Agriculture is the world’s largest consumer of fresh water, with more than 60% of water devoted to irrigation of crops (Wada and Bierkens, 2014). In the United States, irrigated cropland encompasses 18% of all production area (USDA National Agricultural Statistics Service, 2017), but it yields 50% of crop production. Irrigation plays a critical role in increasing crop yield, but we must further increase its efficiency to produce more food with less water to meet future food demands (FAO, 2016; Smidt et al., 2016). Despite the use of new cultivars developed by innovative biotechnology and conventional breeding approaches, high yields are not achieved if water is limited or if crops and soils are not managed appropriately.

Evaporative loss of water from crops (evapotranspiration [ET]) represents the sum of evaporation from the soil (Es) and transpiration (T) by leaves. Maximum or potential ET is limited by the energy available to vaporize liquid water. The primary source of this energy is the net radiation reaching the earth and the sensible heat transferred by wind from local or regional sources. Energy from sensible heat is more important for irrigated fields in arid and semiarid climates where the vapor pressure deficit (VPD) is greater. Values of E and T can be quite variable depending on the wetness of the soil surface, especially for partial ground cover. The water requirement of an annual crop like maize (Zea mays L.), grown with adequate water supply, is the daily ET summed for the duration of the growing season.

Two contrasting approaches have been used to calculate T. One approach uses meteorological principles to calculate ET through use of the energy balance. Separating values for E and T has been accomplished by measurement of E and ET simultaneously. An appealing and relatively simple approach to model T uses a physiological concept of constant transpiration efficiency (TE),...
whereby $T$ is assumed to be proportional to carbon intake. In this approach, the TE varies by species and with the dryness of the air. The most popular version of the TE approach in recent decades uses VPD to normalize TE (Tanner and Sinclair, 1983), hereafter referred to as Tanner–Sinclair.

The objective of the study was to quantify ET in high-yielding maize under current and projected VPD using the energy balance method contrasted with the TE approach. We believe this assessment is needed since both methods have been used to estimate the water requirements of crops under projected climate change and for higher yields with large discrepancies (Basso and Ritchie, 2014; Lobell et al., 2014; Ort and Long, 2014).

**Energy Balance**

Equations for potential evapotranspiration (PET) using the energy balance have been in use since the pioneering work of Penman (1948), who derived a model for potential or maximum daily evaporation using readily available daily weather data. The model as modified and adapted to use SI units by Shuttleworth (2007) is as follows:

$$\text{PET} = \frac{(mRn + g \times 6.13 \times (1 - 0.31 \times U) \times \text{VPD})}{L \times (m + g)}$$

where PET = evaporation rate (mm d$^{-1}$), $m =$ slope of the saturation vapor pressure curve (kPa K$^{-1}$), $Rn =$ net irradiance (MJ m$^{-2}$ d$^{-1}$), $g =$ psychrometric constant = 0.0016286, VPD = vapor pressure deficit (kPa), $U =$ wind speed (m s$^{-1}$), and $L =$ latent heat of vaporization (MJ kg$^{-1}$).

This simplified version neglects a small amount of energy entering or leaving the ground surface. This equation sums a radiation component and an aerodynamic or advective component. Under most circumstances, the radiation component provides the majority of the sum, although in more arid conditions the aerodynamic term becomes more important. The most uncertain part of the equation is associated with quantifying the aerodynamic term because of the use of average daily wind speed, which usually does not reflect the wind speed during the times of maximum ET, and the method of calculating a daily VPD since the VPD varies throughout the day.

Several crop models used to predict and assess ET, such as SALUS (Basso and Ritchie, 2015) and the CERES family of models (Ritchie, 1985; Basso et al., 2016) from which SALUS was derived, use versions of the energy balance that do not use wind. CERES uses the Priestley–Taylor model using only the radiation term multiplied by a constant greater than 1 to account for the aerodynamic component. SALUS uses the Penman equation for PET with wind input as the monthly or seasonal average for the region.

Models of PET are conservative, especially in humid and subhumid climate, because VPD is relatively small and $Rn$ is derived from measurements of daily solar radiation and temperature data. Although they are less conservative for use with irrigated crops in more arid regions, the empiricisms for the assessment of the aerodynamic components have been well quantified (i.e., the FAO method; Allen et al., 1998).

For the assessment of T with the energy balance, Es and T have to be calculated, especially for crops with partial cover. The SALUS model uses the procedures of Ritchie (1972) and some modifications (Suleiman and Ritchie, 2003; Ritchie et al., 2009) to separate Es and T. The Es component is rather well defined when the leaf area index (LAI) is known or reasonably estimated because it is defined by two stages. The first stage is energy controlled when the soil surface is wet and calculated using the radiation component of the energy balance with $Rn$ reaching the soil surface below the canopy. The second stage is controlled by the rate of diffusion of water from a relatively shallow soil depth to the atmosphere. The diffusion process results in Es declining rapidly in the second stage in proportion to the square root of time, with the proportionality constant being in the 3 to 4 mm d$^{-0.5}$. The Es calculated using this two-stage procedure is conservative, with the remaining portion of the ET being T. When crop LAI is small, T values are smaller than PET. Ritchie (1972) defined a relationship describing the fraction of potential T of the total PET (To/PET) as related to LAI for conditions when Es is small owing to a dry soil surface. The $To$ from this functional assessment is added to the calculated Es to calculate the first approximation of actual ET. However, because the function is for conditions of Es = 0, T will usually be lower than the LAI-derived function because the resulting sum Es + To can be greater than PET. The following equations are used to obtain T in the SALUS model:

$$T = \text{PET} - \text{Es}, \text{Es} + \text{To} > \text{PET}$$

$$T = \text{To}, \text{Es} + \text{To} = \text{<PET}$$

The difference between To and T is a result of highly variable sensible heat rising from the soil surface owing to variable Es. These procedures for calculating T assume the soil water content in the root zone does not restrict T. More detail on T and Es model are discussed below.

**Transpiration Efficiency**

The physiological concept of TE is defined as plant biomass produced per unit of water transpired. This constant ratio for a species is an appealing and simple method to estimate $T$, especially for crops whose yield or biomass is known or reasonably estimated. The economic yield of a crop is commonly known, and with a relatively constant harvest index assumed when water and nutrient are not limiting, the total biomass along with the TE results in an approximation of T for the crop. The concept is appealing because the stomata in wet leaf surfaces absorbing CO$_2$ for photosynthesis are the same pathways allowing water vapor to escape. The version of the TE approach as developed by the Tanner–Sinclair equation is

$$T = \frac{G \times \text{VPD}}{\text{TEn}}$$

where G is the biomass produced in a season and TEn is the normalized TE value specific for a crop species as normalized by the VPD averaged for the season. Daily values of VPD are derived from saturated vapor pressure (es)
Average maize yields in the United States and official verified National Corn Growers Association winning yields continue in a general upward trend due to improved cultivars and crop, soil, and pest management (Fig. 1). Notably, contest winners’ yields increased dramatically in the past 5 yr, setting new high yields in 4 of the 5 yr in regions where summer temperatures are warmer during the growing season (Virginia, Georgia, Texas) than in the midwestern Corn Belt where maize production is centered. These record yields demonstrate the potential for production when all known limiting factors are minimized along with hybrids and crop, soil, and pest management. The ET for high-yielding maize was calculated by the energy balance and TE approach (Table 1). The TEn value reported in Tanner–Sinclair for maize (0.01 kPa) along with VP D calculation procedures as used in Tanner–Sinclair [ (esTx − esTn)×0.75] averaged for the growing season excluding the first 30 d after sowing owing to little vegetative cover after planting. The TE approach produced T estimates double those of the energy balance. Using the Es values from SALUS, the sum of ET from the TE approach was about 1.8 times more than the energy balance ET. These differences arise because the TEn procedures result in T being directly proportional to the VPD, whereas in the energy balance, only the relatively small aerodynamic component is proportional to VPD. Several researchers have reported that typical maize crops grown in humid and subhumid regions of the US Midwest use 500 to 600 mm water for ET, whereas 700 to 900 mm may be used in the arid and semiarid climates of the western United States (Howell et al., 1998; Hatfield and

**Evapotranspiration in High-Yielding Maize**

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**Table 1. Maize yield and seasonal transpiration amounts obtained for high-yielding sites using the transpiration efficiency (TE) method and the energy balance approach in Georgia, Virginia, Texas, and Arizona sites.**

<table>
<thead>
<tr>
<th>Sites</th>
<th>VPD</th>
<th>TE method</th>
<th>Energy balance</th>
<th>Maize yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>Transpiration</td>
<td>Transpiration</td>
<td>Es</td>
</tr>
<tr>
<td>Valdosta, GA (2014)</td>
<td>1.97</td>
<td>1076</td>
<td>506</td>
<td>104</td>
</tr>
<tr>
<td>Hart, TX (2013)</td>
<td>2.44</td>
<td>1220</td>
<td>506</td>
<td>170</td>
</tr>
<tr>
<td>Maricopa, AZ (1996)</td>
<td>4.25</td>
<td>1460</td>
<td>640</td>
<td>230</td>
</tr>
<tr>
<td>Richmond, VA (2017)</td>
<td>1.76</td>
<td>1038</td>
<td>580</td>
<td>141</td>
</tr>
<tr>
<td>Richmond, VA (2015)</td>
<td>1.71</td>
<td>1100</td>
<td>567</td>
<td>153</td>
</tr>
<tr>
<td>Richmond, VA (2013)</td>
<td>1.67</td>
<td>865</td>
<td>550</td>
<td>114</td>
</tr>
</tbody>
</table>
Prueger, 2011; Basso et al., 2012), the agreement of energy balance ET for record high yields with measured irrigated high yields from literature reports of Tanner–Sinclair and Howell et al. (1998) of 10 to 12 t ha$^{-1}$ indicates actual ET of high-yielding crops is essentially the same as for lower-yielding crops with similar season lengths when water supply is not a yield-limiting factor.

Details of the SALUS estimation of biomass, ET, Es, and T (Fig. 2) for the 2014 record yield demonstrate that Es dominates ET about 30 d after planting and T dominates thereafter. However, Es continues to contribute to ET during the season, even with dense vegetation when the soil surface is wet due to rainfall or irrigation, owing to some Rn penetrating through the canopy. The magnitudes of Es and T for a season can be highly variable, primarily depending on the frequency and duration of wet soil surfaces.

The function to calculate T is depicted graphically in Fig. 3 as the fraction of PET for a dry soil surface as influenced by LAI when Es is near zero. For reference, a similar curve developed from several measurements of T with wet soil and Es controlled by energy reaching the soil surface. These findings reveal that Es can be a significant factor even with dense canopies. The T/PET varies between these two boundaries, depending on the wetness of the soil surface. For LAI values below 3, when Es is near zero, the soil surface temperature rises rapidly during clear sky conditions, greatly increasing the VPD in the canopy and resulting in considerably higher T from the locally derived sensible heat.

For energy balance calculations, ET is mainly driven by Rn. In the APSIM and other models’ uses of ETn, the daily growth is proportional to the radiation intercepted by the canopy, making T from growth approximately proportional to Rn and also making it proportional to VPD. Using field-measured T and E from several reports, Basso and Ritchie (2012) demonstrated that transpiration per unit of productivity under adequate soil water supply can vary considerably depending on agronomic management decisions such as plant population and fertilizer amounts, as we have found from these comparisons of ET calculations using the energy balance method (Ritchie and Basso, 2008).

**Evapotranspiration under Climate Change**

The TE$\_n$ approach of Tanner–Sinclair was used by Ort and Long (2014) to make projections of water requirements for maize yield of 17.1 Mg ha$^{-1}$ in 2050 for the states of Iowa, Indiana, and Illinois. The resulting T with a VPD changing from 2.2 to 2.65 kPa reported in Lobell et al. (2014) was 907 mm with no genetic improvement using the TE approach, and slightly lower values with possible improvements. Adding 20% more water needed for Es would result in 1188 mm water needed to support anticipated crop yield in 2050 (Ort and Long, 2014). This value is approximately twice the present average ET in the region for crops growing with little water deficit. Using this projection, massive amounts of irrigation water would be required in the Midwest region, where the projection was made, unless precipitation increased dramatically by 2050. This water needs projection would be lower if the VPD used in the calculation corresponded to the season-long values instead of using only July as done by Lobell et al. (2014) and if the VPD values were reduced from the maximum VPD to 0.75 maximum as done in Tanner–Sinclair. Even with more appropriate VPD values, the water
needs would be higher on average than unchanged precipitation would support.

Simulations of yield using the process-based model APSIM for T agreed with statistical model conclusions in Lobell et al. (2014), who found that simulated yields in central Iowa have been declining with constant plant density because of slightly increasing VPD since 1960. They attributed the gradual increase in actual rainfed yields in the region to increases in plant density and earlier planting dates that offsets the losses due to increasing VPD but make the case that improved management may not continue to improve yields and become more acute as VPD continues to increase unless the increase can be reversed. The actual season-long VPD may not be increasing because the high temperatures are decreasing while the minimum temperatures are increasing, giving a gradual mean increase in average temperatures (Mueller et al., 2016). With contest-winning attainable yields double our present average yields when most yield-limiting factors are eliminated, and with radiation not assumed to change appreciably, energy balance-based estimates of future PET suggest that water supply for maize production should be able to keep up with demands except for the possible more frequent droughts expected with climate change.

As temperatures are projected to increase under climate change, and assuming that absolute humidity remains unchanged, VPD increases exponentially relative to temperature increases because of the nonlinear temperature-saturated vapor pressure relationship. Increased VPD would lead to an increase in T in the TE method. Lobell et al. (2014) used a statistically based model and the APSIM crop simulation model to project that increased VPD from climate change would lead to increased drought with yield reductions unless additional rainfall or irrigation become available. Ort and Long (2014) used the Tanner–Sinclair equation with projections from Lobell et al. (2014) where VPD was projected to increase in the US Midwest from the present value of 2.2 kPa to 2.65 kPa by 2050. They found that under these conditions, precipitation in the Midwest would have to increase an average of 35% to be sufficient for maize yield to reach the projected 2050 requirement of 17 t ha\(^{-1}\). In our analysis (Table 1), seasonal VPD values were averaged from 20 d after planting to maturity with data obtained from the US national highest record growers sites (Fig. 1). Using the TE approach and the TE, constant for maize (0.5 g mm\(^{-1}\) Pa\(^{-1}\)) from Tanner–Sinclair, Ort and Long (2014) concluded that current average precipitation (940 mm yr\(^{-1}\)) is sufficient to support the present national production average of 13.4 Mg ha\(^{-1}\), but if VPD rises to 2.65 kPa, the same rainfall will only be able to support production of 12.1 Mg ha\(^{-1}\). To produce the 17.1 Mg ha\(^{-1}\) that has been projected to be needed by 2050, the amount of precipitation calculated would need to be 1270 mm yr\(^{-1}\). The T obtained using the TE approach by Ort and Long (2014) for the record yields is approximately double that obtained from the energy balance approach or from simply comparing it to the growing season potential ET (~700 mm) (Table 1).

**Conclusion**

This study reports a lack of accuracy and bias in the TE approach when future crop water requirements are estimated for higher yields and climate change. It has been projected that maize yield will be affected by more frequent droughts or floods (IPCC 2014), but energy balance calculations as demonstrated herein offer optimism that when the water supply is adequate, either by sufficient rainfall or irrigation (~500 mm in humid to 700 mm in arid environments for the growing season), maize production would not require the additional water that the TE method suggests. These estimates hold true if the temperature increases for the maximum and minimum are the same. If, as has occurred in the Midwest in the last 100 years, the minimum temperature increase contributes more than the maximum temperature increase, water use may be the same or even less than present-day levels (Mueller et al., 2016). High maize yields are achievable with ET of 700 mm as demonstrated by the current record maize grain yield of 34 Mg ha\(^{-1}\) through the adoption of improved genetics and proper agronomic management.

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