

The Differences in Water Use Efficiency between Maize and Soybean in Central Iowa

Emily Marrs

Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

Kati Togliatti – Mentor

Department of Agronomy, Iowa State University, Ames, Iowa

Andy VanLoocke – Mentor

Department of Agronomy, Iowa State University, Ames, Iowa

ABSTRACT

In the future, global population and temperature are predicted to increase, causing greater demand for water and increased competition between agriculture and other important sectors. One way to help meet this demand, is to identify strategies that increase water use efficiency (WUE) which is the ratio of crop production to water uptake. Improving WUE requires a baseline data in water dynamics. While there are lots of data comparing WUE for numerous crops and environments, research isolating evapotranspiration (ET) and WUE from all other environmental factors is limiting. To address this, we conducted a side-by-side evaluation of total ET and WUE of two major crops, maize (corn) and glycine max (soybeans), at a site in the U.S. Corn Belt. ET was determined using micrometeorological measurements, which were replicated for each crop and WUE was calculated using aboveground harvested biomass in the growing season of 2016. Growing season temperatures and precipitation were slightly above climatological normal. Our results indicate that maize concluded with higher cumulative ET but when both canopies are fully developed the two species do not differ significantly in the amount of water used. Maize also concluded with a higher WUE.

1. Introduction

Water scarcity is a major limiting factor in agricultural production around the world (Rijsberman, 2006). With

temperatures predicted to rise in the future, the demand for water will increase in order to grow the sufficient amount of calories for our growing population (Kimball et al., 1994). This

demand for fresh water will further increase due to greater competition between agriculture and other important sectors. With potentially less water available to the plant, the drought sensitivity must be decreased to get higher yields (Lobell et al., 2014).

To keep up with global food demand, yields must increase substantially by quantifying food production on every hectare of currently farmed land. This capacity will be limited by amount of land and water resources available for crop production (Van Ittersum et al., 2013). Given that water is often a limiting factor in increasing productivity, it is necessary to have higher yield production from the same water resources or the same production from less water resources. This ratio of water use to crop production is known as the water use efficiency (WUE) and is defined here as the total yield produced per unit of water lost through evapotranspiration (ET) by means of soil evaporation (E) and plant transpiration (T) (Zwart et al., 2004; Doorenbos et al., 1979; Mudenda et al., 2016).

In order to assess how each crop uses water, a number of variables must be

considered for their impacts. These variables include ET, carbon dioxide [CO₂] concentrations in the atmosphere, and vapor pressure deficient (VPD).

ET, which is water evaporated by land and vegetation into the atmosphere, is an important component to the hydrological cycle and the surface energy balance. This makes it critical to assess the affects from bioenergy crop growth on ET, as moisture from ET contributes to 75% of the annual precipitation in the United States (Suyker and Verma, 2008; Anayah and Kaluarachchi, 2014). Therefore, an accurate estimation of ET can predict changes in the hydrological cycle and improve water resource management.

Another key variable is [CO₂] concentrations and its effect on photosynthesis. A process where the microscopic pores of the leaf (i.e. stomata) open and allow CO₂ to diffuse to the intercellular leaf spaces where it is fixed in photosynthesis. While these pores are open, water vapor simultaneously evaporates through a process called transpiration (Haupt 1978). By increasing the amount of CO₂ concentration available to the plant, the

pores open less, allowing less water to be lost via transpiration. Although this could in return decrease the drought stress in these crops, rising amounts of CO₂ emissions can be a cause for the increasing temperatures, which in result can affect the next variable, VPD.

VPD is defined as the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated which is also directionally proportional to water loss from crop leaves (Nobel 2009).

While increasing VPD will increase the demand for water, the response may vary significantly between crops with differing physiology. Crops can be categorized into C₃ or C₄ based on how they use the resources available to process photosynthesis. The performance of these two are dependent on levels of CO₂ in the atmosphere. C₄ crops concentrate CO₂ around rubisco, an enzyme contributing to carbon fixation during photosynthesis that gives higher photosynthetic rates at lower stomatal conductance contributing to higher WUE.

Maize (corn, *Zea mays*) is a C₄ plant, with efficient use of CO₂, solar radiation, nitrogen and water, which will result in higher productivity than C₃ crops, including Soybeans when in warmer climates (*Glycine max*)(Huang et al., 2006; Mudenda *et al.*, 2016).

A study by Zwart et al. (2004) looked at the differences of crop water productivity between three C₃ crops (wheat, rice, and cotton) and one C₄ crop (maize). In this study measurements were taken from field experiments under various growing conditions, including climate, irrigation, fertilization, soils, etc. The study concluded that maize had a significantly higher crop water efficiency compared to the other C₃ crops studied.

A similar study was conducted at the Iowa State Research farm where WUE values were compared between maize and another C₄ crop, sorghum. Here, Roby et al. (2017) hypothesized the two crops to have similar ET and WUE values. What they discovered was that the difference in ET between the two crops was not significant but maize ended up with higher WUE values over the two-year study. They suggested these

differences in ET and WUE emerge when the growing season undergoes temperature or drought stress in crops that share similar characteristics.

Another study showing the comparison of C₃ and C₄ crops was done by Yu et al. (2004) and was conducted in Matsudo, Japan the summer of 1998 between maize and soybean. Each crop was under similar water and nutrient stresses and concluded maize to have two and a half times higher WUE values as that of soybeans.

Even though this is an area that has been researched before, there is still a gap in research: a side-by-side comparison of water use efficiency between maize and soybean. By conducting the research study in the same field, management methods, soil type, and rainfall amount can all be held constant making it possible to compare VPD and WUE between the two crops (Van Ittersum et al., 2013).

To address this gap, our objective was to compare the water use efficiency among maize and soybean to see how much water is needed for production by looking at the impacts of VPD

throughout the growing season. We hypothesize that maize would have higher water use efficiency due to its C₄ characteristics than soybean. To test this hypothesis, a side-by-side experiment was done during the growing season of 2016 using micrometeorological measurements and above ground biomass from the Ag Engineering and Agronomy Research Farm in Boone, Iowa.

Methods

2.1. Site description and management

Our micrometeorological weather stations were randomized (n=3) between maize and soybean at the Iowa State University Agronomy and Agricultural Engineering Research Farm (42° 01'20.37"N, 93° 46'36.05"W) in Boone County, IA, U.S. during the 2016 growing season in a maize-soybean rotation. The dominant soil series are primarily Nicollet (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Caniesto (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), and Webster (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls) (Soil Survey Staff, 2014; Web Soil Survey). A typical maize

hybrid for the region (Pioneer 1151AM) was planted on May 16th at a seeding rate of 35,000 seeds ac⁻¹ at a depth of 2 inches. Additionally, soybean hybrid (Pioneer 92Y75) was planted on June 3rd at a seeding rate of 140,000 seeds ac⁻¹ at a depth of 1.5 inches. Plots were separated between early and late planting dates (planting dates about a month apart) occupying 12 rows at 30' spacing.

2.3. Micrometeorology

Micrometeorological stations were evenly located three in a row between two late-planted maize and soybean plots, respectively. Each plot occupied 12 rows at 30 inch spacing. Observations were obtained via micrometeorological instruments wired into a datalogger (models CR1000, Campbell Scientific Inc., Logan, UT, USA). Measurements were collected in 10-second intervals by the datalogger. Instrumentation used is described in the following sections. The stations were installed on May 17, 2016 for maize and June 7, 2016 for soybeans. The arms on the towers that held the instruments were raised on June 23rd, July 5th, and July 20th to maintain

adequate distance of 1 meter between crops and instruments.

2.4. Surface Energy Balance

The residual energy balance method was selected due to its ability to detect relative differences of evapotranspiration (ET) due to relatively low sensitivity to fetch constraints (Kimball et al., 1994). This approach allows for estimation by assuming the net of energy fluxes caused by photosynthesis, respiration, and heat storage within the canopy to be negligible (Meyers and Hollinger, 2004).

2.4.1. Latent Heat Flux

Latent heat flux (λET) is the flux of heat from the Earth's surface that is associated with evaporated or transpired water to the atmosphere. λET was estimated by calculating for the residual in the surface energy balance equation (Huband and Montieth, 1986; Jackson *et. al.*, 1987):

$$\lambda ET = R_n - G_0 - H \quad (1)$$

Where λET is latent heat flux ($W m^{-2}$; positive upward), R_n is net radiation (Wm^{-2} ; positive downward), G_0 is soil surface heat flux ($W m^{-2}$; positive upward), and H is sensible heat flux ($W m^{-2}$; positive upward). From this,

evapotranspiration (ET; mm), defined as the sum of plant transpiration and evaporation from the soil and canopy. ET can be estimated by dividing λET by λ (latent heat of vaporization of water; J kg⁻¹). Total ET (mm) was calculated as the cumulative sum of ET from emergence to harvest.

2.4.2. Net Radiation

Net radiation (R_n) was measured using measurements provided by a 4-component radiometer (NR01, Hukseflux Thermal Sensor, Delft, The Netherlands) in each plot. Prior to experiment, radiometers were factory calibrated.

2.4.3. Soil Heat Flux

Soil heat flux (G_0) was calculated as:

$$G_0 = G_{10} + C\Delta z \left(\frac{\Delta T}{\Delta t} \right) \quad (2)$$

where G_{10} is the soil heat flux at 0.10 m soil depth, C is the soil volumetric heat capacity (approximated as 2 MJ m⁻³ °C⁻¹; Campbell and Norman, 1998), and ΔT is the change in soil temperature in time Δt over soil depth Δz . One soil heat flux plate (HFP01, Hukseflux Thermal Sensors, Delft, The Netherlands) buried

at a depth of 0.10 m was located in each plot. Heat storage was measured using a thermistor (109, Campbell Scientific, Logan, UT, U.S.) buried directly above each soil heat flux plate.

2.4.4. Sensible Heat Flux

Sensible heat flux (H) was calculated as:

$$H = \rho_a c_p \frac{T_s - T_a}{r_a} \quad (3)$$

where ρ_a is the air density (kg m⁻³), c_p is the specific heat capacity of air (J kg⁻¹ °C⁻¹), T_s and T_a are the surface and air temperatures (°C) respectively, and r_a is the aerodynamic resistance (s m⁻¹). To measure T_s , an infrared radiometer (SI-111, Apogee Instruments, Logan, UT, U.S) was used and positioned at a 30° angle from the vertical to view along the crop row. The height of the radiation instrument was adjusted regularly to maintain a separation distance of 0.2 m from the developing canopy.

2.4.5. Atmospheric Resistance

Atmospheric resistance was calculated following the method in previous residual energy balance studies (Kimball et al., 1994; Hickman et al., 2010; Roby et al., 2017) using different equations

based on wind speed, atmospheric stability, and canopy height (Jackson et al., 1987). Wind speed (u) was measured using a cup anemometer (14A, Met One, Grants Pass, Or, U.S.) and T_a was measured an air temperature and humidity probe (CS215-L, Campbell Scientific, Logan, UT, U.S.). These instruments were periodically raised to maintain separation between the developing canopies (Hickman et al., 2010).

When wind speed (u) experienced neutral conditions, defined as $<0.1 \text{ ms}^{-1}$, $|T_s - T_a| < 0.1^\circ\text{C}$, r_a was set to a value of 1720 sm^{-1} (Triggs et al., 2004). Under non-neutral conditions, $|T_s - T_a| > 0.1^\circ\text{C}$, r_a was calculated as (Hickman et al., 2010):

$$r_a = \frac{p_a c_p}{1.52 |T_s - T_a|^{1/3}} \quad (4)$$

And when u was $> 0.1 \text{ m s}^{-1}$, r_a was solved as:

$$r_a = \frac{1}{u} \left\{ \frac{1}{k} \ln \left[\frac{z - d + z_0}{z_0} \right] \right\}^2 \phi \quad (5)$$

Where k is the von Kármán constant (0.4), z is the height of the wind measurement (m), d is the zero plane displacement ($0.65 \times$ canopy height),

z_0 is the roughness length ($0.1 \times$ canopy height) and ϕ is the stability correction (Hickman et al., 2010; Campbell and Norman, 1998). Canopy height was measured biweekly by averaging the height of 2 randomly selected locations within each plot and fitted to an equation that best described the measurements to calculate r_a (Bernacchi et al., 2007).

For stable conditions when $T_s < T_a$, ϕ was calculated as:

$$\phi = (1 + 15Ri)(1 + 5Ri)^{0.5} \quad (6)$$

For unstable conditions when $T_s > T_a$, as:

$$\phi = \left\{ \frac{1 + K(-Ri)^{0.5}}{1 - 15Ri} \right\} \quad (7)$$

Where Ri is the Richardson number was calculated as:

$$Ri = \frac{g(T_s - T_a)(z - d)}{(T_a + 273.15)u^2} \quad (8)$$

And K is solved as:

$$K = 75k^2 \frac{[(z - d + z_0)/z_0]^{0.5}}{\{\ln[(z - d + z_0)/z_0]\}^2} \quad (9)$$

(Mahrt and Ek, 1984).

2.5. Climate

On-site observations of air temperature and relative humidity were used to calculate the vapor pressure deficit (VPD; kPa).

The National Weather Service (NWS) Cooperative Observer Program (COOP) provided independent climate data for daily precipitation and air temperature for Ames, IA (Iowa Environmental Mesonet (IEM), 2017; accessed October 8, 2017). This climatological data was used to analyze and compare the daily temperature and precipitation for the growing season of 2016 to the 1981-2010 average.

2.6. Water Use Efficiency

WUE (g DM (mm H₂O)⁻¹) was calculated as:

$$WUE = \frac{Y_{Grain}}{ET_{Tot}} \quad (10)$$

Where Y_{Grain} is the total grain yield obtained by the combine from the location of the weather stations at the time of harvest, and ET_{Tot} is the total growing season ET (Hickman et al., 2010).

2.7. Data Analysis

Micrometeorological data were collected in 10-s increments and averaged over 10-min intervals. Data gaps due to instrument failure were resolved by taking the average of the other two working stations within the same treatment. Instrument failure never occurred in more than one plot in the same treatment at the same time giving an accurate representation for the average. We used the methodology described above to calculate and compare total ET and WUE for both maize and soybean during the 2016 growing season.

Results

3.1. Climate

For the study period, daily minimum temperatures were consistently higher than the climatological average. Daily maximum temperatures fluctuated between higher and lower than climatological average with a short period at the beginning of the growing season of above average temperatures (Fig. 1). Precipitation throughout the season was cumulatively above average (Table 1), but prolonged dryness was evident. Although these events were

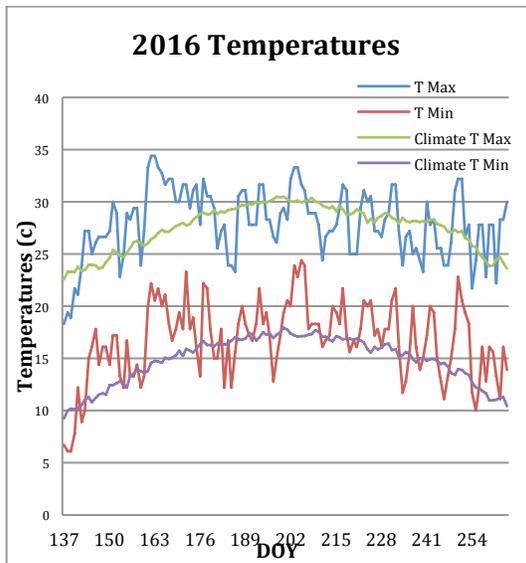


Fig. 1. Daily maximum (T Max, blue) and minimum (T Min, red) air temperature relative to climatological average maximum (Climate T Max, green) and minimum (Climate T Min, purple) air temperature during the 2016 growing season.

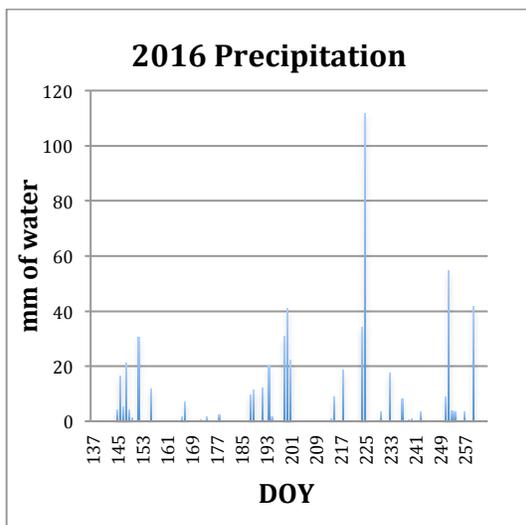


Fig. 2. Daily precipitation totals during the 2016-growing season (mm of water).

followed by ample rainfall amounts (Fig. 2), the extended period of dryness from day of year (DOY) 157-188 occurred during the early stages of the soybeans growth cycle where rainfall is critical for development. This period also lines up with above climatological mean temperatures.

3.2. ET, VPD, and WUE

Total ET varied between the two species during the growing season with maize having higher cumulative water use (Fig. 3a). Variation in planting dates occurred between the two species (Table 1 and 2). Maize was planted on May 16th and soybean almost a month later on June 3rd. These extra days accumulate to almost 95 mm more ET for maize relative to soybean. Daily variations in precipitation, temperature, and cloud cover cause fluctuations of maximum ET during different stages of the crops growth cycle (Fig. 3b). By taking the difference of maize-soybean for when both canopies are fully developed (DOY 190; Fig 3c), soybean displays higher fluctuations of ET during the beginning (until DOY 221) and end (from DOY 240 on) of the growing season.

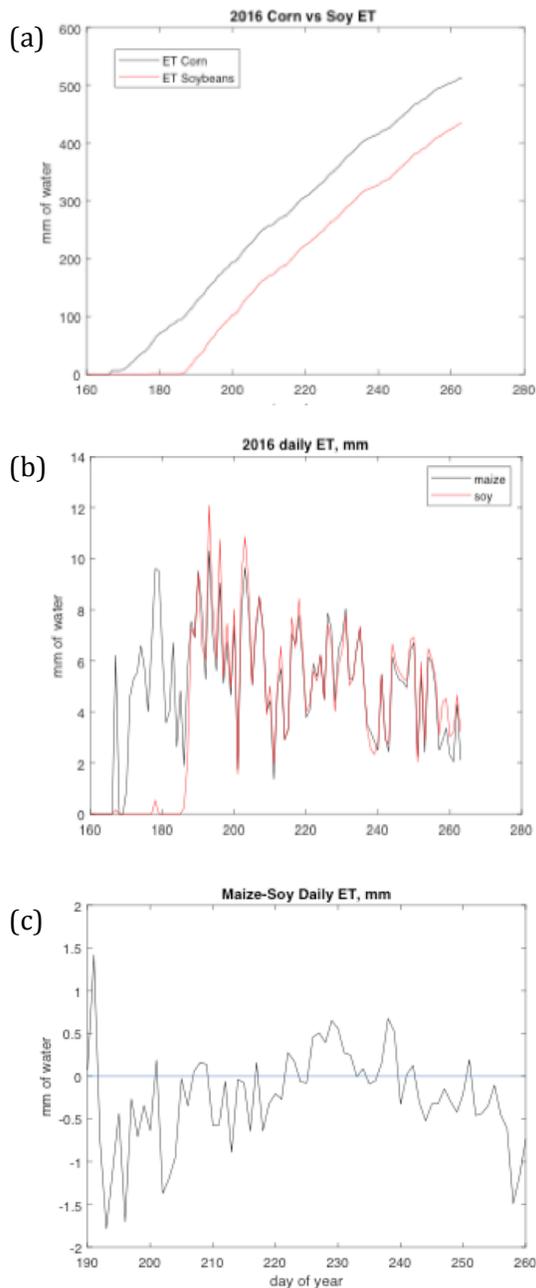


Fig. 3. Day of year (x-axis) and cumulative ET throughout the growing season (a), daily fluctuations in ET (b), and the difference of maize-soybean ET (c).

Overall, maize and soybean use very similar amounts of water throughout the growing season. The total cumulative VPD (Table 2) showed little difference between maize and soybean, and variation was not significant during the growing season (Fig. 4f; Table 2). This means that the role of canopy temperature was not significantly different between the two species and did not affect the ending VPD.

The total WUE based on harvest grain was 3.5 times greater for maize compared to soybean (Table 2).

4. Discussion and Conclusion

This study compared the water dynamics of maize and soybean in a rain fed field in central Iowa during the growing season of 2016. Here we looked at a replication of maize and soybean plots each occupying 12 rows at 30 inch spacing with 3 micrometeorological weather stations located evenly in a row within each species. These stations were used to collect measurements for the surface energy balance model to compute ET. Yield data was recorded from the end

Table 1

Weather variables for growing season during the study period and the 30-year climatological mean. Mean daily temperature (\bar{T}), daily mean maximum (\bar{T}_{max}), and mean minimum (\bar{T}_{min}) temperatures averaged over the growing season. Also shown is precipitation (Precip) for the 2016 growing season and 30-year climatological mean (data provided by the Iowa Environmental Mesonet).

Year	\bar{T}	\bar{T}_{max}	\bar{T}_{min}	Precip
	(°C)	(°C)	(°C)	(mm)
1981-2010	21.2	30.5	18	528
2016	22.3	34.4	24.4	580

Table 2

Planting date, harvest date, and growing season duration for the study. Total grain yield (Yield_{Grain}), total evapotranspiration (ET), water use efficiency at harvest (WUE), and cumulative vapor pressure deficit (VPD).

	Planting	Harvest	Duration	Yield _{grain}	ET	WUE	VPD
	(date)	(date)	(date)	(kg m ⁻²)	(mm)	(g DM m ⁻² mm H ₂ O)	(kPa)
Maize	May 16 th	Sept 20	127	1.33	513.4	2.78	1.15x10 ⁴
Soybean	June 3 rd	Sept 20	109	0.33	435.7	.823	1.02x10 ⁴

of season combine measurements obtained by the Iowa State Research Farm to compute the final WUE, and micrometeorological data was used to compute VPD throughout the growing season.

While maize has been reported to have higher WUE than soybeans (Yu et al., 2004), the conclusions have not been drawn from field-scale experiments

where the water dynamics can be directly compared.

Our study addressed this gap to answer the question: How much water does it take to grow maize and soybean and which is more efficient? While our cumulative results of ET from the entire growing season suggest maize to use more water, ET for when both crop canopies are fully developed indicate

similar water use with soybean using slightly higher.

As hypothesized, maize resulted with higher WUE than soybeans by as much as 3.5 times. These results compare to the findings from previous studies of WUE between C₃ and C₄ crops. Zwart et al., (2004) compared wheat, rice, and cotton to maize and found almost double the efficiency in maize. Even though soybeans are not as efficient at using water to produce grain, our results suggest that the two species may not be fundamentally different in the amount of water it takes to grow under similar environmental conditions.

A large spike in ET found near DOY 201 occurred right after an extended period of rainfall and cloud cover at the research site (Fig 2). A component of the surface energy balance equation to compute ET is net radiation (R_n). When cloud cover is present, the net radiation will be smaller resulting in less ET. At this point in its maturing process, soybean was found to have a greater response in ET compared to maize. This spike can also be seen in Fig 4 b and the difference of maize-soybean in Fig 4 c.

A similar prolonged rainfall that encompassed two days occurred near DOY 225 where higher amounts of precipitation were recorded compared to DOY 201, yet a smaller spike in ET was found for both species with slightly higher values for maize than soybean. Daily fluctuations in ET were highest in soybean before the formation of full pods (DOY 221) and again after the maize started to senesce (DOY 240), a naturally occurring part of the plants life as it nears the end of filling its grain. At this point, the upper leaflets start to turn yellow as the crop starts to die, requiring less water.

A possible explanation for this occurrence is given the leaf area per soybean plant compared to corn. Although maize has been found to be more efficient in previous studies, it is considered to be more susceptible to water stress due to its floral structure with separate male and female organs and near-synchronous development of florets (Mudenda et al., 2016). During the process of photosynthesis, water loss by transpiration is an inescapable consequence of carbon assimilation by a crop. While the pores of the stomata are

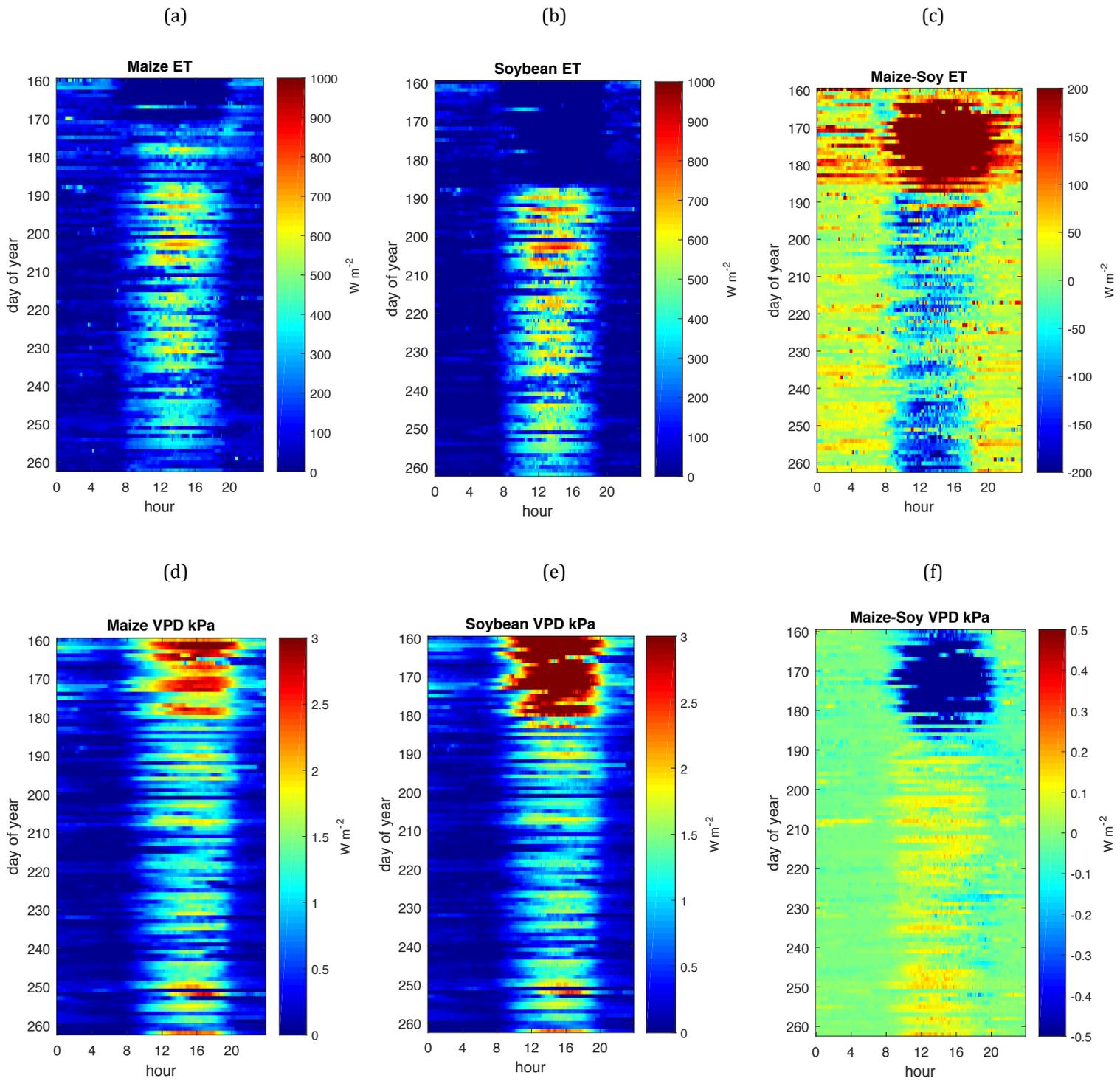


Fig. 4. Diurnal (x-axis) and seasonal (y-axis) evapotranspiration for maize (a), soybean (b), and maize-soybean (c); also included: vapor pressure deficit for maize (d), soybean (e), and maize-soybean (f).

open to allow CO₂ in, water vapor can escape (Haupt 1978). Soybean having a much higher leaf area index (LAI; m² m⁻²); the ratio of covered canopy area to ground area, more water vapor can escape due to greater amount of leaves.

Environmental conditions within the canopy play an important role on the atmospheric demand for water vapor from the crop. This occurs when the actual vapor pressure is lower than the saturation vapor pressure (Bernacchi and VanLoocke, 2015). The affect of VPD has a large influence on the amount of ET to be recorded for each crop. Higher amounts of VPD mean the atmosphere has a greater potential to take moisture from the plant. In this study, we were able to calculate VPD using the canopy temperature, due to assumed similar environments (side-by-side trial), in order to see a relationship between the two species. By taking the difference of each crops daily VPD fluctuations, maize resulted with slightly higher VPD accumulations throughout the growing season (Fig 4f). These results suggest that the canopy remains warmer in maize compared to soybean, and in theory more water loss should be recorded. In

this study, we have found that when both canopies are fully developed this is not the case. Restricted transpiration at high VPD results from limiting hydraulic conductance within the plant, which constraints the flow of water to the transpiration sites on the leaves (Brodribb and Jordan, 2008; Sinclair et al., 2008; Sadok and Sinclair, 2010; Yang et al., 2012). A possible explanation for this occurrence is caused by a higher stomatal response in maize than soybean, resulting in less water to be lost.

For this study, the surface energy balance model was used to compute ET. A flaw in the model occurs when soil is fully exposed to the instruments above. To minimize this affect, the infrared thermometer (SI-111, Apogee Instruments, Logan, UT, U.S) was positioned at a 30 ° angle from the vertical. This causes the influence of the soil to be too high, causing minimal amounts of ET to be calculated.

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