Transpiration and Yield Relationships of Grain Sorghum Grown in a Field Environment

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ABSTRACT

The ability of plants to convert transpiration (T) into dry matter has been studied since the early 20th century. Research has compared differences among species using transpiration efficiency (TE), the ratio of biomass yield (Yb) to T; and m and k, which are the slopes of the linear Yb/T relationship normalized by atmospheric evaporative demand. The objective of this research was to develop transpiration and biomass relationships (TE, m, and k) and the transpiration and grain relationship (TEg) of grain sorghum (Sorghum bicolor L. Moench) grown in a field environment. Grain sorghum was grown in 1998 and 1999 in weighable lysimeters using stored soil water only and in a rain shelter facility. This approach limited the irrigation and precipitation evaporation components of E so that T estimated (Test) using lysimetry in a field environment was emphasized. The TE remained constant through a range of water availability. The TE was similar between the 2 yr, and the combined data produced a slope of the Yb/Test relationship of 3.5 g m⁻² mm⁻¹. This was similar to the 3.3 g m⁻² mm⁻¹ reported for sorghum in the early 20th century, but smaller than current field studies which ranged from 4.0 g m⁻² mm⁻¹ to 5.7 g m⁻² mm⁻¹. The TEg was 2.6 g m⁻² mm⁻¹. Normalization of Test by seasonal averages of reference evapotranspiration and vapor pressure deficit produced significant differences between years in the slopes of the relationships. Transpiration efficiency did not require normalization for variations in climate between years.

The ability of plants to convert T into dry matter has been studied by researchers since the beginning of the 20th century. The early work of L.J. Briggs and H.L. Shantz in the U.S. Great Plains investigated the “water requirement” (or T ratio), which was “the ratio of the weight (mass in kilograms) of water absorbed by a plant during its growth to the weight (mass in grams) of dry matter produced”, of a variety of plants ranging from field crops to native species (Briggs and Shantz, 1913, 1914). Their goal was to determine the crop or variety that was best adapted to regions having a limited water supply. Shantz and Piemeisel (1927) showed that the lowest T ratios based on total dry matter (excluding roots) were obtained for “the millets, sorghums, and corns; the highest values for the native plants, flaxes, and legumes”.

Increasing TE was one factor proposed by Passioua (1977) to increase yield under limiting water supply. Transpiration efficiency, the inverse of the T ratio, is the ratio of dry biomass produced (g) to T (kg), and is also expressed as the slope of the regression between cumulative biomass (g m⁻²) and T (mm⁻¹). Early researchers realized that the T efficiencies measured in the early container work could not be applied to crops in the fields without allowing for the important effects of plant exposure, climate, and soil fertility (Stanhill, 1986). It was recognized that the variation of T with climate caused changes in water use within the growing season, between years, and between locations and that T needed to be adjusted, or normalized, to be made applicable across years and locations. de Wit (1958) normalized T measured in the early container studies using mean daily pan evaporation, which was applicable for climates with a large percentage of sunshine and where production was limited by the availability of water. His equation for dry climates was

\[ Y_b = m \cdot T \cdot E_o^{-1} \]  \[ 1 \]

where Yb is total dry aboveground biomass per area (g m⁻²), T is the total transpiration (mm) during the growth period per unit area, E_o is the mean daily “free water evaporation” for the same period (mm d⁻¹), and m is the slope (g m⁻² d⁻¹) which was considered to be constant for both species and water use. Reference evapotranspiration (ET_r) has been substituted more recently for E_o (Steduto and Albrizio, 2005).

Tanner and Sinclair (1983) normalized T using vapor pressure deficit (VPD) following earlier work by Bierhuizen and Slatyer (1965). Their equation was

\[ Y_b = k \cdot T \cdot VPD^{-1} \]  \[ 2 \]

where Yb is in units of g m⁻², T is in units of kg m⁻², VPD is in kPa, and k is also a slope (Pa) that was considered to be constant for both species and water use.

Measurement of TE in the field is difficult because the water loss from a land area often includes both T and soil water evaporation (E). Briggs and Shantz (1913, 1914) grew plants in

Abbreviations: RMSE, root mean square error; T, transpiration; TE, transpiration efficiency; TEg, transpiration and grain relationship; VPD, vapor pressure deficit; Yb, biomass yield.
an outdoor enclosure in large containers with the soil surface covered to minimize $E$. Hanks et al. (1969) measured ET of sorghum using lysimeters and measured $E$ from an adjacent fallow area and adjusted $E$ for differences in soil shading due to changes in leaf area. Young et al. (2008) also calculated $E$ using methodology based on soil shading by leaf area. Steduto and Albrizio (2005) measured ET of sorghum using a closed-system canopy chamber and calculated $E$ using the approach outlined in Ritchie (1972). The calculated $E$ ranged between 5 and 8%, which they did not factor out of ET to obtain $T$ for their calculation of $TE$.

The objective of this research was to develop $T$ and above-ground biomass relationships ($TE$, $m$, and $k$) and the $T$ and grain relationship ($TE_{g}$) of grain sorghum grown in a field environment in weighable lysimeters using stored soil water only and in a rain shelter facility. This approach limited the irrigation and precipitation evaporation components of $E$ so that the measurement of $T$ using lysimetry in a field environment was emphasized. The $TE$ determined in this experiment could then be compared with the $TE$ reported in earlier and more recent studies, and evaluated as to whether it varied with water availability between years and needed to be normalized for differences in climate between years.

**MATERIALS AND METHODS**

**Site Description**

The experiment was conducted at the Soil-Plant-Environment Research (SPER) facility, USDA-Agricultural Research Service, Bushland, TX, USA (35° 11’ N, 102° 06’ W, 1170 m elevation above MSL). The SPER facility is located in a 0.25-ha field with a rain shelter facility with 48 weighing or weighable lysimeters using stored soil water only and in a rain shelter facility. This approach limited the irrigation and precipitation evaporation components of $E$ so that the measurement of $T$ using lysimetry in a field environment was emphasized. The $TE$ determined in this experiment could then be compared with the $TE$ reported in earlier and more recent studies, and evaluated as to whether it varied with water availability between years and needed to be normalized for differences in climate between years.

**Ulysses Soil**

The Ulysses is a very deep, well drained, moderately permeable upland soil that formed in calcareous loess and has a high water-holding capacity. The Ulysses typically is classified as a silt loam, but slightly lower silt contents of the soil in its surface layers at the monolith collection site resulted in its designation as a clay loam. This is within the allowable variation of the series.

Data for the calculation of $ET_{c}$, and daytime VPD were collected at a weather station with irrigated, cool season grass about 1000 m from the SPER facility. The type of weather station instrumentation was described fully in Dusek et al. (1987). Calculation of $ET_{c}$ followed procedures outlined in Allen et al. (2005). Vapor pressure deficit was calculated as the difference between saturation and actual vapor pressure. Saturation vapor pressure was calculated according to Allen et al. (2005). Actual vapor pressure was calculated using dew point temperature, which was calculated from Murray’s (1967) dew point temperature equation which used measured 2-m air temperature and relative humidity. Daytime hours were those periods when measured solar radiation was not zero.

**Agronomy**

The lysimeters were planted with grain sorghum (‘Pioneer-8699’$^1$) in 1998 and 1999 at a density of 16 plants m$^{-2}$. The plants were in a single row down the center of each lysimeter (N-S orientation), which maintained a 0.75-m row spacing with the adjacent lysimeters and surrounding cropped area. In 1998, planting was on Day of Year (DOY) 181 (30 June), emergence on DOY 187 (6 July), beginning bloom (Vanderlip and Reeves, 1972) on DOY 229 (17 August), and harvest on DOY 272 (29 September). In 1999, planting was on DOY 188 (7 July), emergence on DOY 194 (13 July), beginning bloom on DOY 235 (23 August) and harvest on DOY 292 (19 October). The lysimeters were fertilized according to recommendations based on soil analyses before planting for each soil. Tillage was done by hand to a depth of about 0.2 m. All plants on the lysimeters were hand harvested, the grain mechanically threshed, and stover and grain were dried in an oven at 70°C. Total grain and biomass yields of each lysimeter are reported at 0% water content.

**Soil Water Content Measurement**

Volumetric soil water contents were measured by neutron moisture meter (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) in a centrally located access tube in each lysimeter. The measurements were taken at 0.2-m increments starting at 0.1 m and ending at 2.1 m. The meter was calibrated in situ at the Garden City, KS monolithic collection site using techniques described by Evett and Steiner (1999). Separate

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$^1$The mention of trade names or 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.
calibration equations were developed for each major soil horizon with coefficient of determination ($R^2$) values > 0.9 and root mean square error (RMSE) value ± 0.01 m$^3$ m$^{-3}$. Based on the RMSE values, mass water content measurement error for 2.2 m is ≤ 22 mm.

### Soil Water Treatments

The main experiment involved prewatering 15 lysimeters each year to achieve a range of available soil water at planting. The 2.2-m profile soil water content at planting ranged from 493 to 649 mm in 1998 and 375 to 562 mm in 1999. After which, the lysimeters received no irrigation and only minimal amounts of rainfall as the rain shelter was closing.

### Evapotranspiration Measurements

The seasonal ET was measured by manually weighing the lysimeters periodically using a suspended load cell interfaced with a datalogger. The ET was calculated from the difference in lysimeter mass between weighing intervals minus any drainage water which was periodically checked but did not occur. In 1998, measurements were made approximately weekly from planting through the end of pollination, then once at the end of soft dough and at harvest. In 1999, measurements were made at emergence, three-leaf growth stage, eight-leaf growth stage, beginning bloom, and at harvest.

### Normalization of Transpiration

Transpiration was normalized seasonally for the evaporative demand of the atmosphere using 24-h $E_{To}$ substituted for $E_o$ and VPD. Seasonal normalization of $T$ consisted of the seasonal sum of $T$ divided by the seasonal daily mean of either $E_{To}$ in mm d$^{-1}$ or VPD in kPa averaged for the daytime hours. Following de Wit (1958), the seasonal value of $E_{To}$ and VPD was the mean of the period during which most of the biomass was accumulated, which was from emergence to soft dough (Vanderlip and Reeves, 1972) or about 70 d following emergence.

### Statistical Procedures

To determine whether the data for both years could be combined into a single analysis, the difference between years of the slope and intercept of the ET or $E_{To}$ and biomass relationship was analyzed using the procedures outlined by Freese (1964). Linear regression analysis was performed using a general linear regression model (SigmaPlot for Windows, v. 10, Systat Software, Inc., San Jose, CA).

### RESULTS

#### Crop Development and Climate

The crop in 1998 was planted 7 d earlier than in 1999, and crop development between years generally maintained this difference throughout the growing season. Reference ET indicated hotter and drier conditions in July of 1998 compared with those in 1999 (Table 1). In August, conditions were similar between years, but in September, daily $E_{To}$ was larger in 1998 than in 1999. For the equivalent period in each growing season (DOY 193 through DOY 270), $E_{To}$ totals were 476 mm in 1998 and 436 mm in 1999.

### Soil Water Treatments

The initial soil water contents ranged from about 375 to 650 mm with ET increasing linearly through this range (Fig. 1). The lysimeters received a total of 10.9 mm of rainfall in 12 events in 1998, with all events being <2 mm except one, which was 3.1 mm. In 1999, the lysimeters received a total of 8.4 mm of rainfall in ten events, all <2 mm.

### Biomass Yield and Evapotranspiration

Biomass yield and ET averaged for a soil water treatment ranged from 357 g m$^{-2}$ of biomass produced with 127 mm of ET in 1999 to 1152 g m$^{-2}$ of biomass produced with 340 mm ET in 1998. The linear relationships produced were $Y_b = 4.0 (ET-64.7 \text{ mm}) g m^{-2} mm^{-1}$ ($R^2 = 0.93$) in 1998, and $Y_b = 3.5 (ET-25.3 \text{ mm}) g m^{-2} mm^{-1}$ ($R^2 = 0.95$) in 1999 (Fig. 2A). The analyses of the ET and $Y_b$ relationships for 1998 and 1999 showed that there were no significant differences in slope ($P = 0.19$) or intercept ($P = 0.06$) between years which allowed the data to be combined (Fig. 2B). The combined data produced the linear relationship (including the standard error of the slope, SE) of $Y_b = 3.5(ET-28.1 \text{ mm}) g m^{-2} mm^{-1}$ ($R^2 = 0.95$, SE = 0.1 g m$^{-2}$ mm$^{-1}$). The large $R^2$ value showed the direct association between the measured ET of this experiment and biomass production.

| Table 1. Average climatic parameters for each month of the cropping season in 1998 and 1999, including $E_{To}$, 0.12-m grass reference evapotranspiration; $T_{max}$, maximum temperature; $T_{min}$, minimum temperature; $T_{dew}$, dew point temperature; U, 2-m wind speed; R, solar radiation; and VPD, vapor pressure deficit. |
|---|---|---|---|---|---|---|---|---|
| | $E_{To}$ | $T_{max}$ | $T_{min}$ | $T_{dew}$ | U | R | VPD |
| | mm d$^{-1}$ | °C | °C | °C | m s$^{-1}$ | MJ m$^{-2}$ d$^{-1}$ | kPa |
| 1998 | | | | | | | |
| July | 7.5 | 33.5 | 18.9 | 15.2 | 3.6 | 25.9 | 2.2 |
| August | 5.9 | 30.5 | 16.8 | 14.9 | 3.2 | 23.1 | 1.4 |
| September | 5.5 | 30.2 | 15.5 | 12.6 | 3.4 | 19.9 | 1.5 |
| 1999 | | | | | | | |
| July | 6.6 | 30.8 | 18.0 | 17.0 | 3.8 | 27.0 | 1.2 |
| August | 6.3 | 31.5 | 17.7 | 16.0 | 3.3 | 24.6 | 1.3 |
| September | 4.1 | 24.8 | 12.5 | 11.2 | 3.3 | 17.6 | 0.9 |
| October | 4.1 | 22.1 | 6.0 | 3.4 | 4.0 | 16.4 | 0.9 |
reflecting the conservative relationship between biomass production and ET through a range of limited soil water availability. Other reported regression slopes (no intercept reported) for the relationship between Yb and ET include 5.7 g m\(^{-2}\) mm\(^{-1}\) for well-fertilized grain sorghum (Steduto and Albrizio, 2005) and 4.3 g m\(^{-2}\) mm\(^{-1}\) for grain sorghum grown under a range of irrigation treatments (Farre and Faci, 2006).

The intercept of Fig. 2B was significantly different from zero (P = 0.02). According to Hanks et al. (1969), French and Schultz (1984), and Angus and van Herwaarden (2001), the abscissa intercept represents the 2-yr average of the seasonal soil water evaporation. Given the limited rainfall and the absence of irrigation, 28.1 mm seems a reasonable estimate of average seasonal soil water evaporation from a soil primarily in stage 2 drying (Ritchie, 1972). In stage 2 drying, E below a canopy is considered to be identical to evaporation from a bare soil surface that is more dependent on the soil hydraulic properties and less dependent on available energy that would be impacted by changes in leaf area (Ritchie, 1972). The soil water evaporation estimate allowed a fairly accurate estimate of T from the measurement of ET.

**Biomass Transpiration Efficiency**

To evaluate the relationships between T and biomass yield, the average estimated soil water evaporation of 28.1 mm was subtracted from the seasonal ET for both seasons to estimate transpiration (T\(_{est}\)). Transpiration efficiency, calculated as the slope of dry biomass (g m\(^{-2}\)) at harvest to T (mm), was 3.5 g m\(^{-2}\) mm\(^{-1}\) (SE = 0.15 g m\(^{-2}\) mm\(^{-1}\)) with an \(R^2\) of 0.95. The intercept was not significant at P = 0.96. Using harvest biomass and T data for sorghum compiled by de Wit (1958) from the 20th century historical container studies, TE was 3.3 g m\(^{-2}\) mm\(^{-1}\) (SE = 0.22 g m\(^{-2}\) mm\(^{-1}\)) with an \(R^2\) of 0.95 and an intercept not significant at P = 0.14. Young et al. (2008) calculated an average TE of 4.0 g m\(^{-2}\) mm\(^{-1}\) for sorghum grown in Australia using biomass at harvest. Steduto and Albrizio (2005) reported a TE of 4.4 g m\(^{-2}\) mm\(^{-1}\) for an unfertilized sorghum crop and 5.7 g m\(^{-2}\) mm\(^{-1}\) for a well-fertilized sorghum crop.

**The Slope m**

To determine m (Eq. [1]), the ET\(_o\) values used were 6.6 mm d\(^{-1}\) for 1998 and 6.1 mm d\(^{-1}\) for 1999, which were somewhat lower than the average pan evaporation E\(_o\) value of 6.7 mm d\(^{-1}\) used by de Wit (1958). The slope of the Yb/ T\(_{est}\) ET\(_o\) \(^{-1}\) relationship, or m, for this experiment was 26.4 g m\(^{-2}\) d\(^{-1}\) (\(R^2\) = 0.94, SE = 1.9 g m\(^{-2}\) d\(^{-1}\)) in 1998 and 21.5 g m\(^{-2}\) d\(^{-1}\) (\(R^2\) = 0.95, SE = 1.3 g m\(^{-2}\) d\(^{-1}\)) in 1999 (Fig. 3). The data for each year could not be combined because of a significant difference between slopes (P = 0.04). The intercept of the Yb/T\(_{est}\) ET\(_o\) \(^{-1}\) relationship in both years was not significantly different from zero (P = 0.17). Both slopes were larger than de Wit’s reported value of 20.7 g m\(^{-2}\) d\(^{-1}\) for sorghum, but were smaller than the 32.9 g m\(^{-2}\) d\(^{-1}\) reported by Steduto and Albrizio (2005) in a study on well-fertilized grain sorghum. Using only the best yielding sorghum cultivars of the early container studies by Briggs and Shantz (1913, 1914), Tanner and Sinclair (1983) reported an m value of 24 g m\(^{-2}\) d\(^{-1}\). Hanks et al. (1969) determined an m for sorghum of 14.1 g m\(^{-2}\) d\(^{-1}\) based on estimates of E from fallow land.

**The Slope k**

Average daytime VPDs of 2.3 kPa in 1998 and 1.8 kPa in 1999 were used to normalize T\(_{est}\) to determine k using Eq. [2]. The slopes of the Yb/ T\(_{est}\) VPD\(^{-1}\) relationship, or k, were 9.2 Pa (\(R^2\) = 0.93, SE = 0.7 Pa) in 1998 and 6.3 Pa (\(R^2\) = 0.95,
Transpiration efficiencies were similar in both years, but normalizing $T_{est}$ using VPD resulted in significant differences between years in both slope ($P < 0.01$) and intercept ($P < 0.01$). Tanner and Sinclair (1983) reported a value of $k$ of 13.8 Pa for grain sorghum when leaf area index was 3.0 or larger and Young et al. (2008) a value of 8.1 Pa calculated using sorghum biomass at harvest. Steduto and Albrizio (2005) reported a $k$ of 8.5 Pa for unfertilized sorghum and 11.3 Pa for fertilized sorghum. Mortlock and Hammer (1999) gave 9 Pa as an accepted value for $k$ of grain sorghum.

Grain Transpiration Efficiency

Angus and van Herwaarden (2001) gave an upper limit of TEg based on grain yields of wheat as 2 g m$^{-2}$ mm$^{-1}$ which Passioura (2006) later applied to well-managed, disease free, water-limited cereal crops. In this experiment, there were no significant differences in slopes ($P = 0.37$) or intercepts ($P = 0.55$) between years so the data were combined. The $T_{g}$ was 2.6 g m$^{-2}$ mm$^{-1}$ (Fig. 5) for grain at 0% moisture and 2.9 g m$^{-2}$ mm$^{-1}$ for grain at 12% moisture with the latter being 45% larger than the limit proposed by Passioura (2006). Based on a regression of $Y_{g}$ on $T_{est}$ of grain sorghum grown in Australia, Young et al. (2008) reported a $T_{g}$ of 2.2 to 2.4 g m$^{-2}$ mm$^{-1}$ with grain at 12% moisture. Young et al. (2008) credited their lower $T_{g}$ compared with other reported crops to reduced leaf area, lower then desirable plant population, delays in germination, and harsher climate.

A crop may have sufficient water to support biomass development, but not to produce grain yield. The abscissa intercept for $Y_{g}/T_{est}$ relationship suggests that 88 mm of $T_{est}$ would be required to produce grain yield (Fig. 5). The $R^{2}$ of the $Y_{g}/T_{est}$ relationship was slightly smaller than that of the $Y_{b}/T_{est}$ relationship, which suggests that other factors such as water stress and climate interactions may have variably affected grain yield. The ratio of grain yield to biomass yield, or harvest index (HI), had considerable scatter throughout most of the range of $T_{est}$ (Fig. 6). The HI did not become fairly constant until the maximum HI of about 0.55 when $T_{est}$ exceeded 300 mm.

DISCUSSION

de Wit (1958) stated that TE was proportional to the evaporation from a free water surface, but more or less independent of fertility and the availability of water. The soil water treatments in this experiment ranged from 493 to 649 mm in 1998 and 375 to 562 mm in 1999 for a 2.2-m depth (Fig. 1), and TE remained fairly constant throughout the range of water availability and the differences in climate between years.

Stanhill (1986) noted that TE increased markedly with atmospheric demand. While VPD and $E_{To}$ were slightly larger in 1998 compared with 1999, the similarity in TE between years suggests that the differences in climate between years were not substantial enough to significantly affect TE. Normalization of $T_{est}$ by seasonal averages of $E_{To}$ and VPD produced significant differences in the slopes $m$ and $k$ between years (Fig. 3 and 4). Normalization by daily time steps (Tanner and Sinclair, 1983) or in smaller time intervals (Steduto and
Albrizio, 2005) may be required to reflect the impact of within season climatic variability on TE.

The TE in this research was 3.5 g m\(^{-2}\) mm\(^{-1}\), which was similar to the 3.3 g m\(^{-2}\) mm\(^{-1}\) of the early container studies, but smaller than the 4.3 g m\(^{-2}\) mm\(^{-1}\) reported by Young et al. (2008), all based on sorghum biomass at harvest. According to Hanks (1983), the variations reported through the years may be mostly dependent on variety. de Wit (1958) also stated that variations could occur if the nutrient level was too low, the water availability was too high, or the leaf mass too dense. Variations may also have occurred due to the different methodology in accounting for or preventing soil water evaporation. However, Tanner and Sinclair (1983) commented that to the extent \( m \) is a measure of TE for total biomass production that there has been no consistent improvement in \( m \) between the crops grown in the early container studies and recently.

Hammer et al. (1997) examined 49 diverse sorghum lines for variations in TE in a glasshouse study and reported a TE range of 4.4 to 7.7 kg m\(^{-1}\). Donatelli et al. (1992) found a TE range of 9.4 to 12.6 g kg\(^{-1}\) in six genotypes, also in a glasshouse study. While the glasshouse studies were designed to identify lines that will improve the TE of sorghum, the larger efficiencies may also have been related to the timing of the biomass samples. The larger TE came from studies of shorter duration than a full season, for example, those measuring T and biomass at the flag leaf stage (Hammer et al., 1997), at anthesis (Donatelli et al., 1992), or example, those measuring T and biomass at the fl age leaf stage (Hammer et al., 1997), at anthesis (Donatelli et al., 1992), or at leaf area indices >3 (Tanner and Sinclair, 1983). Young et al. (Hammer et al., 1997), at anthesis (Donatelli et al., 1992), or at leaf area indices >3 (Tanner and Sinclair, 1983). Young et al. (2008) reported that \( k \) increased from 5.2 kPa for preanthesis sorghum to 7.2 kPa for postanthesis sorghum, with a \( k \) at final harvest of 8.1 kPa. However, Steduto and Albrizio (2005) found TE, \( m \), and \( k \) of sorghum constant throughout the season.

CONCLUSIONS

Transpiration efficiency remained constant through a range of water availability and differences in climate between years in this experiment. The TE was similar between the 2 yr, and the combined data produced a slope of the biomass at harvest and seasonal T\(_{\text{est}}\) relationship of 3.5 g m\(^{-2}\) mm\(^{-1}\). This was similar to the 3.3 g m\(^{-2}\) mm\(^{-1}\) reported for sorghum in the early 20th century, but smaller than other field studies which ranged from 4.0 to 5.7 g m\(^{-2}\) mm\(^{-1}\). The T\(_{\text{est}}\) was 2.6 g m\(^{-2}\) mm\(^{-1}\) which slightly larger than other reported values. Variations in TE may be due to differences in variety, agronomic management, timing of biomass samples, and methods for determining soil water evaporation. Normalization of T\(_{\text{est}}\) by seasonal averages of ET\(_{o}\) and VPD produced significant differences in the slopes of the Y\(_{o}/T_{\text{est}}\), ET\(_{o}\), and the Y\(_{o}/T_{\text{est}}\) VPD\(^{-1}\) relationship, or \( m \), and the Y\(_{o}/T_{\text{est}}\) VPD\(^{-1}\) relationship, or \( k \), between years. Transpiration efficiency did not require normalization for variations in climate between years in this experiment.

REFERENCES

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