Sensible Heat Balance Measurements of Soil Water Evaporation beneath a Maize Canopy

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Abstract
Soil water evaporation is an important component of the water budget in cropped fields; few methods are available for continuous and independent measurement. A sensible heat balance (SHB) approach has been demonstrated for continuously determining soil water evaporation under bare surface conditions. Applicability of SHB measurements beneath a crop canopy cover has not been evaluated. We tested SHB using heat-pulse sensors to estimate evaporation beneath a full maize (Zea mays L.) canopy. We also implemented a modified SHB approach incorporating below-canopy net radiation, which extended the range of conditions under which SHB is applicable. Evaporation was measured at three positions: row (R), interrow (I), and interrow with roots excluded (IE). Evaporation rates were generally small, averaging −1 across all dates, positions, and measurement methods during the drying period. The SHB evaporation estimates varied among R, I, and IE, with cumulative totals of 4.4, 7.4, and 7.9 mm, respectively, during a 12-d drying period. Lower soil water contents from plant water uptake reduced evaporation rates at R more appreciably with time than at the other positions; I and IE provided similar evaporation patterns. The SHB evaporation estimates at R and I were compared with microlysimeter data on 8 d. Correlation between approaches was modest ($r^2 = 0.61$) but significant ($p < 0.001$) when compared separately at R and I positions. Correlation was improved ($r^2 = 0.81$) when evaporation estimates were combined across positions, with differences between SHB and microlysimeters typically within the range of values obtained from microlysimeter replicates. Overall, the results suggest good potential for using SHB and modified SHB approaches to determine soil water evaporation in a cropped field. The SHB approach allowed continuous daily estimates of evaporation, separate from evapotranspiration and without destructive sampling.

Disciplines
Agriculture | Hydrology | Soil Science

Comments

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Sensible Heat Balance Measurements of Soil Water Evaporation beneath a Maize Canopy

Soil water evaporation is an important component of the water budget in cropped fields; few methods are available for continuous and independent measurement. A sensible heat balance (SHB) approach has been demonstrated for continuously determining soil water evaporation under bare surface conditions. Applicability of SHB measurements beneath a crop canopy cover has not been evaluated. We tested SHB using heat-pulse sensors to estimate evaporation beneath a full maize (Zea mays L.) canopy. We also implemented a modified SHB approach incorporating below-canopy net radiation, which extended the range of conditions under which SHB is applicable. Evaporation was measured at three positions: row (R), interrow (I), and interrow with roots excluded (IE). Evaporation rates were generally small, averaging <0.7 mm d⁻¹ across all dates, positions, and measurement methods during the drying period. The SHB evaporation estimates varied among R, I, and IE, with cumulative totals of 4.4, 7.4, and 7.9 mm, respectively, during a 12-d drying period. Lower soil water contents from plant water uptake reduced evaporation rates at R more appreciably with time than at the other positions; I and IE provided similar evaporation patterns. The SHB evaporation estimates at R and I were compared with microlysimeter data on 8 d. Correlation between approaches was modest ($r^2 = 0.61$) but significant ($p < 0.001$) when compared separately at R and I positions. Correlation was improved ($r^2 = 0.81$) when evaporation estimates were combined across positions, with differences between SHB and microlysimeters typically within the range of values obtained from microlysimeter replicates. Overall, the results suggest good potential for using SHB and modified SHB approaches to determine soil water evaporation in a cropped field. The SHB approach allowed continuous daily estimates of evaporation, separate from evaporapotranspiration and without destructive sampling.

Abbreviations: DOY, day of the year; HP, heat pulse; I, interrow position; IE, interrow position with roots excluded; R, row position; SHB, sensible heat balance.

Soil water evaporation is an important component of the water budget in a variety of agronomic settings (Lascano et al., 1987; Allen, 1990; Heilman et al., 1994; Thompson et al., 1997). Evaporation can contribute as much as 70% of evaporapotranspiration, depending on, among other things, crop species and development stage, row width, and time of year (Herbst et al., 1996; Kang et al., 2003; Zeggaf et al., 2008). Proper planning of cropping systems and irrigation management depends on accurately accounting for evaporation as a component of the field water budget.

Few methods are available to continuously and independently measure soil water evaporation. Lysimeters (van Bavel, 1961; Robins, 1965; Tanner, 1967) and soil moisture depletion (Bohm et al., 1977) are long-established methods to determine soil water evaporation directly. Eddy covariance (Meyers and Baldocchi, 2005; Moncrieff et al., 1997) and Bowen ratio energy balance (Fritsch and Fritsch...
yet, to date, the SHB approach for determining soil water evaporation separate from evapotranspiration in cropped fields, except microlysimetry (Boast and Roberson, 1982), which typically has limitations for continuous measurement and/or because of labor requirements and disturbance.

Recent work has led to the development of a sensible heat balance (SHB) approach for continuous measurement of soil water evaporation. In the SHB approach, the measured sensible heat terms, soil conduction heat flux at two depths and the change in sensible heat storage between these depths, are used to compute a heat balance for a soil layer. The residual to the balance is used to estimate latent heat flux within the soil layer (i.e., soil water evaporation). Heitman et al. (2008a) implemented the approach using three-needle heat-pulse (HP) sensors to determine soil temperature and thermal property distributions, and subsequently determined the SHB of millimeter-thick layers of near-surface soil under a bare surface. Heitman et al. (2008b) compared SHB to microlysimeter and Bowen ratio evaporation measurements for bare surface conditions; their results showed strong agreement ($r^2 = 0.96$) for daily evaporation estimates. Xiao et al. (2011) tested SHB for measurements of cumulative evaporation with time and depth, also under bare surface conditions. Sakai et al. (2011) and Xiao et al. (2012) provided modifications of the SHB method for calculation and sensor design, respectively, to further improve the resolution of evaporation measurements. Deol et al. (2012) provided precise and accurate evaporation estimates using the SHB approach in the laboratory with evaporation occurring at soil depths as shallow as 0.5 mm. Yet, to date, the SHB approach for determining soil water evaporation has not been tested under cropped field conditions with a full or partial canopy cover.

Given the importance of evaporation in field water budgets and the lack of methods available for continuously and independently determining soil water evaporation, our goal was to implement the SHB approach for determining evaporation in a cropped field. We hypothesized that the SHB approach could be applied to measure evaporation occurring below a plant canopy. We implemented the SHB approach using HP sensors for three positions within a full-canopy maize field (row, interrow, and interrow with roots excluded). We also developed a modified SHB approach, incorporating net radiation at the soil surface, to better capture evaporation occurring at shallow depths during early-stage drying. Evaporation estimates from SHB and modified SHB were compared with estimates obtained from microlysimeters.

**MATERIAL AND METHODS**

**Field Site**

The study was performed in a maize field located near Ames (41.98°N, 93.68°W), IA, during the summer of 2009. The field had been planted in a maize–soybean [*Glycine max* (L.) Merr.] rotation for many years before the experiment. In 2009, maize was planted on day of the year (DOY) 136 with 0.75-m row spacing in east–west rows. The soil at the site was Canisteo clay loam (a fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll). The surface soil layer (0–60-mm) bulk density was 1.2 Mg m$^{-3}$. The soil consisted of 44, 30, and 26% sand, silt, and clay, respectively, and the topography was relatively flat (slope <2%). Soil cores (7.6-cm diameter by 7.6-cm length, three replicates) were collected before the experiment for water retention measurements using a combination of tension table (Romano et al., 2002) and pressure plate (Dane and Hopmans, 2002) methods.

Heat-pulse sensors (described below) were installed at three positions within the field: row (R), interrow (I), and interrow with roots excluded (IE) (Fig. 1). The positions were chosen to consider potential differences between management positions (R vs. I) under the full-canopy covered maize field and to test the influence of root water uptake on measurements (I vs. IE). The IE position was a small area (2 by 0.45 m); on each side, 0.5-m-deep narrow trenches were cut with a chain saw. Plastic sheets were placed in each trench before backfilling the trenches with soil when the maize leaf area index was approximately 2. The plastic sheets served as barriers to prevent roots from growing into the position.

In the same maize field, a weather station tower measured and recorded rainfall (Model TE525 tipping bucket precipitation gauge, Texas Electronics), net radiation (above the crop canopy) (Model CNR-1 net radiometer, Kipp and Zonen), air temperature and humidity (Model HMP45C temperature and relative humidity sensor, Vaisala), atmospheric pressure (Model PTB101B barometer, Vaisala), and wind speed (Model 014A cup anemometer, Met One). An additional tube net radiometer (TRL, Delta-T Devices) was installed 5 cm above the soil surface across one entire maize row (i.e., perpendicular to the row direction) to measure net radiation beneath the maize canopy. These data were recorded every 5 min and stored as 15-min averages.

**Heat-Pulse Sensor Measurements**

Heat-pulse measurements were made for 20 consecutive days when the maize was at or approaching full canopy. Eleven-needle HP sensors (Xiao et al., 2012; Deol et al., 2012) were used to collect measurements for the SHB (Fig. 2). The sensors were a modification of the three-needle HP sensors used by Ren et al. (2003). Each sensor consisted of four long parallel stainless steel needles (1.3-mm diameter, 40-mm length) and seven short parallel stain-
less steel needles (1.3-mm diameter, 20-mm length). Two short needles were offset from the top short needle in a T shape with a vertical spacing of 1 mm between each of the top three needles. The four long needles and the other five short needles alternated in a straight line in an epoxy body, with about 6-mm spacing between adjacent needles. Each needle contained a chromel–constantan (Type E) thermocouple for measuring temperature. In each long needle, there was also a resistance heater wire through which a small current could be applied to generate a heat pulse, leading to temperature increases at the adjacent short needles. The precise distances between neighboring needles were determined from HP measurements made in agar-stabilized water (6 g L−1) before installation in the field (Ren et al., 2003).

One 11-needle HP sensor was installed at each of the three locations: R, I, and IE. A narrow trench was dug and the sensors were inserted vertically into the undisturbed soil profile, with the top sensor needle at the soil surface and the bottom sensor needle at a depth of 48 mm. The trench was then carefully backfilled with soil. The thermocouples and heater wires of the HP sensors were connected to an AM16/32 multiplexer and an AM416 multiplexer (Campbell Scientific), respectively. Both multiplexers were controlled by a CR10X datalogger (Campbell Scientific). The datalogger was powered by a 12-V power supply.

Heat-pulse measurements of soil thermal conductivity and volumetric heat capacity (Xiao et al., 2012; Deol et al., 2012) were performed with each heating needle every 8 h. The purpose of the longer interval between measurements (compared with previous bare field experiments) was for practical reasons. Less frequent measurement reduced data storage and processing and limited potential damage to heaters with repeated firing. This was done with the expectation that full canopy cover and moist soil conditions would moderate thermal property dynamics compared with those observed in bare field experiments. The heating sequence was to apply a heat pulse to a single heater needle per location for each activation. In sequence from top to bottom, individual heater needles were fired at 1, 3, 5, and 7 h for each sensor and then the series was repeated. The sequence for each HP measurement consisted of a 30-s background temperature measurement, an 8-s heating duration at the heater needle, and 72-s temperature measurements after heating. Thus, the temperature response at the adjacent thermocouple needles during HP measurements was recorded for a total time of 110 s with a 2-Hz sensing interval. The 30-s background temperatures were used to correct for temperature drift (Ochsner et al., 2006). In addition, the ambient soil temperature at each needle position was measured and recorded every hour (before initiating heaters for intervals when heating occurred). Thermal property data were linearly interpolated (time-weighted average between measurements) to provide thermal property estimates each hour to match the frequency of the ambient temperature data.

Sensible Heat Balance

Heat-pulse data were used to calculate evaporation with a sensible heat balance (Heitman et al., 2008a):

\[
LE = G_1 - G_2 - \Delta S
\]

where \(G_1\) and \(G_2\) (W m\(^{-2}\)) are heat fluxes from two depths, \(\Delta S\) (W m\(^{-2}\)) is the change in sensible heat storage in the soil layer between these depths, \(L\) (J m\(^{-3}\)) is the latent heat of vaporization, and \(E\) (m s\(^{-1}\)) is the evaporation rate. Soil heat flux \(G\) was calculated as the product of the measured soil thermal conductivity (W m\(^{-1}\) °C\(^{-1}\)) and the change in temperature with depth (°C m\(^{-1}\)), measured from adjacent HP sensor needles. The change in sensible heat storage \(\Delta S\) was calculated as the product of the measured soil volumetric heat capacity (J m\(^{-3}\) °C\(^{-1}\)), the change in temperature with time from the sensor needles (°C s\(^{-1}\)), and the depth increment (m) (Ochsner et al., 2007). Evaporation was calculated from HP data on an hourly basis and then accumulated on a daily basis to estimate the daily evaporation rates at each position.

For Eq. [1] and the HP sensor configuration used in this study, evaporation occurring at or below the midpoint depth between the uppermost sensor needles (0.5 mm) can be detected, whereas evaporation occurring at shallower depths (<0.5 mm) is not (Sakai et al., 2011; Deol et al., 2012). It is implicitly assumed that all energy not accounted for as \(G\) or \(\Delta S\) within a soil layer is attributable to \(LE\). Liquid water loss, whether via evaporation or plant water uptake, is accounted for by measured changes in the soil volumetric heat capacity. Heat transfer associated with liquid water flow (convective liquid heat transfer) into or out of the measured soil layer is neglected; this assumption was shown to be appropriate for intervals when liquid water redistribution was driven by evaporation (Sakai et al., 2011). The SHB was not determined for periods with rainfall.

To extend the conditions for which evaporation could be detected beneath the canopy, we also considered an alternate approach. For wet soil surfaces with non-water-limited conditions (Stage I), evaporation occurs at the soil surface (Or et al., 2013). Given the limitation of SHB for detecting surface (Stage I) evaporation (Heitman et al., 2008b; Sakai et al., 2011), we modified Eq. [1] by replacing \(G_1\) with net radiation \(R_n\) (W m\(^{-2}\)) beneath the canopy:

![Fig. 2. Photo and side view sketch of an 11-needle heat-pulse sensor.](image-url)
$LE = R_n - G_s - \Delta S$ \[2\]

This approach, hereafter referred to as the modified SHB, corresponds to the common surface energy balance, assuming that the surface sensible heat flux is negligible. This was a practical assumption to allow implementation of Eq. [2] without a ready means to detect the surface sensible heat flux but was also plausible for moist soil conditions during Stage I evaporation, especially with low wind speed and small soil-air temperature gradients expected beneath the canopy. The measured $R_n$, determined with a tube net radiometer, was used as a common value for all HP measurement positions. The modified SHB was calculated each hour and accumulated each day to estimate daily evaporation.

The SHB and modified SHB provide two possible approaches for determining soil water evaporation. These approaches, however, are not applicable under common sets of conditions. During early-stage evaporation, Eq. [1] cannot account for surface evaporation. During later stage (subsurface) evaporation, Eq. [2] neglects the partitioning of a portion of available energy to surface sensible heat flux. This assumption is probably invalid when the dry soil surface, with relatively low heat capacity, begins to warm and water for evaporation (i.e., $LE$) is limited. To determine which approach is appropriate on a given day, we considered criteria based on the soil water characteristic curve.

Lehmann et al. (2008) proposed that Stage I evaporation terminates when the soil dries sufficiently to reach a threshold tension at which air penetration disrupts the hydraulic continuity to the surface. For a field soil with a range of pore sizes, Dexter and Bird (2001) proposed that the inflection point in the water retention curve can be used to indicate the soil water content at which air has penetrated the soil. Thus, we chose the water content corresponding to the inflection point in the water retention curve as the threshold for switching between the modified SHB and SHB approaches, indicating transition from Stage I to Stage II evaporation. The inflection point for our field soil, 0.25 m$^3$ m$^{-3}$, was calculated following the approach outlined by Dexter and Bird (2001), using the van Genuchten water retention model implemented in RETC (van Genuchten et al., 1991) fitted to water retention measurements (Fig. 3). Daily soil water content values for the upper 1 cm of the soil profile were computed from HP sensor heat capacity measurements following the approach described by Heitman et al. (2003). Evaporation was computed using Eq. [2] (the modified SHB) for daily water contents > 0.25 m$^3$ m$^{-3}$ and Eq. [1] (the SHB) for daily water contents ≤ 0.25 m$^3$ m$^{-3}$.

We also note that both Eq. [1] and [2] assume a one-dimensional (vertical) approximation of the energy balance at a given position. This is an inherent limitation in the proposed measurement approach. This simplified approximation warrants some consideration due to the added complexity of the cropped field compared with earlier bare field experiments (Heitman et al., 2008a,b; Xiao et al., 2011, 2012). However, for the present experiment under canopy conditions, radiation, wind speed, temperature, and humidity near the surface were moderated and assumed to be relatively uniform. A preliminary analysis of the soil temperature data also indicated that the vertical temperature gradients near the surface had magnitudes several orders larger than those observed in the transverse direction (data not shown).

**Microlysimeter Evaporation Measurements**

Microlysimeters were used to measure daily soil water evaporation at the R and I locations for 8 d (DOY 236 and 241–247) during the HP measurement period. No microlysimeter measurements were made at the IE location because of the limited area (0.9 m$^2$). The microlysimeters were the same type used by Singer et al. (2010) and Heitman et al. (2010). They were white polyvinyl chloride cylinders, 10 cm long by 7.6-cm inner diameter, with a wall thickness of 3 mm. Microlysimeters were tapped into the soil with a hammer until the top rim was level with the soil surface and were left in place until a rainfall event occurred.

At 0800 h on the day after the first rainfall event in the measurement interval, five microlysimeters were excavated at each location (R and I). Each microlysimeter was cleaned of loose soil, trimmed even at the bottom, sealed at the bottom end with a thin plastic sheet, and then weighed at a 0.1-g resolution scale. The microlysimeters were then reinstalled at their original positions, with the surrounding soil carefully packed around them. Twenty-four hours later, the microlysimeters, with the ends still sealed, were again excavated and reweighed. This process was repeated for each day of microlysimeter measurements. Each microlysimeter was used for two consecutive days and then discarded. The daily soil water evaporation (mm) from the microlysimeters was the ratio of the difference in mass (g) of two consecutive days divided by the density of water (g mm$^{-3}$), divided by the microlysimeter’s cross-sectional area (mm$^2$).

**RESULTS AND DISCUSSION**

**Field Conditions**

Rain totaling 27 mm occurred on DOY 231 to 233, just before HP measurements. The HP measurement interval (DOY 233–252) included 3 d with rainfall (DOY 237–239) totaling about 30 mm (Fig. 4). This was followed by 13 d without rainfall.
Maize leaf area index values were between 4.0 and 4.3, and the maize height was between 2 and 3 m during the measurement period. Net radiation measured above the maize canopy typically peaked at >500 W m\(^{-2}\), except for the days with rainfall (Fig. 4). Net radiation below the canopy was much less; peak daily values were about 100 W m\(^{-2}\). The reduction in incoming radiation through the maize canopy, and ultimately the magnitude of net radiation below the canopy, was characteristic of full-canopy conditions with significant shading. The soil heat flux density, averaged across R and I positions, typically peaked at <20 W m\(^{-2}\) each day and was lower on days with, and shortly after, rainfall.

Surface soil water contents were >0.25 m\(^3\) m\(^{-3}\) at all three measurement positions at the beginning of the HP measurement interval (Fig. 5). A short dry-down occurred before rainfall on DOY 237 to 239. After DOY 237, the water content again exceeded 0.25 m\(^3\) m\(^{-3}\) at all three positions. The greater water contents observed shortly after rainfall at R (0.45 m\(^3\) m\(^{-3}\) than I and IE might be the result of stem flow in the plant row, which funneled rainfall from the canopy to the ground surface at the plant stem (Paltineanu and Starr, 2000). During a longer dry-down period from DOY 239 to 252, the water content dropped below 0.20 m\(^3\) m\(^{-3}\) at R but remained >0.20 m\(^3\) m\(^{-3}\) at I and IE. Greater sustained water contents several days after rainfall (after DOY 244) at I and IE were consistent with less (or zero for IE) plant water uptake at these positions than at R. No obvious differences in water content were detected between I and IE.

**Sensible Heat Balance Evaporation Measurements**

Daily soil water evaporation measured with the SHB varied across days and among positions (Fig. 6). The maximum observed daily evaporation exceeded 1 mm d\(^{-1}\) on DOY 234 to 236 for R when both surface soil water content and below-canopy net radiation were relatively large (Fig. 4 and 5). Compared with lower evaporation rates on DOY 241 to 252, the water content dropped below 0.20 m\(^3\) m\(^{-3}\) at R but remained >0.20 m\(^3\) m\(^{-3}\) at I and IE. Greater sustained water contents several days after rainfall (after DOY 244) at I and IE were consistent with less (or zero for IE) plant water uptake at these positions than at R. No obvious differences in water content were detected between I and IE.

diation was relatively large (>115 W m\(^{-2}\)), declining evaporation rates at R coincided with decreasing soil water content.

A large daily evaporation rate (1.48 mm d\(^{-1}\)) was observed just after rainfall on DOY 241 at I (Fig. 6), which coincided with the largest soil water content observed at this position (Fig. 5). Despite this single large value, evaporation rates were on the same average magnitude (0.62 mm d\(^{-1}\)) for I and IE during the measurement interval. Position IE had a clearer trend toward a decreasing evaporation rate with time after rainfall from DOY 241 to 252 than did I (Fig. 6). Some variation in evaporation between days could be attributed to varying radiation (Fig. 4), but the overall temporal trend for both I and IE coincided with declining soil water contents (Fig. 5).

Cumulative evaporation for the long (12-d) dry-down period beginning on DOY 241 allows additional comparison among the three measurement positions (Fig. 7). Cumulative evaporation totals were 4.4, 7.4, and 7.9 mm for R, I, and IE, respectively. The difference between R and the other two positions is distinct
(>40%) and probably due to differences in plant water uptake. Even though R had a greater water content after rainfall (DOY 241–244), limited available energy below the canopy led to similar cumulative evaporation at all positions. Thereafter, when plant uptake significantly reduced the soil water content at R, evaporation became water limited, evaporation rates decreased (Fig. 6), and cumulative evaporation totals departed from those occurring at other positions (Fig. 7). Similar daily evaporation rates and cumulative evaporation totals at I and IE (where roots were excluded) suggest that root water uptake had little influence at I.

Comparing Sensible Heat Balance and Microlysimeter Evaporation

Microlysimeter evaporation estimates were collected from the R and I positions on 8 d. Daily evaporation varied between 1.03 and 0.42 mm d⁻¹ at R and between 1.02 and 0.53 mm d⁻¹ at I (Fig. 8). The average daily coefficients of variation were 11 and 16% for R and I, respectively. In general, evaporation was greatest on the first observation after rainfall (DOY 241) when soil water content was greatest, and was lower with a slight decline over time on the following days. The lowest evaporation amounts were observed at each position on the last day of observation. Observed evaporation rates were greater at I than at R on each of the last 5 d of observation.

Evaporation estimates for microlysimeters and the SHB were of similar average magnitude across all days: 0.63 and 0.61 mm d⁻¹, respectively, for R and 0.67 and 0.72 mm d⁻¹, respectively, for I (Fig. 8). The maximum difference between microlysimeters and the SHB was 0.46 mm d⁻¹ on DOY 241 at I. Overall, the difference between the two approaches was <0.2 mm d⁻¹ for 13 of 16 paired comparisons, which was smaller than the range of values obtained from the microlysimeters (five replicates) at a given position and on a given date (0.35 mm d⁻¹). Correlation between the microlysimeter and SHB approaches was modest ($r^2 = 0.61$) but significant ($p < 0.001$) when compared separately at the R and I positions on each measurement date (Fig. 9a). When grouped by date (i.e., averaged across position) to represent overall below-canopy evaporation, the correlation was improved ($r^2 = 0.81$, $p = 0.002$).

Previous comparisons between independent measurements (microlysimeters and Bowen ratio) and SHB have been favorable (Heitman et al., 2008b) but were performed in relatively simple bare-surface conditions. To put the present data set into context, we also plotted measurements from the maize field together with those from bare-field studies presented by Heitman et al. (2008b), which were conducted on a similar soil type (Fig. 9b). The present data set obviously covers a smaller range of evaporation rates than Heitman et al. (2008b) but generally shows similar agreement. Heitman et al. (2008b) also limited their comparison to evaporation occurring several days after rainfall because of an inability to detect evaporation occurring during Stage I, at the soil surface. In this study, we introduced a modified SHB to allow estimation of evaporation when the evaporation front remained at the surface, which was expected to be a more frequent occurrence for moist, low-radiation conditions beneath the maize canopy. To demonstrate the importance of this modification, we show both SHB and modified SHB approaches computed separately for the dates of microlysimeter measurement (Fig. 10). Based on the soil mois-

Fig. 7. Cumulative evaporation for days of the year (DOY) 240 to 252 after rainfall on DOY 237 to 239, determined from sensible heat balance at row (R), interrow (I), and interrow with roots excluded (IE) measurement positions.

Fig. 8. Sensible heat balance (SHB) and microlysimeter evaporation estimates for (A) row and (B) interrow measurement positions. Error bars indicate one standard deviation on either side of the mean for five replicate microlysimeter measurements. Note the break in the time axis, excluding the interval when no microlysimeter data were available. Here SHB refers to either SHB or modified SHB on a given day, as determined according to water content criteria.
ture threshold used to determine the appropriate approach, the modified SHB was implemented for DOY 241 to 243 at the R position (Fig. 10a) and DOY 241 for the I position (Fig. 10b). While there remains some disparity between microlysimeters and the SHB (combined original and modified approaches, Fig. 8), it is clear that the modified SHB approach was necessary to account for Stage I evaporation occurring in the shallow soil (depth <0.5 mm). For the four dates when the modified SHB was implemented, the original SHB approach underestimated microlysimeter evaporation rates by an average of 75% (Fig. 10). Likewise, once the surface dried below the threshold moisture content, the modified SHB overestimated microlysimeter evaporation rates by an average of 80%, probably because the neglected surface sensible heat flux was then a more important term in the surface energy balance. Clearly, the modified SHB approach extended the capability of detecting soil water evaporation, but it must be implemented under the appropriate condition of a wet soil surface with unlimited water for evaporation.

SUMMARY AND CONCLUSIONS

We implemented the SHB approach, along with a modification including the measured net radiation to capture Stage I evaporation, to determine evaporation in a cropped field. Overall, evaporation rates measured beneath the fully developed maize canopy were generally small (<0.7 mm d⁻¹ average). Three separate measurement positions (R, I, and IE) differed in their observed evaporation rates on a given date, but all showed temporal trends related to declining soil water content. The greatest difference in the temporal patterns was observed between R and the remaining two positions. Position R had peak evaporation rates of similar or slightly larger magnitude than the other positions shortly after rainfall, but evaporation rates declined significantly during the drying period as plant water uptake lowered the soil water content. There was little apparent influence of root water uptake at I, based on similar observed evaporation rates, cumulative evaporation totals, and soil water contents at IE, where root water uptake was excluded.

Comparison with microlysimeter evaporation measurements indicates that the SHB approach provided accurate results. Disparity between the two approaches was generally simi-
lar to the range in results obtained from microsyrtem replicates on a given date. The modification extending the SHB to account for Stage I evaporation also provided an improvement for the measurement of conditions when the soil surface was moist after rainfall, which was not possible in previous SHB experiments. Overall, the results suggest that the SHB approach has a good potential for application as a method to determine evaporation beneath crop canopies. Based on these experiments, the SHB approach can provide continuous daily evaporation estimates, independent of evapotranspiration, without destructive sampling required for microsyrtemy. Future experiments that further evaluate the range of conditions under which the SHB and modified SHB approaches can be implemented will be helpful, but even in the present experiment, SHB provided plausible, practical results on soil water evaporation.

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