	TRs $W\ m^{-2}$	TPAR $\mu mol\ m^{-2}\ s^{-1}$	RRs $W\ m^{-2}$	RPAR $\mu mol\ m^{-2}\ s^{-1}$	Rn $W\ m^{-2}$
n	789	789	775	518	789
mean Obs	256.4	418.9	136.0	67.5	512.8
mean Pred	287.3	446.3	131.8	63.4	548.7
Slope	0.955	1.000[a]	0.677	0.898	0.983[a]
Intercept	42.6	27.4	39.6	2.8	44.6
r^2	0.870	0.923	0.746	0.829	0.840
RMSE	73.0	111.2	15.4	7.8	64.1
Bias	30.9	27.5	-4.2	-4.1	35.8
D	0.826	0.886	0.700	0.731	0.771
ε	0.655	0.769	0.482	0.471	0.507
MAE	54.4	78.0	11.6	6.1	49.1
RMSE/$\bar{O}_{obs}$	28%	27%	11%	12%	12%

[a] Slope or intercept is not significantly different from one or zero, respectively (two-tailed Student t test, α = 0.05).

Table 4. Statistical parameters of agreement between observed and modeled transmitted shortwave radiation (TRs), transmitted photosynthetically active radiation (TPAR), reflected shortwave radiation (RRs), reflected photosynthetically active radiation (RPAR), and total net radiation (Rn) for upland cotton.

	TRs $W\ m^{-2}$	TPAR $\mu mol\ m^{-2}\ s^{-1}$	RRs $W\ m^{-2}$	RPAR $\mu mol\ m^{-2}\ s^{-1}$	Rn $W\ m^{-2}$
n	319	319	349	1273	1273
mean Obs	356.7	601.0	145.3	101.1	582.1
mean Pred	351.3	606.8	145.3	100.0	508.4
Slope	0.756	0.952[a]	0.977[a]	1.047	0.995[a]
Intercept	81.6	34.5	3.4[a]	-5.9	-71.1
r^2	0.732	0.754	0.910	0.814	0.946
RMSE	64.5	97.6	7.2	22.2	79.4
Bias	-5.5	5.8	0.0	-1.1	-73.7
D	0.722	0.757	0.837	0.775	0.664
ε	0.470	0.470	0.675	0.518	0.273
MAE	55.3	75.5	6.2	15.9	74.0
RMSE/$\bar{O}_{obs}$	18%	16%	5%	22%	14%

[a] Slope or intercept is not significantly different from one or zero, respectively (two-tailed Student t test, α = 0.05).

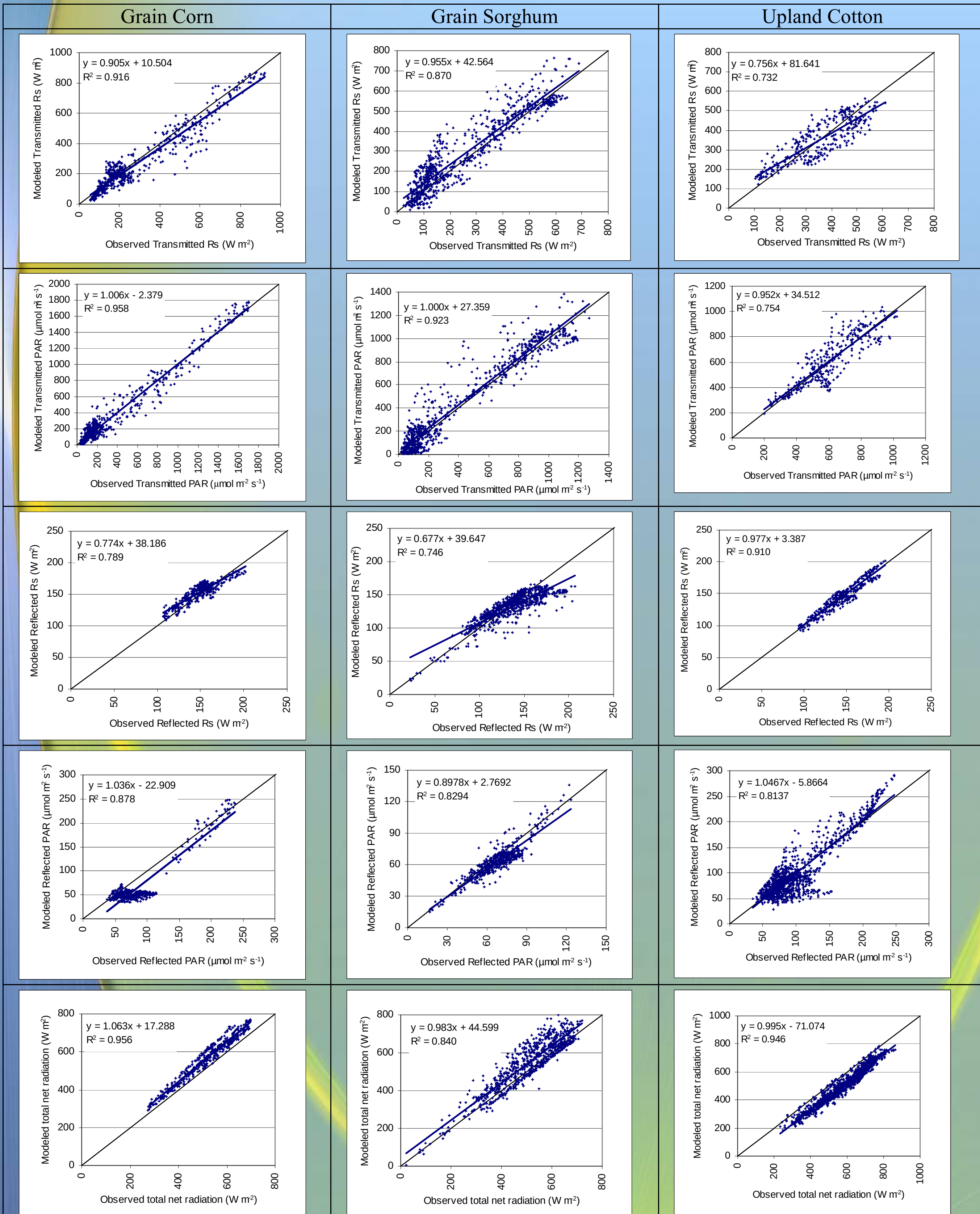

Figure 1. Predicted vs. observed parameters for grain corn, grain sorghum, and upland cotton (see Tables 2, 3, and 4 for additional statistical parameters of agreement).

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Louis Baumhardt attended the statewide "Oklahoma No-Till Conference" for an invited presentation of research results on "Integrated crop-livestock production and tillage effects on crop yields", Oklahoma City; February 11 and 12, 2008.

From February 2-15, 2008, Research Soil Scientist Steve Evett traveled to Jordan to work with partners in the National Centre for Agricultural Research and Extension, the counterpart of USDA-ARS. A large (2.4 by 3.0 by 2.5-m deep, 40-ton) weighing lysimeter was completed, calibrated and commissioned for service to determine crop water use and crop coefficients for irrigation scheduling in the Jordan Valley, where >80% of Jordanian irrigated agriculture exists. The weighing lysimeter is a key part of infrastructure for the Middle Eastern Regional Irrigation Management Information Systems project, a quadrilateral project managed by USDA-OIRP with research partners, weather stations, and irrigation trials in Israel, Jordan and Palestine and with USDA-ARS partners at Bushland, Texas, and Fresno, California. The first crop for the lysimeter will be sweet corn, a high value crop in the Jordan Valley, which will be planted in April. Training on lysimeter operation, planning and conduct of field experiments, and analysis of lysimeter and weather data to complete knowledge of crop water use and irrigation scheduling coefficients was planned for the trip, but was postponed to a later time due to poor weather, equipment that was broken in shipping and the subsequent slippage in scheduling required to overcome these obstacles. Still, the completion of the $65,000.00 lysimeter after a multi-year effort is a major milestone on the road to more efficient utilization of water in irrigated agriculture of the region.

José L. Chávez, Paul Colaizzi, Prasanna Gowda and Susan O'Shaughness welcomed students at a booth set up for the West Texas A&M University Spring Career Fair, February 28, 2008, West Texas A& M University campus, Canyon, TX.

Susan O'Shaughnessy led: In-House Training with Karen Copeland, Brice Ruthardt, and Chad Ford on Basic Electronics- Theory and Hands on Applications on March 17-20, 2008 at Bushland, TX.

Paul Colaizzi led presented information to the Panhandle Groundwater Conservation District in White Deer, TX on Mar 26, 2008 on Cotton performance with Spray, LEPA and subsurface drip irrigation.

Steve Evett led the Radiation Safety Training for neutron soil water meters and Hazardous Materials Transport Training for Radioactive Materials on June 3, 2008 at Bushland, Texas for 23 persons from ARS and partnering agencies in Texas, Oklahoma and North Carolina.

On June 4, 2008, Kevin Welch of the Amarillo Globe News newspaper was hosted by Steve Evett for a tour of the Bushland Evapotranspiration and Agricultural Remote Sensing Experiment 2008 (BEAREX08) field research activities. This resulted in an article "Measuring Water: Project aims to reduce use of aquifer by farms' crops" by Mr. Welch in the Amarillo Globe News on Tuesday, June 10, 2008, page 6D.

June 16, 2008, USDA Radio News interviewed Steve Evett about automated irrigation systems using infrared temperature sensors. Steve discussed the development of the automation system, first for drip irrigation and now for center pivot irrigation, and he pointed out that earlier research proved that the system works and developed the underlying theory and methods. System development is now focused on engineering robustness by including weather and soil water sensors and developing control code to produce as reliable a system as possible.

Check it out: Texas High Plains ET Network
http://txhighplainset.tamu.edu/

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MEETINGS & PRESENTATIONS

Terry Howell, José Chávez, and Susan O'Shaughnessy attended the 28th Annual International Irrigation Show December 9-11, 2007 in San Diego, CA. José Chávez presented the paper "Evaluating Three Evapotranspiration Mapping Algorithms with Lysimetric Data in the Semi-arid Texas High Plains"; Terry Howell presented "Is Irrigation Real or Am I Imagining It?"; Freddie Lamm with Terry Howell and James Bordovosky presented "Ensuring Equal Opportunity Sprinkler Irrigation"; Robert Lascano with Steve Evett presented "Experimental Verification of a Recursive Method to Calculate Evapotranspiration"; Giovanni Piccinni with Jonghan Ko, Amy Wentz, Daniel Leskovar, Terry Howell, and Thomas Marek presented "Determination of Crop Coefficients (Kc) For Irrigation Management of Crops"; and Susan O'Shaughnessy presented "IRT Wireless Interface for Automatic Irrigation Scheduling of a Center Pivot System".

Susan O'Shaughnessy, Terry Howell, Paul Colaizzi, Louis Baumhardt, Brice Ruthardt, Ed Hutcherson, Jim Cresap, Chad Ford, Don McRoberts, and Jennifer Childers attended the Texas North High Plains Conference, January 16, 2008, Amarillo, TX.

R. Louis Baumhardt was an invited speaker for the No-Till Oklahoma Conference and presented a paper entitled "Integrating Cattle Grazing into the Dryland Wheat-Sorghum-Fallow Rotation". The conference dates were February 10–12, 2008 , Oklahoma City, OK.

Susan O'Shaughnessy attended the Central Plains Irrigation Short Course and Exposition, February 19–20, 2008, in Greeley, CO.

Terry Howell and Carole Perryman attended the 2008 SPA Leadership Conference in Galveston, TX., February 20–21, 2008.

Paul Colaizzi attended the EWRI Leadership Council Weekend February 23-24, 2008 in Los Angeles, CA.
On March 3–6, 2008, Prasanna Gowda attended a CR1000/ Loggernet Training in Logan, UT.

The Ogallala Aquifer Program Workshop was held in Amarillo, TX. on March 11-13, 2008. All SWMRU scientists participated.

Terry Howell and R. Nolan Clark attended the Calera Aquifer Workshop on March 17–19, 2008, in Zacatecas, Mexico.

Louis Baumhardt attended the 38th Biological Systems Simulation Group Conference April 8-10, 2008, in Temple, TX. and presented a paper on "Simulating the effects of growing season length and irrigation practices on cotton growth and yield".

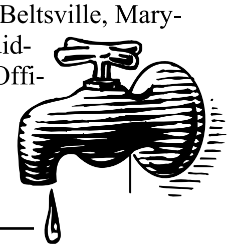
José Chávez participated in the Open Path Gas Analyzer Eddy Covariance (OPEC) Training at Campbell Scientific Inc., May 12-16, Logan, UT.

Paul Colaizzi, Prasanna Gowda and Terry Howell attended the World Environmental & Water Resources Congress '08, May 12-16, Honolulu, HI. Prasanna Gowda presented "Comparing SEBAL ET with Lysimeter Data in the Semi-Arid Texas High Plains"; Terry Howell presented "Evapotranspiration of Corn and Forage Sorghum for Silage"; and Thomas Marek presented with Dana Porter, Terry Howell, Prasanna Gowda, Paul Colaizzi, Steve Amosson, and Fran Bretz "Cotton Production Potential and Water Conservation Impact using the Regional Irrigation Demand Model of Northern Texas". Paul Colaizzi chaired On-Farm Irrigation Systems Committee attended Task Committee on Putting Irrigated Agriculture in Perspective, and Presented paper "A review of evolving critical priorities in irrigated agriculture."

Terry Howell attended the Consortium for Irrigation Research and Education (CIRE) Annual Meeting, May 21-22, 2008, Uvalde, TX.

Prasanna Gowda attended the ARS Congressional Briefing Conference in Washington, D.C. on June 2-5, 2008.

On June 11-12, 2008, Steve Evett attended the Information Technology Steering Committee meeting at Beltsville, Maryland. The committee provides review and guidance to the Office of the Chief Information Officer for ARS.



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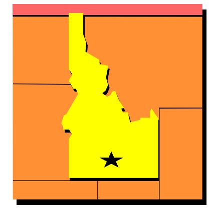

On September 2, 2008, Steve Evett plans to begin work at the Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho as Research Leader. Steve expects to continue strong collaborations with the Bushland research team, particularly since there are many parallel problems in irrigated agriculture being tackled by the two laboratories. This is a chance for Steve to assume a leadership role in ARS and to return to Southern Idaho where he was raised. Steve's e-mail address remains the same: Steve.Evett@ars.usda.gov. The main office number at USDA-ARS, Kimberly is 208-423-5582.

"We want everyone to know that we do not make this move lightly, particularly in light of the strong friendships that we have in the Amarillo area. There are a lot of pluses along with the minuses associated with leaving our Bushland family. In particular, we are excited to join the great ARS team at Kimberly and the Kimberly community and schools. Over the years there has been strong collaboration between the Bushland and Kimberly ARS teams, and I expect that this will only be reinforced by our move. Priscilla Sheets, my wife, will teach 5th grade at the Kimberly elementary school and Matthew, our son, will continue his education at the University of Colorado, Boulder. We want to express our sincere gratitude for all the friendships, collaborations, adventures and support that we experienced during the past 18 years in the Texas Panhandle as part of the Amarillo and Bushland communities and the great ARS team at Bushland. Anytime you all are in Southern Idaho, please look us up. We will be very glad to see you."

Congratulations Go To:

Dr. R. Louis Baumhardt recognized as one of four outstanding Associate Editors by the Soil Science Society of America Journal for 2007.

Authors listed in the following paper will be receiving an ASABE Superior Paper Award at the ASABE Annual International Meeting, June 29 to July 2, 2008 in Providence, RI: Enciso-Medina, J. M., P. D. Colaizzi, W. L. Multer, and C. R. Stichler. 2007. Cotton response to phosphorus fertigation using subsurface drip irrigation. Applied Engineering Agriculture. 23(3): 299-304.

Dr. Steve Evett has been selected as a Fellow of the Soil Science Society of America. He will receive the award at the Annual International Meetings in October at Houston, TX.

Jourdan Bell, Biological Science Technician recently completed a year at Texas A&M University in College Station, Texas for advanced training towards a Ph.D. in Soil Physics.

Jennifer Childers, Biological Science Technician, and husband, Casey, welcomed the arrival of Garrett Lee Childers, born on 6/5/2008.

A retirement luncheon was held May 30th recognizing 20 years of Federal Service by Carole Perryman, Program Assistant for the Soil and Water Management Research Unit (SWMRU).

Check out a feature story

Measuring water Project aims to reduce use of aquifer by farms' crops

In Amarillo Globe News, June 10, 2008, at http://www.amarillo.com/stories/061008/bus_10471335.shtml

Photo Courtesy Kevin Welch / Amarillo Globe-News

Paul Colaizzi, agricultural engineer at the Agricultural Research Service Laboratory at Bushland, holds one of the devices researchers are putting in place in the lab's fields to measure water usage by cotton plants.

SOIL AND WATER MANAGEMENT RESEARCH UNIT
2008 Summer Seminar Series
CPRL Conference Room at 3:30 pm on Thursday

June 26	Radiation Transmission Through Row Crop Canopies: A Submodel for the Two-Source Energy Balance (TSEB) Model by Paul Colaizzi
July 3	ASABE Meeting
July 10	Assessing Crop Evapotranspiration from Point to Regional Scale in the Texas High Plains by Prasanna Gowda
July 17	CSREES 202/ASCE ET
July 24	Treating and Recycling Animal Wastewater for Irrigation Re-Use by Susan O'Shaughnessy
TBA	Mineraology of the Pullman Soil by Jourdan Bell

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New Addition

Hello everybody! My name is Jairo Hernandez, and I joined the Soil and Water Management Research Unit in the USDA-ARS Conservation and Production Research Laboratory (CPRL), Bushland, TX as a post-doctoral researcher for Dr. Prasanna Gowda this May. My main research interests include groundwater modeling, ET remote sensing, and the application of artificial intelligence in water resources management. Currently I am involved in modeling of a 4-county area in the Texas Panhandle using the MODFLOW and ET remote sensing. This research is a part of the larger project titled "Impacts of alternative water policies on rural economies and aquifer hydrology" funded by the Ogallala Research Initiative.

I am a Ph.D. graduate from Utah State University (USU) in the Biological and Irrigation Engineering Department specializing in irrigation engineering. I graduated in spring of 2008 and my dissertation's title was "Canal Structure Automation Rules Using a Hydraulic Simulation Model, an Accuracy-based Learning Classifier System, and Genetic Algorithms." Also, I have a M.S. degree in Water Resources and a B.S. degree in Civil Engineering from "Nacional de Colombia" University and "La Gran Colombia" University, respectively.

I have more than twenty years of experience in hydrology and hydraulics, and I have worked for both private and public agencies in Bogota, Colombia before I moved to the USU to join the Ph.D. program under Dr. Gary Merkley. At USU, I worked in the Remote Sensing Services Laboratory as a graduate research associate and participated in developing a Geographic Information System (GIS) layers for irrigation management in the Dominican Republic. Finally, before starting with the USDA-ARS, I held a research assistant position at the USU Geomorphology Laboratory using remote sensing and GIS for monitoring sediment storage throughout river main channels, and mentored graduate students, too. I love computer programming, and I am proficient in Visual Basic, C++ and C#. I am very pleased to be a part of the magnificent research team at CPRL.

With the cost of gas soaring, a group of employees at the Conservation and Production Research Laboratory recently invested in a used vehicle that was previously used by an adult daycare center. The "Bushland Express" is offered to fellow employees for a small fee. The route is approximately 50 miles round-trip.

The Conservation and Production Research Laboratory employees have taken on the challenge of recycling materials used daily around the office. A trailer was purchased to transport cardboard to the recycling center. All boxes have to be completely flattened so that the recycler (Allied Waste) will accept the cardboard.

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