2016

Partitioning evaporation and transpiration in a maize field using heat-pulse sensors for evaporation measurement

X. Xiao
North Carolina State University at Raleigh

T. J. Sauer
U.S. Department of Agriculture, tom.sauer@ars.usda.gov

J. W. Singer
BASF Plant Science

R. Horton
Iowa State University, rhorton@iastate.edu

T. Ren
China Agricultural University

See next page for additional authors

Partitioning evaporation and transpiration in a maize field using heat-pulse sensors for evaporation measurement

Abstract

Evapotranspiration (ET) is the sum of soil water evaporation (E) and plant transpiration (T). E and T occur simultaneously in many systems with varying levels of importance, yet it is often very challenging to distinguish these fluxes separately in the field. Few studies have measured all three terms (ET, E, and T), and in the few cases where such measurements have been obtained, E is typically determined via destructive lysimetery. For 43 days in a fully developed maize (Zea mays L.) field, we continuously measured E using heat-pulse sensors and soil sensible heat balance, T using sap-flow gauges, and ET using an eddy covariance system. Crop evapotranspiration (ETc) was also calculated from the crop coefficient (Kc) and the reference evapotranspiration (ETo), which was determined with the standardized Penman- Monteith equation. During the measurement period, E and T accounted for 13% and 87% of E+T, respectively. E responded to variations in soil moisture and net radiation, whereas T changed primarily with net radiation. All three ET estimation methods (individually measured E+T, eddy covariance ET, and crop ETc) demonstrated similar temporal trends and strong correlations (R2 of 0.76 for ETc vs. E+T and 0.77 for ET vs. E+T), with the values of individually measured E+T close to crop ETc but larger than eddy covariance ET during the measurement period. Disparities in measurements were likely due to variations in measurement scale, which did not reflect the full range of field variability for individually measured E and T, and differences in response to declining soil moisture among the three approaches. Overall, the results support the need for individual measurement of each term (E, T, and ET) when attempting to interpret ET partitioning and suggest that soil heat-pulse sensors provide a viable complement to previously tested approaches for continuously determining E for ET partitioning during wetting-drying periods.

Keywords

Eddy covariance, Evaporation, Evapotranspiration, Heat pulse method, Sap flow, Sensible heat balance, Standardized Penman-Monteith Equation, Transpiration

Disciplines

Agricultural Science | Agronomy and Crop Sciences

Comments

This article is from Xiao, X., T.J. Sauer, J.W. Singer, R. Horton, J.L. Heitman, and T. Ren. 2016. Partitioning evaporation and transpiration in a maize field using heat pulse sensors for evaporation measurement. Transactions of the ASABE 59:591-599. doi: 10.13031/trans.59.11059.

Authors

X. Xiao, T. J. Sauer, J. W. Singer, R. Horton, T. Ren, and J. L. Heitman

PARTITIONING EVAPORATION AND TRANSPIRATION IN A MAIZE FIELD USING HEAT-PULSE SENSORS FOR EVAPORATION MEASUREMENT

X. Xiao, T. J. Sauer, J. W. Singer, R. Horton, T. Ren, J. L. Heitman

ABSTRACT. *Evapotranspiration (ET) is the sum of soil water evaporation (E) and plant transpiration (T). E and T occur simultaneously in many systems with varying levels of importance, yet it is often very challenging to distinguish these fluxes separately in the field. Few studies have measured all three terms (ET, E, and T), and in the few cases where such measurements have been obtained, E is typically determined via destructive lysimetery. For 43 days in a fully developed maize (*Zea mays *L.) field, we continuously measured E using heat-pulse sensors and soil sensible heat balance, T using sap-flow gauges, and ET using an eddy covariance system. Crop evapotranspiration (ET_c) was also calculated from the crop coefficient (K_c) and the reference evapotranspiration (ET_o), which was determined with the standardized Penman-Monteith equation. During the measurement period, E and T accounted for 13% and 87% of E+T, respectively. E responded to variations in soil moisture and net radiation, whereas T changed primarily with net radiation. All three ET estimation methods (individually measured E+T, eddy covariance ET, and crop ET_c) demonstrated similar temporal trends and strong correlations (R^2 of 0.76 for ET_c vs. E+T and 0.77 for ET vs. E+T), with the values of individually measured E+T close to crop ET_c but larger than eddy covariance ET during the measurement period. Disparities in measurements were likely due to variations in measurement scale, which did not reflect the full range of field variability for individually measured E and T, and differences in response to declining soil moisture among the three approaches. Overall, the results support the need for individual measurement of each term (E, T, and ET) when attempting to interpret ET partitioning and suggest that soil heat-pulse sensors provide a viable complement to previously tested approaches for continuously determining E for ET partitioning during wetting-drying periods.*

Keywords. *Eddy covariance, Evaporation, Evapotranspiration, Heat pulse method, Sap flow, Sensible heat balance, Standardized Penman-Monteith Equation, Transpiration.*

Evapotranspiration (ET) is the sum of soil water evaporation (E) and plant transpiration (T). E and T processes occur simultaneously in many systems. Both processes have importance in agricultural systems, with T usually considered a positive process associated with plant productivity, and E sometimes considered a negative process associated with non-productive loss of water. This difference makes it useful to determine the relative magnitude of each component flux within overall ET. However, it is often very challenging to distinguish these fluxes separately in the field.

Typically, ET and either E or T are measured, and the difference between these measurements is used as an estimate of the missing component (T or E) (Kool et al., 2014). Eddy covariance and Bowen ratio are widely used micrometeorological approaches for estimating ET at large spatial scales (Wolf et al., 2008). Sap-flow gauges, using heat as a tracer for sap movement, are common sensors for determining T (Sakuratani, 1981; Heilman and Ham, 1990; Steinberg et al., 1988). The lysimeter method (van Bavel, 1961) is the most common direct way to measure E (or ET when plants are included) by gauging the mass loss of water from lysimeters buried in the soil. Chamber and Bowen ratio approaches have occasionally been used to independently determine E (Raz-Yaseef et al., 2010; Holland et al., 2013). Stable isotopes have been used to measure ET components by collecting samples of soil water, plant water, and vapor and tracing the isotopic compositions of the water evolved as E or T at steady-state conditions (Williams et al., 2004; Rothfuss et al., 2010). Maximum entropy

Submitted for review in November 2014 as manuscript number NRES 11059; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in December 2015.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Xinhua Xiao,** Postdoctoral Researcher, formerly at Department of Soil Science, North Carolina State University, Raleigh, North Carolina, currently at Department of Biological and Environmental Sciences, Alabama A&M University, Normal, Alabama; **Tom J. Sauer,** Supervisory Research Soil Scientist, USDA-ARS National Laboratory for Agriculture and Environment, Ames, Iowa; **Jeremy W. Singer,** Principal Scientist, BASF Plant Science, Research Triangle Park, North Carolina; **Robert Horton,** Professor, Department of Agronomy, Iowa State University, Ames, Iowa; **Tusheng Ren,** Professor, Department of Soil and Water, China Agricultural University, Beijing, China; **Josh L. Heitman,** Associate Professor, Department of Soil Science, North Carolina State University, Raleigh, North Carolina. **Corresponding author:** Josh Heitman, P.O. Box 7619, North Carolina State University, Raleigh, NC 27695-7619; phone: 919-513-1593; e-mail: jlheitman@ncsu.edu.

production theory has been recently used to estimate ET in the entire range of soil wetness from dry to saturation (Wang and Bras, 2011). Recently, heat-pulse sensors, with a sensible heat balance (SHB) theory, have also been implemented as a means to continually measure E with minimal soil disturbance (Heitman et al., 2008a, 2008b; Xiao et al., 2011, 2014).

A number of studies in various agronomic and forest settings have been performed to partition ET into E and T (see review by Kool et al., 2014). Few of these studies have included independent measurements of ET, T, and E, particularly in row crops such as maize, which is necessary to assess the accuracy of partitioning. Among the few studies in which all three terms have been measured, Jara et al. (1998) found T representing 82% to 98% of ET, Thompson et al. (1997) found T representing 48% to 74% of ET, and Zeggaf et al. (2008) found T representing 25% to 58% of ET, each in irrigated maize, and Herbst et al. (1996) found T representing between 77% and 116% of ET in non-irrigated maize. Given the worldwide importance of maize as a crop, additional reports of ET partitioning and relative magnitudes of T compared to system water use via ET (water use efficiency) would be helpful to understand cropping systems, especially in rainfed and drought-prone regions. Furthermore, in each of the studies described above, with the exception of Zeggaf et al. (2008), micro-lysimeters were used to obtain E estimates for ET partitioning. Micro-lysimeters are destructive and labor intensive (Kool et al., 2014), which may contribute to the lack of studies providing reports of ET partitioning in maize.

Xiao et al. (2014) measured soil water E using heat-pulse sensors based on SHB in a maize field. They found good agreement between daily E measured with SHB and with micro-lysimeters for eight days when the soil was drying. In this study, we continually measured ET and its components (E and T) during wetting-drying periods in the same maize field. Our objectives were to (1) assess the feasibility of heat-pulse measurements for continuously determining E and for partitioning ET during wetting-drying periods, (2) compare patterns observed in E and T measured independently, and (3) compare and evaluate ET estimates obtained by three independent approaches. We measured soil water E with heat-pulse sensors, maize T with sap-flow gauges, and system ET with an eddy covariance system. We also calculated field ET_c by combining the crop coefficient (K_c) with the reference evapotranspiration (ET_o) determined with the standardized Penman-Monteith equation.

Materials and Methods

Field Site

The study was performed in an 800 m × 1000 m maize field located near Ames, Iowa (41.98° N, 93.68° W) during the summer of 2009 (fig. 1). The field had been planted in a maize and soybean (*Zea mays* L. and *Glycine max*) rotation for many years without any irrigation. The total rainfall was 905 mm in 2009. Maize was planted on day of year (DOY) 136 with 0.75 m row spacing in east-west rows. Leaf area index (LAI) was measured periodically using an LAI meter (LAI 2000, LiCor Biosciences, Inc., Lincoln, Neb.) following procedures described in the sensor manual. The soil at

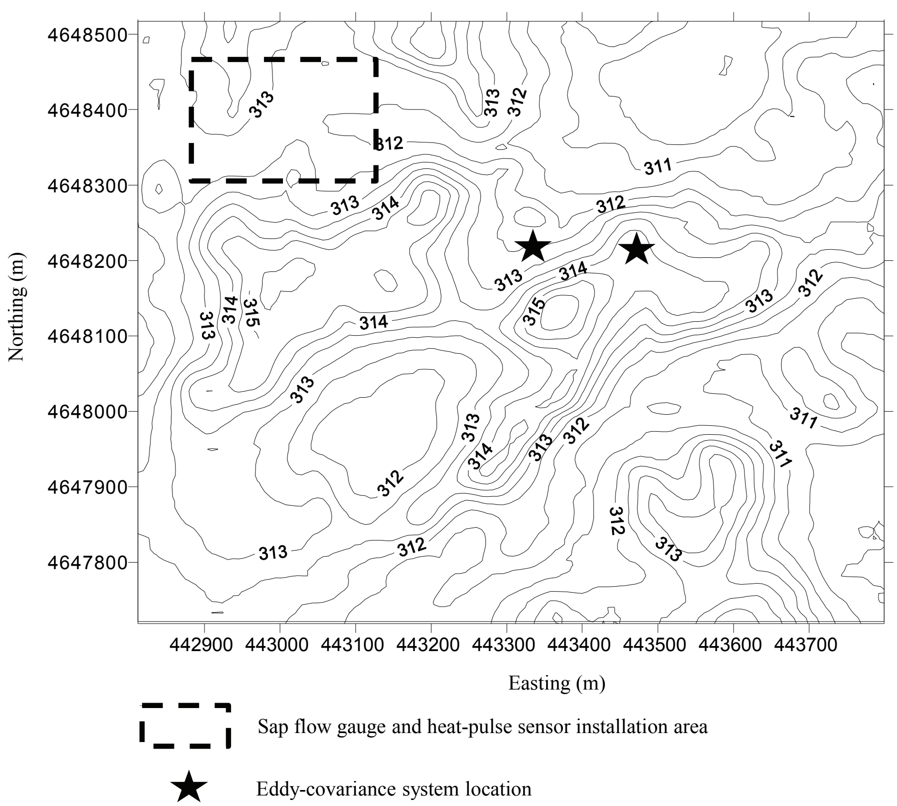

Figure 1. Map of the field site and the locations of instrumentation. Contours are elevation above mean sea level in meters.

the site was Canisteo clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls). The surface soil layer (0-60 mm) bulk density was 1.2 Mg m^{-3}. The soil consisted of 44% sand, 30% silt, and 26% clay, and the topography was relatively flat (slope < 2%).

Evaporation Measurements

Sensible heat balance (SHB) measurements for E, collected from DOY 210 to DOY 252, when the maize canopy was fully developed, were described in detail by Xiao et al. (2014). Briefly, 11-needle heat-pulse sensors (Zhang et al., 2012), with thermocouple needles and heater needles alternated in the epoxy body, were used to measure temperature and thermal properties, which enabled estimation of the net sensible soil heat flux ($G_1 - G_2$) and the change in sensible heat storage (ΔS) of a soil layer. The latent heat of vaporization (LE) in the soil layer was then calculated based on a sensible heat balance ($\mathrm{LE} = G_1 - G_2 - \Delta S$). One sensor was installed in the 0-48 mm soil layer at both the row and inter-row positions. Sensor thermocouples and heaters were connected to an AM16/32 multiplexer and an AM416 multiplexer (Campbell Scientific, Logan, Utah), respectively, and logged with a datalogger (CR10X, Campbell Scientific, Logan, Utah). The SHB approach was applied to measure subsurface (0.5 mm soil depth and below) soil water E (Sakai et al., 2011; Deol et al., 2012) when the soil was relatively dry (evaporation stages II and III). A modified SHB approach was implemented for E in the 0-0.5 mm soil layer (evaporation stage I) by incorporating below-canopy net radiation measured with a tube net radiometer (TRL, Delta-T Devices, Cambridge, U.K.) installed at 5 cm height across a row (see details in Xiao et al., 2014). The modified SHB method approximated the upper boundary heat flux (G_1) of the 0-0.5 mm soil layer as soil surface net radiation (R_n) when the soil was relatively wet ($\mathrm{LE} = R_n - G_2 - \Delta S$). A threshold for switching between the SHB and modified SHB approaches at row and inter-row positions was set based on soil water content (threshold = 0.25 m^3 m^{-3}), determined in the field according to heat-pulse thermal property measurements of volumetric heat capacity. The SHB method was used when soil water content was at and below 0.25 m^3 m^{-3}, and the modified SHB was used when soil water content was larger than 0.25 m^3 m^{-3}. Therefore, the SHB E reported in this study is the combination of these two approaches.

Transpiration Measurements

Whole-plant T was measured from silking (R1) to physiological maturity (R6) (Ritchie et al., 1993) using 19 mm diameter Dynagage sap-flow sensors (Dynamax, Inc., Houston, Tex.). Sensors were installed on six consecutive maize plants, approximately 0.3 m above the soil surface. Lower maize leaves and sheaths were removed to enhance sensor placement on the maize stem. Sensors were insulated with foam and covered with foil to minimize environmental fluctuations. Input voltage was set at 4.5 V for all sensors. Stem diameter was determined by averaging two measurements on opposite sides of the stem with electronic calipers approximately 0.3 m above the soil surface. Sap flow was measured using an energy balance method determined by a constant heat source (Sakuratani, 1981). Sap flow was measured every 60 s and averaged every 12 min with a datalogger (CR5000, Campbell Scientific, Logan, Utah). Data collected from 7:00 to 19:00 h were used to calculate daily plant T. The sensors were always deployed on six consecutive plants (to capture the true plant-to-plant variability) and were moved three times during the measurement period to increase the number of plants sampled. A total of 18 plants were measured during the field study. Data were converted from water mass per plant (g h^{-1} $plant^{-1}$) to water depth (mm h^{-1}) by multiplying by the plant density (average = 6.7 plants m^{-2}).

Evapotranspiration Measurements

Two eddy covariance flux stations were positioned in the field 1.6 m above the soil surface or 1 m above the canopy when the canopy height was >0.6 m (fig. 1). Each station consisted of a fast-response open-path H_2O vapor analyzer (LI-7500, LICOR Biosciences Inc., Lincoln, Neb.), a three-dimensional sonic anemometer (CSAT, Campbell Scientific, Logan, Utah), a net radiometer (CNR 1, Kipp and Zonen, Delft, The Netherlands), and two soil heat flux plates (HFT-3, Radiation and Energy Balance Systems, Seattle, Wash.) installed 6 cm below the soil surface. Pairs of soil thermocouples (copper-constantan) were placed 2 and 8 cm below the surface near each soil heat flux plate. Soil water content in the top 6 cm at each site was measured with a soil moisture sensor (ML2X, Delta-T Devices, Cambridge, U.K.). Signals from the eddy covariance flux sensors were recorded at 10 Hz, and 15 min averages for all sensors were stored in a datalogger (CR5000, Campbell Scientific, Logan, Utah). Turbulent fluxes were corrected following the density correction of Webb-Pearman-Leuning (Webb et al., 1980). Soil heat flux plate data were corrected for heat storage in the surface soil layer using measured soil temperature and water content (Sauer, 2002). Data were screened for anomalous values beyond preselected ranges. With the exception of rainy periods, intervals of missing data were gap-filled using an iterative interpolation technique (Hernandez-Ramirez et al., 2009).

As the ratios ($\mathrm{LE} + H$) / ($R_n - G_0$) of the two eddy covariance systems were 0.88 and 0.90, respectively, we forced energy balance closure and corrected the measured eddy covariance (ET_m) with the following equation (Twine et al., 2000):

$$\mathrm{ET} = \frac{\mathrm{ET}_m}{(\mathrm{LE} + H)/(R_n - G)} \qquad (1)$$

The difference of the corrected ET was within 2%, so the eddy covariance ET data presented in this article are the average corrected ET values of the two eddy covariance systems.

Crop Evapotranspiration

Reference evapotranspiration (ET_o, mm h^{-1}) for 0.12 m tall grass was estimated from the standardized Penman-Monteith method (ASCE, 2005):

$$\mathrm{ET}_o = \frac{0.408\Delta\left(R_n - G_0\right) + \gamma \frac{37}{T_{air} + 273} U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + C_d U_2\right)} \quad (2)$$

where R_n is the net radiation at the crop surface (MJ m^{-2} h^{-1}), G_0 is the surface soil heat flux density (MJ m^{-2} h^{-1}), T_{air} is the air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the relationship between saturation vapor pressure and air temperature (kPa K^{-1}), γ is the psychrometric constant (0.067 kPa $°C^{-1}$), and C_d is a coefficient (s m^{-1}) that differs with calculation time of day: C_d = 0.24 for hourly time steps during daytime (defined as when the surface $R_n > 0$), and C_d = 0.96 for hourly time steps during nighttime. For calculations in this study, net radiation, soil heat flux, and wind speed (adjusted for 2 m height) data were obtained from instruments used as part of the eddy covariance system, as described above. Air temperature and humidity were measured with a temperature and relative humidity sensor (HMP45C, Vaisala, Vantaa, Finland). Calculations were performed at both hourly and daily time steps.

Crop evapotranspiration (ET_c) was estimated from ET_o and the coefficient (K_c =1.2) with maize in mid-season during the measurement period (Allen et al., 1998):

$$\mathrm{ET}_c = K_c\left(\mathrm{ET}_o\right) \quad (3)$$

Results and Discussion

Measurements were performed with all instrumentation for E, T, and ET for 43 days (DOY 210-252) when maize was in growing stages R1 to R6 with LAI values between 3.9 and 4.3. Daily values of the measurements used in this study included the sum of daytime values from 7:00 to 19:00 each day. Meteorological data, including daily net radiation above the canopy, soil water content and rainfall, wind speed, and air temperature, are presented for the measurement period and the 20 days prior (DOY 190-252) in figure 2. There were two rainfall events with total precipitation of 20 mm before the measurement period and four rainfall events with total precipitation of 88 mm during the measurement period.

Evaporation

Soil water evaporation, as a component of evapotranspiration, was measured at row and inter-row positions. For the present analysis, E measurements were averaged across positions to provide a single value representing below-canopy E (fig. 3b). Xiao et al. (2014) provides details on E by position as well as comparison to independent micro-lysimeter E measurements on a subset of days. There was strong correlation (R^2 = 0.79) and regression slope near unity (1.03 with intercept set at 0) between SHB and micro-lysimeter daily E estimates for eight days of comparison during a soil drying period (fig. 3b inset), with differences

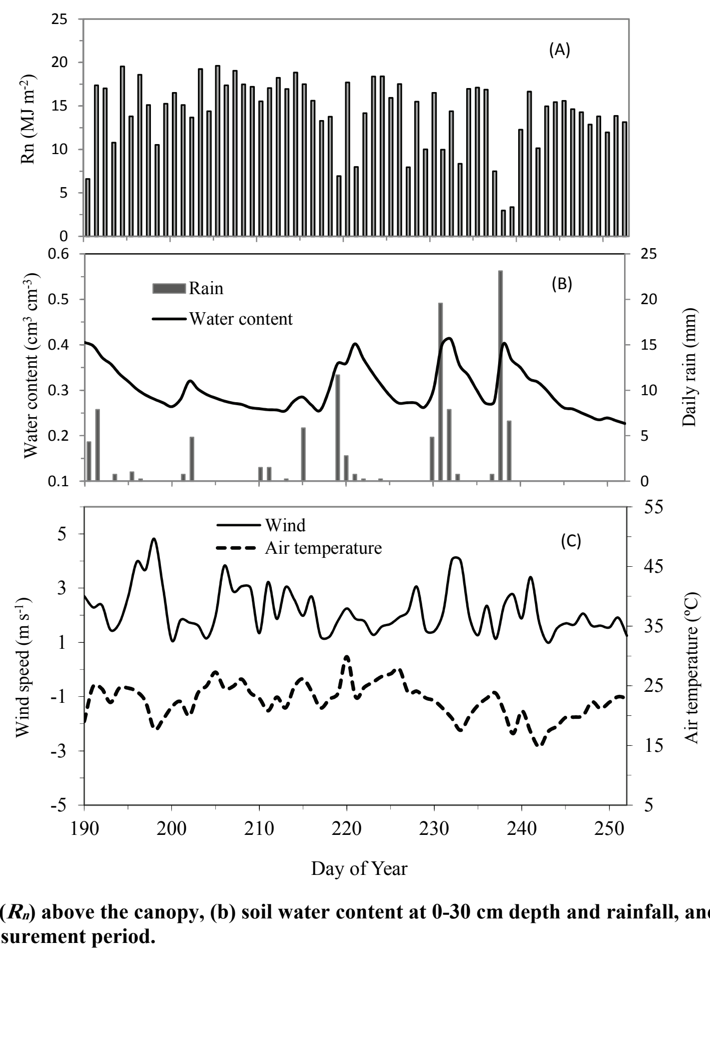

Figure 2. (a) Daily net radiation (R_n) above the canopy, (b) soil water content at 0-30 cm depth and rainfall, and (c) wind speed and air temperature (2 m height) during the measurement period.

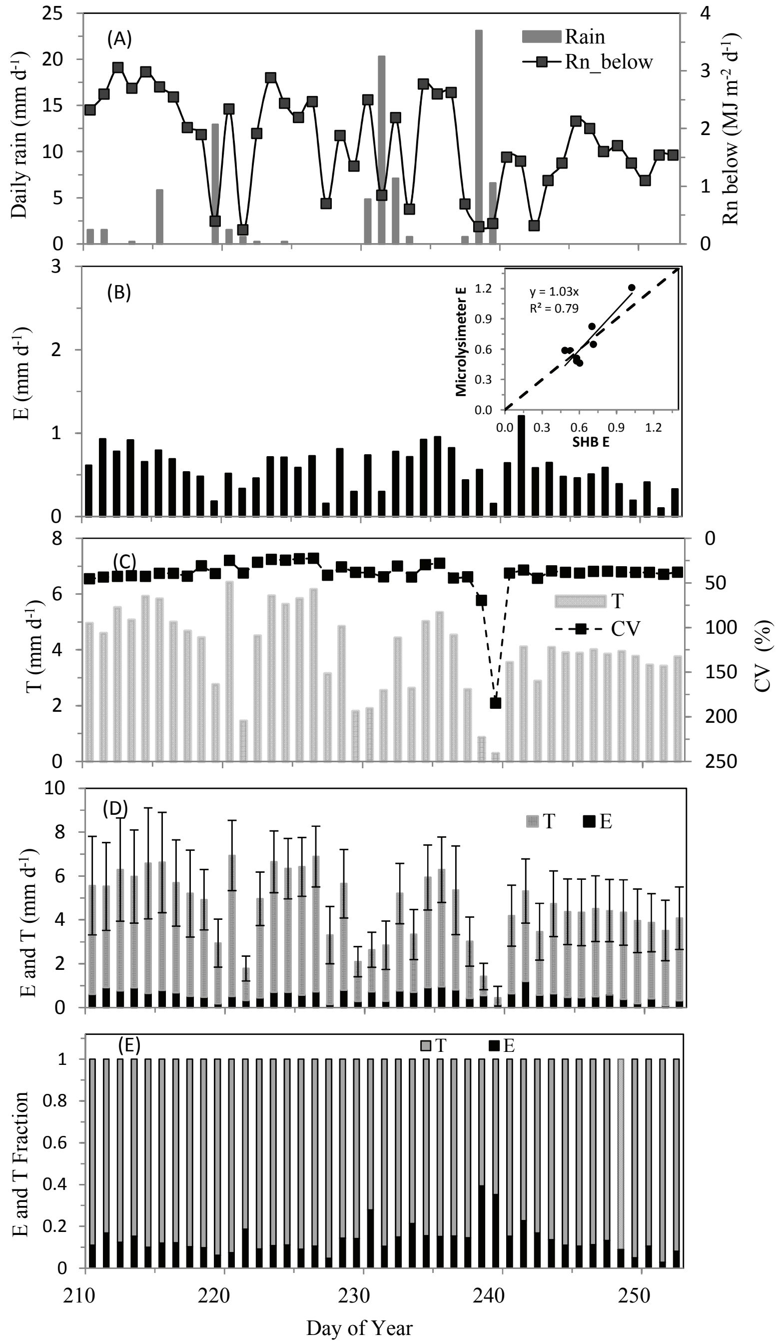

Figure 3. (a) Daily rain and net radiation (R_n) below the canopy, (b) sensible heat balance (SHB) evaporation (E) (inset: comparison to micro-lysimeter (ML) evaporation; data from Xiao et al., 2014), (c) sap-flow transpiration (T) and coefficient of variation (CV) over six plants, (d) sum of E and T with error bars as standard deviation of T, and (e) E and T as a fraction of E+T.

between micro-lysimeter means and SHB E typically on the same order as differences among micro-lysimeter replicates (<0.2 mm d^{-1}).

Across all dates, E ranged from 0.1 to 1.2 mm d^{-1} with an average of 0.6 mm d^{-1} during the 43 d measurement period (fig. 3b). Soil water evaporation rate was controlled by both available energy and available water in the soil. Overall, evaporation rates were relatively low because the canopy effectively fully covered the ground during measurements, and shading limited available energy at the soil surface. The measured net radiation below the canopy was 0.2 to 3.1 MJ m^{-2} d^{-1} with an average of 1.8 MJ m^{-2} d^{-1} (fig. 3a). The soil water evaporation dropped to <0.5 mm d^{-1} immediately after large rainfall events (>12 mm d^{-1}) on DOY 219-221, DOY 231, and DOY 237-239 when surface R_n was low (<1 MJ m^{-2}). During the measurement period, with soil remaining relatively wet, soil evaporation rates had a greater correlation ($R^2 = 0.35$) with the surface R_n than with soil water content ($R^2 < 0.1$).

Overall, the SHB method for measuring E agreed well with micro-lysimeters, when data were available, and provided the advantage of non-destructive, continuous measurements with minimal labor. We note that these measurements were most indicative of the local scale immediately within the measurement area. There was only one heat-pulse sensor installed at each row and inter-row position. When SHB E is scaled to the field, uncertainty may exist due to the spatial heterogeneity of the crop and soil conditions within the field.

TRANSPIRATION

Transpiration (T) was measured from six maize plants at a time, selected from an area near where the E measurements were performed. Overall, sap-flow T ranged from 0.3 to 6.4 mm d^{-1} with an average daily value of 4.1 mm (fig. 3c). Transpiration rate was relatively low (<3 mm d^{-1}) when net radiation above the canopy was relatively small (≤12 MJ m^{-2}) during rainy days when the soil was wet, and T was relatively high (≥3.0 mm d^{-1}) when net radiation was relatively large (>12 MJ m^{-2}) and soil was drying (fig. 3a). There was a co-linearity between daily sap-flow T and net radiation, as indicated by the strong correlation ($R^2 = 0.83$). Similar responses of T to radiation have been reported by Zhang et al. (2011), where daily sap-flow T was found to increase linearly with solar radiation in a vineyard.

Within the mean patterns, transpiration measurements for a given date showed some variability among individual plants. The coefficients of variation (CVs) for the six replicates of T were consistent across the measurement dates, ranging from 23% to 45% with an average of 40% (except for days of very high T values on DOY 238 and 239) (fig. 3c). Such a magnitude of CV values in daily sap-flow T is similar to the 20% to 40% CV for short-interval sap-flow T measurements in a maize field reported previously (Jara et al., 1998).

It is not surprising to observe some uncertainty for sap-flow T measurements given the normal plant-to-plant variation in a cropped field. There are two primary types of uncertainty in sap-flow measurements, with one related to the sap-flow sensor measurements, and the other related to the upscaling of microplot T to T of the entire canopy (Chabot et al., 2005). In our study, intra-row plant spacing may have contributed to the variability in sap flow among the six plants. For the first set of six plants sampled, plant spacing within a row ranged from 11 to 18 cm. The intra-row plant spacing likely resulted in stem diameter differences among the six plants. Stem diameter of the six plants ranged from 18 to 21 mm. Even small differences in plant spacing in a microplot can contribute to variability in plant-to-plant responses. This level of variability is typically compounded when scaling up from microplots to entire fields that contain landscape-induced plant growth responses. Similar variability existed for the second and third sets of six plants used to measure T. Despite some plant-to-plant variability, mean T values appear reasonable for maize grown in the region. For comparison to the present observations, Wiggans et al. (2012) measured average maize T, also by sap flow, of 2.9 mm d^{-1} between DOY 238 and DOY 267 at a field site within 5 km of this field site in the same year.

TOTAL E+T AND FRACTIONAL E AND T

Summing up daily E obtained by the SHB approach and daily T obtained by the sap-flow method provided a way to estimate daily ET. The additive E+T values are shown in figure 3d. Overall, E+T ranged from 0.4 to 6.9 mm d^{-1} with an average of 4.7 mm d^{-1}. E+T increased as net radiation above the canopy increased during the measurement period. Generally, E+T tracked with a similar temporal trend as T, as it was T that contributed the majority of ET in this field condition, with full maize canopy. In fact, the standard deviation for daily sap-flow T over six plants, ranging from 0.5 to 2.5 mm d^{-1}, was typically larger than the observed values for E, < 1.2 mm d^{-1} (figs. 3b and 3c).

The E and T fractions, relative to E+T, are shown in figure 3e. Overall, E accounted for a small average proportion of 13% (ranging from 3% to 39%), while T accounted for a large average proportion of 87% (ranging from 61% to 97%) of E+T. The fraction of T as E+T is similar to those reported by Herbst et al. (1998) for non-irrigated maize and by Jara et al. (1998) for furrow-irrigated maize but larger than those reported for sprinkler-irrigated maize systems by Thompson et al. (1997) and Zeggaf et al. (2008).

Both E and T respond to available water as source and/or to net radiation as driving force, but the responses can be different and thus result in variable fractions over time. During rainy days (DOY 210-115, 219-222, 230-234, and 237-239), when the soil was quite wet and net radiation was low, there was a greater drop in T values than in E values, which led to an increase of the E fraction and a decrease of the T fraction. The fraction of E had a decreasing trend when the soil surface was drying during non-rainy days. At this stage, E occurred in the soil surface layer where soil water was being depleted, while T followed water uptake via plant roots at deeper soil depths where soil water was still readily available. Soil water thus became a limiting factor for E, yet not for T, which rendered a quicker decrease and thus smaller fraction for E.

While the values and the range for E were much smaller than those for T, E was poorly correlated with net radiation both above and below the canopy (R^2 = 0.32 and 0.35, respectively), but a high correlation was observed between T and net radiation above the canopy ($R^2 = 0.83$). This is because the plant canopy was full, and much of the radiation was intercepted before reaching the ground surface during the measurement period. Canopy shading reduced net radiation, wind speed, and the difference in saturated vapor pressure and actual vapor pressure at the soil surface. Thus, in general, the fractions of E and T to ET varied primarily with soil water content during this portion of the season with full canopy.

COMPARISON OF ET ESTIMATES

Evapotranspiration estimates were obtained in three ways: individually measured E+T from SHB and sap-flow measurements, eddy covariance measurements of ET, and crop ET_c calculated from the combination of K_c and the standardized Penman-Monteith equation. The diurnal ET estimates from the three methods are shown in figure 4. All three estimates of ET had similar temporal trends, with ET having large diurnal fluctuations and values on sunny days and small ET fluctuations and values for rainy days and/or for low net radiation days during the whole measurement period. The values and fluctuations of E+T were close to those of ET_c, and both were larger than eddy covariance

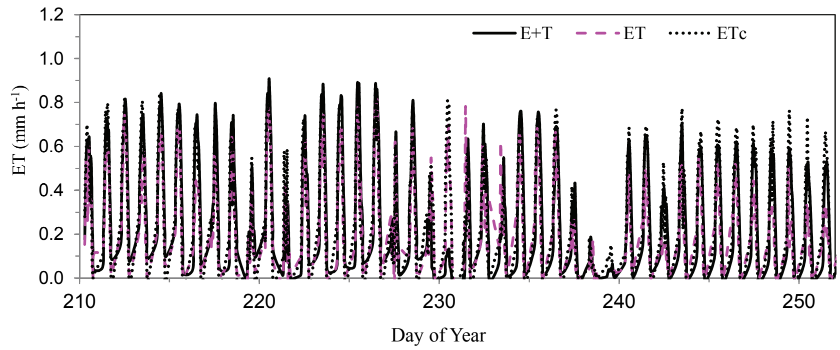

Figure 4. Diurnal evapotranspiration (ET) from the sum of evaporation and transpiration (E+T) measured with sensible heat balance and sap flow, respectively, eddy covariance ET, and field evapotranspiration (ET_c) from the standard Penman-Monteith equation.

ET. Individually measured daily E+T ranged from 0.4 to 6.9 mm d^{-1} with an average value of 4.7 mm d^{-1}, ET_c ranged from 0.8 to 6.5 mm d^{-1} with an average value of 4.5 mm d^{-1} and eddy covariance ET ranged from 0.3 to 5.8 mm d^{-1} with an average value of 3.5 mm d^{-1} (fig. 5).

The field ET_c represents the potential ET of the maize, completely shading the ground, with uniform height and adequate water status in the soil profile (Allen et al., 1998). Thus, ET_c should be close to actual ET when the soil is wet (without water stress in the soil-plant system), and ET_c should be larger than actual ET when the soil is dry (with water supply limited). In the early period (DOY 210-244), the soil was wet with water content above 0.25 m^3 m^{-3} (fig. 2b), and ET_c was close to E+T both in temporal trends and in fluctuation. ET_c was slightly larger than E+T when the soil was relatively dry in DOY 245-252. For the individually measured E+T, T was the average of T among six plants. Although some variation existed in T among the six plants (40% CV except for heavy rainy days on DOY 238-239), the variation was consistent during the measurement period (fig. 3c). That ET_c agreed well with E+T when the soil was wet and was slightly larger than E+T when soil was relatively dry appeared reasonable (fig. 5).

The eddy covariance ET agreed well with individually measured E+T, with the fluctuations slightly smaller than E+T when the soil was wet in DOY 210-240, but the difference between them was larger when the soil was drying during the last part of the measurement period (figs. 4 and 5). The disparities between eddy covariance ET and individual E+T may be due to a combination of factors. One possible reason was the difference in spatial scales among the methods. Individual measurements of E+T from the SHB and sap-flow methods represented a local scale of a few square meters, while eddy covariance ET estimates represented thousands of square meters. Individual measurements of E and T at a small spatial scale might not well represent all of the maize plants within the footprint of the eddy covariance flux measurements. Indeed, we observed variation in LAI in the maize field. Maize plants close to the heat-pulse sensors and sap-flow gauges had LAI of 4.1, while LAI at other field locations was as low as 3.7. Thus, the maize samples we chose for sap-flow gauge measurement of T might not fully represent the entire area sampled by the eddy covariance system. However, even given this spatial variability, differences in spatial scale did not completely explain the disparity between eddy covariance ET and individually measured E+T.

Eddy covariance measurements may underestimate ET, or individual component measurements of E and T may overestimate ET, due to measurement errors or bias. During the measurement period, the soil was relatively wet and there was little water stress evident in the soil-plant system, but the ET estimates from the eddy covariance measurements were consistently lower than E+T. When the soil was wet, E was estimated with the modified SHB method, where we assumed soil water E was in stage I and occurring in the soil surface, which possibly resulted in an overestimation of E. Nonetheless, these E estimates agreed well with the micro-lysimeter data and, when combined with T measurements, compared favorably to ET_c. This suggests

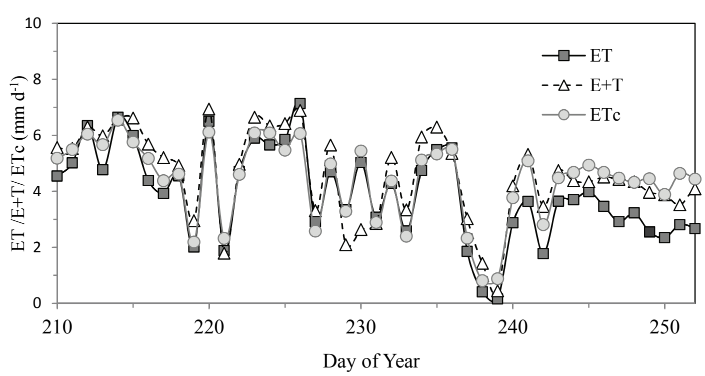

Figure 5. Daily evapotranspiration (ET) from the sum of evaporation and transpiration (E+T) measured with sensible heat balance and sap flow, respectively, eddy covariance ET, and field evapotranspiration (ET_c) from the Penman-Monteith equation.

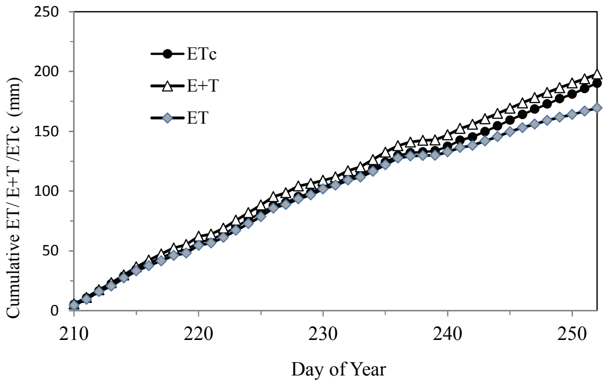

Figure 6. Cumulative evapotranspiration (ET) from the sum of evaporation and transpiration (E+T) measured with sensible heat balance and sap flow, respectively, eddy covariance ET, and crop evapotranspiration (ET_c) from the Penman-Monteith equation.

that, even with forced energy balance closure, uncertainty in the present comparison may come from eddy covariance ET.

During the entire measurement period, the cumulative evapotranspiration values were 197, 190, and 146 mm for individually measured E+T, crop ET_c and eddy covariance ET, respectively (fig. 6). The total E+T was close to ET_c with the difference within 4% during the measurement period, while E+T was 26% larger than eddy covariance ET.

Although disparities existed among the three methods during the measurement period, the individually measured E+T was highly correlated with eddy covariance ET and ET_c (R^2 = 0.77 and R^2 = 0.76, respectively) (fig. 7). Eddy covariance ET was 74% of E+T, and ET_c was 96% of E+T. That the E+T estimates provided a well-correlated estimate to other approaches is valuable. E+T measurements provide a way to estimate small-scale (e.g., treatment) differences that cannot be easily measured with standard micrometeorological approaches, and the SHB method provides a new opportunity to measure soil water E alone during wetting-drying periods in longer-term periods.

CONCLUSION

Our goal was to compare individually measured components of E+T from continuous SHB and sap-flow measurements to other estimates of ET. Soil water evaporation accounted for a relatively small portion of the individually measured E+T (3% to 39%) while T accounted for a relatively large portion of E+T (61% to 97%) during the measurement period. The temporal trends of individually measured E+T, eddy covariance ET, and ET_c agreed well, with small ET estimates observed on rainy days and on low net radiation days and large ET estimates observed on sunny days. Individually measured E+T was close to the field ET_c estimated from K_c and the standardized Penman-Monteith equation, but it was slightly smaller than ET_c when the soil was dry. Eddy covariance ET was only 74% of the individually measured E+T. The combination of SHB E with sap-flow T implemented in this experiment provides a new opportunity for continuous, non-destructive measurements of E+T during wetting-drying periods. Measurements of E with the SHB method in this study appear to have similar outcome, but with the advantage of continuous measurement, compared to E measurements from micro-lysimeters used in most previous studies. At the same time, some uncertainty remains regarding the combination and consistency of any of the various approaches (E+T, ET, and ET_c) applied together. Our measurements allowed us to detect obvious discrepancies between E+T and measured ET. In previous studies where only E or T was measured, and the other term was found by difference from ET, which was often the case, there was potential for serious error in ET partitioning estimates. Thus, we recommend that ET partitioning be considered with caution, and when possible, with a full suite of measurements separately accounting for each component as well as for the total.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation (Grant Nos. 0809656 and 1215864) and by the Hatch Act, State of Iowa funds, and State of North Carolina funds.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Rome, Italy: United Nations FAO.

ASCE. (2005). The ASCE standardized reference evapotranspiration equation. Technical report from the task

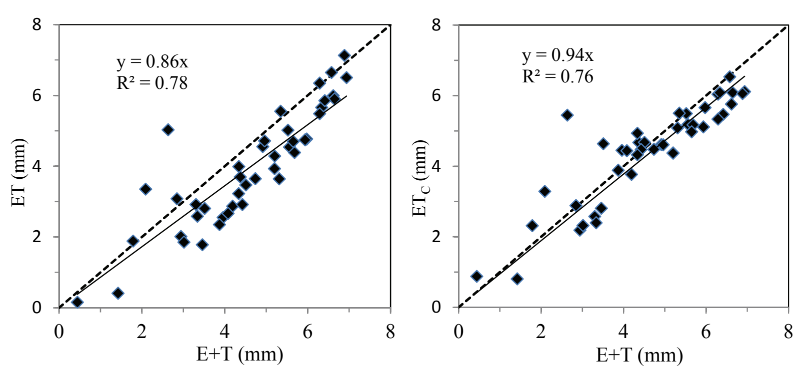

Figure 7. Relationships between the daily sum of individually measured evaporation from sensible heat balance and transpiration from sap flow (E+T) with eddy covariance evapotranspiration (ET) (left) and with crop evapotranspiration (ET_c) (right). The dashed lines are 1:1 lines.

committee on standardization of reference evapotranspiration. Reston, Va.: ASCE Environmental and Water Resources Institute.
Chabot, R., Bouarfa, S., Zimmer, D., Chaumont, C., & Moreau, S. (2005). Evaluation of the sap flow determined with a heat balance method to measure the transpiration of a sugarcane canopy. *Agric. Water Mgmt., 75*(1), 10-24. http://dx.doi.org/10.1016/j.agwat.2004.12.010
Deol, P. K., Heitman, J. L., Amoozegar, A., Ren, T., & Horton, R. (2014). Inception and magnitude of subsurface evaporation for a bare soil with natural surface boundary conditions. *SSSA J., 78*(5), 1544-1551. http://dx.doi.org/10.2136/sssaj2013.12.0520
Heilman, J. L., & Ham, J. M. (1990). Measurement of mass flow rate of sap in *Ligustrum japonicum*. *American Soc. Hort. Sci., 25*(4), 465-467.
Heitman, J. L., Horton, R., Sauer, T. J., & DeSutter, T. M. (2008a). Sensible heat observations reveal soil-water evaporation dynamics. *J. Hydrometeorol., 9*(1), 165-171. http://dx.doi.org/10.1175/2007JHM963.1
Heitman, J. L., Xiao, X., Horton, R., & Sauer, T. J. (2008b). Sensible heat measurements indicating depth and magnitude of subsurface soil water evaporation. *Water Resour. Res., 44*(4), W00D05. http://dx.doi.org/10.1029/2008WR006961
Herbst, M., Kappen, L., Thamm, F., & Vanselow, R. (1996). Simultaneous measurements of transpiration, soil evaporation, and total evaporation in a maize field in northern Germany. *J. Exp. Botany, 47*(12), 1957-1962. http://dx.doi.org/10.1093/jxb/47.12.1957
Hernandez-Ramirez, G., Hatfield, J. L., Parkin, T. B., Prueger, J. H., & Sauer, T. J. (2010). Energy balance and turbulent flux partitioning in a corn-soybean rotation in the Midwestern U.S. *Theor. Appl. Climatol., 100*(1), 79-92. http://dx.doi.org/10.1007/s00704-009-0169-y
Holland, S., Heitman, J. L., Howard, A., Sauer, T. J., Giese, W., Ben-Gal, A., ... Havlin, J. (2013). Micro-Bowen ratio system for measuring evapotranspiration in a vineyard interrow. *Agric. Forest Meteorol., 177*, 93-100. http://dx.doi.org/10.1016/j.agrformet.2013.04.009
Jara, J., Stockle, C. O., & Kjelgaard, J. (1998). Measurement of evapotranspiration and its components in a corn (*Zea mays* L.) field. *Agric. Forest Meteorol., 92*(2), 131-145. http://dx.doi.org/10.1016/S0168-1923(98)00083-5
Kool, D., Agam, N., Lazarovitch, N., Heitman, J. L., Sauer, T. J., & Ben-Gal, A. (2014). A review of approaches for evapotranspiration partitioning. *Agric. Forest Meteorol., 184*, 56-70. http://dx.doi.org/10.1016/j.agrformet.2013.09.003
Raz-Yaseef, N., Yakir, D., Schiller, G., & Cohen, S. (2010). Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns. *Agric. Forest Meteorol., 157*, 77-85. http://dx.doi.org/10.1016/j.agrformet.2012.01.015
Ritchie, S. W., Hanwayand, J. J., & & Benson, G. O. (1993). How a corn plant develops. Special report 48. Ames, Iowa: Iowa State University Cooperative Extension Service.
Rothfuss, Y., Biron, P., Braud, I., Canale, L., Durand, J., Gaudet, J., ... Bariac, T. (2010). Partitioning evapotranspiration fluxes into soil evaporation and plant transpiration using water stable isotopes under controlled conditions. *Hydrol. Proc., 24*(22), 3177-3194. http://dx.doi.org/10.1002/hyp.7743
Sakai, M., Jones, S. B., & Tuller, M. (2011). Numerical evaluation of subsurface soil water evaporation derived from sensible heat balance. *Water Resour. Res., 47*(2), W02547. http://dx.doi.org/10.1029/2010WR009866
Sakuratani, T. (1981). A heat balance method for measuring water flux in the stem of intact plants. *Agric. Meteorol., 37*(1), 9-17. http://dx.doi.org/10.2480/agrmet.37.9
Sauer, T. J. (2002). Heat flux density. In *Methods of Soil Analysis: Part 1, Physical and Mineralogical Methods* (pp. 1233-1248). Madison, Wisc.: ASA.
Steinberg, S., van Bavel, C. H. M.., & Mcfarland, M. J. (1988). A gauge to measure mass flow rate of sap in stems and trunks of woody plants. *American Soc. Hort. Sci. J., 114*, 466-472.
Thompson, A. L., Martin, D. L., Norman, J. M., Tolk, J. A., Howell, T. A., Gilley, J. R., & Schneider, A. D. (1997). Testing of a water loss distribution model for moving sprinkler systems. *Trans. ASAE, 40*(1), 81-88. http://dx.doi.org/10.13031/2013.21251
Twine, T. E., Kustas, W. P., Norman, J. M., Cook, D. R., Houser, P. R., Meyers, T. P., ... Wesely, M. L. (2000). Correcting eddy covariance flux underestimates over a grassland. *Agric. Forest Meteorol., 103*(3), 279-300. http://dx.doi.org/10.1016/S0168-1923(00)00123-4
van Bavel, C. H. M. (1961). Lysimetric measurements of evapotranspiration rates in the eastern United States. *SSSA J., 25*(2), 138-141. http://dx.doi.org/10.2136/sssaj1961.03615995002500020021x
Wang, J., & Bras, R. L. (2011). A model of evapotranspiration based on the theory of maximum entropy production. *Water Resour. Res., 47*(3), W03521. http://dx.doi.org/10.1029/2010WR009392
Webb, E. K., Pearman, G. I., & Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *J. Royal Meteorol. Soc., 106*(447), 85-100. http://dx.doi.org/10.1002/qj.49710644707
Wiggans, D. R., Singer, J. W., Moore, K. J., & Lamkey, K. R. (2012). Maize water use in living mulch systems with stover removal. *Crop Sci., 52*(1), 327-338. http://dx.doi.org/10.2135/cropsci2011.06.0316
Williams, D. G., Cable, W., Hultine, K., Hoedjes, J. C., Yepez, E. A., Simonneaux, V., ... Timouk, F. (2004). Evapotranspiration components determined by stable isotope, sap flow, and eddy covariance techniques. *Agric. Forest Meteorol., 125*(3-4), 241-258. http://dx.doi.org/10.1016/j.agrformet.2004.04.008
Wolf, A., Saliendra, N., Akshalov, K., Johnson, D. A., & Laca, E. (2008). Effects of different eddy covariance correction schemes on energy balance closure and comparisons with the modified Bowen ratio system. *Agric. Forest Meteorol., 148*(6-7), 942-952. http://dx.doi.org/10.1016/j.agrformet.2008.01.005
Xiao, X., Heitman, J. L., Sauer, T. J., Ren, T., & Horton, R. (2014). Sensible heat balance measurements of soil water evaporation beneath a maize canopy. *SSSA J., 78*(2), 361-368. http://dx.doi.org/10.2136/sssaj2013.08.0371
Xiao, X., Horton, R., Sauer, T. J., Heitman, J. L., & Ren, T. (2011). Cumulative soil water evaporation as a function of depth and time. *Vadose Zone J., 10*(3), 1016-1022. http://dx.doi.org/10.2136/vzj2010.0070
Zeggaf, A. T., Takeuchi, S., Dehghanisanij, H., Anyoji, H., & Yano, T. (2008). A Bowen ratio technique for partitioning energy fluxes between maize transpiration and soil surface evaporation. *Agron. J., 100*(4), 988-996. http://dx.doi.org/10.2134/agronj2007.0201
Zhang, X., Lu, S., Heitman, J., Horton, R., & Ren, T. (2012). Measuring subsurface soil-water evaporation with an improved heat-pulse probe. *SSSA J., 76*(3), 876-879. http://dx.doi.org/10.2136/sssaj2011.0052n
Zhang, Y., Kang, S., Ward, E. J., Ding, R., Zhang, X., & Zheng, R. (2011). Evapotranspiration components determined by sap flow and microlysimetry techniques of a vineyard in northwest China: Dynamics and influential factors. *Agric. Water Mgmt., 98*(8), 1207-1214. http://dx.doi.org/10.1016/j.agwat.2011.03.006