Portable canopy chamber measurements of evapotranspiration in corn, soybean, and reconstructed prairie

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Abstract
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Keywords
Portable canopy chamber, Evapotranspiration, Field water balance

Disciplines
Agriculture | Agronomy and Crop Sciences | Bioresource and Agricultural Engineering | Sustainability | Water Resource Management

Comments

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Portable canopy chamber measurements of evapotranspiration in corn, soybean, and reconstructed prairie

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A R T I C L E   I N F O
Article history:
Received 30 August 2017
Received in revised form 27 November 2017
Accepted 29 November 2017
Available online 7 December 2017

Keywords:
Portable canopy chamber
Evapotranspiration
Field water balance

A B S T R A C T
Evapotranspiration (ET) is a vital component of a field water balance. Canopy chambers are a promising method for determining crop ET because they are portable and applicable at a relatively small plot (m²) scale. Although a variety of canopy chamber designs have been proposed, field tests are still necessary to evaluate chamber performance for measuring crop ET. The objectives of this study are (1) to construct and use an improved canopy chamber to measure ET of three crops [corn (Zea mays, L), soybean (Glycine max), and reconstructed mixed prairie] and (2) to compare the canopy chamber measurements with flux tower results and field water balance measurements (i.e., rainfall, soil water storage, ET and drainage). Three cropping systems including corn/soybean in a corn-soybean rotation, and reconstructed mixed prairie were studied in central Iowa. Canopy chamber ET daily measurements were performed on 18 days in 2013 (a relatively dry growing season) and on 15 days in 2014 (a relatively wet growing season). Based on the results, the differences in daily ET and seasonal cumulative ET between canopy chambers and an eddy covariance flux tower over the measurement periods were within 5%, providing evidence that the portable canopy chamber can accurately measured ET. The chamber ET values and field water balance ET values had similar patterns over the 2013 and 2014 measurement periods, and the differences of cumulative results were less than 10%. In conclusion, the canopy chamber was proven to be an effective method for measuring small plot ET.

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1. Introduction

Evaporation (E) is the process of liquid water being converted to water vapor; transpiration (T) consists of the vaporization of liquid water contained in plant tissues and the movement of the vapor to the atmosphere, especially through the leaf stomata. Evapotranspiration (ET) is the combination of E and T. Because T occurs simultaneously with the photosynthetic gas exchange (Grau, 1995; Wagner and Reicosky, 1992), it is widely considered in plant physiological studies, and is often a major component of ET during a growing season. At a field scale, accurate determination of crop ET is important for evaluating plant water use, which provides useful information for field water management (Wagner and Reicosky, 1992; Reicosky and Peters, 1977). ET is a key component of field water fluxes in the soil-water-atmosphere continuum (Yang et al., 2006), and it is a major sink of precipitation and irrigation, particularly in arid and semiarid areas. Thus, ET becomes an indicator of plant water stress (Wagner and Reicosky, 1992; Reicosky and Peters, 1977). Because of the large latent heat of vaporization of water, ET is also an important component in the surface energy balance (Gowda et al., 2013). With an increasing interest in climate change and crop water use, it is important to improve measurements of soil-vegetation-atmosphere interactions, especially ET (Intergovernmental Panel on Climate Change (IPCC), 2001; Burkart et al., 2007). Solar radiation, air temperature, humidity and wind speed are the main climate parameters that influence ET, and soil water content, which is the reservoir for ET, is another factor that influences ET (Allen et al., 1998; Campbell and Norman, 1998).

Indirect and direct methods have been used to quantify ET fluxes. Indirect methods include the use of micrometeorological techniques such as eddy covariance (EC) (Baldocchi et al., 1996; Rana and Katerji, 2000; Burkart et al., 2007), surface energy balance and field water balance approaches (Livingston and Hutchinson, 1994; Baldocchi et al., 1996; Rana and Katerji, 2000; Bowen, 1926;
The indirect methods do not disturb the plant canopy; however, they require large homogeneous fields to obtain stable, valid results. In many agricultural studies, the size of research plots is often too small to enable the use of micrometeorological methods (Stewart, 1984; Baldocchi et al., 1988). A direct method may include equipment to obtain and isolate gas samples from plant canopies, and analyze the changes of water vapor concentration to determine ET. A common strategy is to use a canopy chamber to sample the air. There are many categories of chamber design, such as leaf chambers for plant physiology studies and canopy chambers for field crop studies. Although a chamber was first used approximately 80 years ago by Thomas and Hill (1937), ongoing development of gas analyzers enables even more accurate and rapid measurements with canopy chambers of varying shapes and dimensions.

Canopy chambers can be classified as open or closed systems. For an open system, the gas is continuously pumped into and out of the chamber through opennings (or channels). The differences of water vapor concentration between the chamber inlet and outlet are measured and used to determine the ET flux. The measurements can be obtained continuously over time periods from several days to whole growing seasons; however, complex systems are required to maintain the climate within chambers to be similar to the ambient conditions (Musgrave and Moss, 1961; Burkart et al., 2007). Thus, the portability of open chambers is usually limited. A closed chamber is usually designed as a portable system, i.e., it can be transported among several sampling locations in the field. A closed chamber system measures the changes of water vapor concentration inside the chamber to evaluate the instantaneous ET. Rapid measurements for brief periods (1 min or so) are used to avoid chamber-induced canopy microclimate changes (Garrity et al., 1984; Wagner and Reicosky, 1992; Reicosky and Peters, 1977).

Closed canopy chambers can be cross-validated with local micrometeorological or field water balance measurements to provide a small scale complement to the large scale measurements (Angell and Svejcar, 1999; Dugas et al., 1997). Due to the usefulness of the chamber techniques, multiple designs have been reported. Steduto et al. (2002) reported a chamber design with comprehensive tests of climate changes within the chamber during measurements. However, actual field measurements are still necessary to evaluate how well canopy chambers measure crop ET under a range of time scales and weather conditions.

In this study, the basic structure of the canopy chamber is similar to the chamber reported by Steduto et al. (2002). However, a unique feature of this chamber is that a LI-7500 open-path CO$_2$/H$_2$O infrared gas analyzer (LI-COR Biosciences Inc., Lincoln, NE) is mounted in the center of the chamber, instead of a closed-path analyzer installed outside of the chamber, where air samples from the chamber have to be pumped through the analyzer. The closed-path analyzer has potential limitations, such as the time lag between the air sampling and the analysis, and difficulties in obtaining a representative air sample. The LI-7500 is designed for EC measurements, which involve long-term deployment in extreme weather conditions. It can provide water vapor and CO$_2$ concentration values at a frequency of 20 Hz and does not require frequent recalibration. By placing the sensor in the middle of the air space and using multiple fans to thoroughly mix the air, the time lag in water vapor measurement is eliminated and data can be collected rapidly, potentially reducing the measurement time.

The objectives of this study are: (1) to construct canopy chambers and perform ET measurements on corn, soybean and reconstructed prairie and (2) to validate the canopy chamber results with EC measurements and with field water balance measurements over a range of time scales. Steduto et al. (2002) already provided detailed information on chamber induced microclimate conditions and on how they influence the measured ET results, and the growth patterns of the crops (corn, soybean and reconstructed prairie) have already been reported, such as in Dietzel et al. (2015a). Thus, the focus of this paper is limited to the field ET measurements.

2. Materials and methods

2.1. The portable canopy chamber design and data interpretation

A portable canopy chamber (Fig. 1) was constructed of aluminum framing with “Mylar” film (clear polyester film of 0.08 mm thickness) covering. A flexible rubber layer was placed around the bottom edges. The canopy chamber has a footprint area of 1.5 m$^2$. Three canopy chambers with different heights (0.6 m, 1.0 m, and 1.6 m) were used to match the different crop growth stages. The “Mylar” film is durable, resisting punctures and tears (Musgrave and Moss, 1961); while the rubber layer was used to seal the chamber against any leaks at the soil surface. An LI-7500 was mounted inside the chamber to measure water vapor concentrations inside the chamber with respect to time, which were used to calculate the ET flux. A LI-7500 interface unit was used to control the LI-7500 IRGA.

Additional auxiliary sensors were used to measure the chamber and ambient climate conditions, e.g., air temperature, solar radiation, atmospheric pressure, and canopy temperature, which were used to verify the similarity of climate conditions inside and outside of the chamber. Because of the greenhouse effect, the air tem-

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**Fig. 1.** Portable canopy chamber placed on a field plot.

**Fig. 2.** Canopy chamber measurements in a corn plot at 9:00 a.m. on DOY 171, 2014. The measured values and fitted QR curve are shown.
per temperature inside of the chamber increases during a measurement (Wagner and Reicosky, 1992). In order to monitor the temperature difference, four copper–constantan thermocouples were mounted inside and outside of the chamber to measure air temperature (approximately 0.2–1.2 m above the ground surface), and two infrared thermometers (IRR-111, Apogee Instruments Inc., Logan, UT) were mounted inside and outside of the chamber to measure the canopy temperature. Temperature differences were kept within 2°C before and during each measurement. Atmospheric pressure could also alter the ET flux (Lund et al., 1999). Therefore, two barometers (SB-100, Apogee Instruments Inc., Logan, UT) were mounted to measure the air pressure inside and outside of the chamber, and a vent at a bottom corner of the chamber connected to outside air via a 1 m tube inside the chamber was used to balance the air pressure inside and outside the chamber. The 1 m tube was used to minimize gas loss by diffusion during a measurement. Two LI-190SB quantum sensors (LI-COR Biosciences Inc., Lincoln, NE) were mounted inside and outside of the chamber to monitor the differences in photosynthetic active radiation (Steduto et al., 2002). DC Axial fans (80 mm-diameter) with flow rates of 0.93 m³ min⁻¹ (NMB Technologies Inc., Chatsworth, CA) were installed at lower and upper corners of the chambers to mix the gas inside of the chamber. Although the fans caused minor convection at the leaf-air interface and soil-air interface, Steduto et al. (2002) reported that impact on ET was not significant. A CR-3000 micro-logger (Campbell Scientific Inc., Logan, UT) was used for collection and storage of data from the canopy chamber sensors. The sampling frequency was 20 Hz for all of the sensors.

The chamber LI-7500 directly measures water vapor concentrations with time. A quadratic regression (QR) of the water vapor concentration (w, mmol L⁻¹) versus time is used to determine ET fluxes (Wagner et al., 1997). The QR model is

\[ w = a_0t^2 + b_0t + c_w \]  

where \( t \) is the sampling time, and \( a_0, b_0, c_w \) are fitted parameters. An example of the QR model fitted to the measured water vapor concentrations is shown in Fig. 2. A reason for the quadratic pattern is that the water vapor concentration inside of the chamber increased with time, leading to a decreasing water vapor deficit, which reduces the measured ET. The slope of the water vapor curves at the initial time, \( t = 0 \), is selected to determine the instantaneous ET at the time that the crop canopy is first covered by the chamber. In the following discussion, ET fluxes will be presented with units of “mm h⁻¹”.

By the end of each of the field measurements, the temperature differences between inside and outside of the chamber did not extend 2°C for the thermocouples and IRTs. The air pressure within the chamber was ~0.1 kPa larger than the ambient air pressure. During the field measurements, the PAR inside the chamber was about 30% less than the outside PAR, which was about 5–10% larger than the results reported by Musgrave and Moss (1961) and Steduto et al. (2002).

2.2. Laboratory tests

A mass balance method was used in a laboratory pre-test of the canopy chamber to determine the accuracy and stability of chamber measurements. To obtain a range of E fluxes, water-filled evaporation pans were positioned under canopy chambers, and the mass change of each evaporation pan, measured with an electronic balance, was used to determine the actual E flux. A canopy chamber was placed over the evaporation pan and measured simultaneously with the mass balance method. The E fluxes determined by the canopy chamber method were compared with the mass balance method. Laboratory experiments were performed more than 50 times with various E fluxes for the small, medium and large chambers.

The laboratory test results of the canopy chambers are presented in Fig. 3. Small chamber measured values and mass balance estimated values match the 1:1 line for E fluxes ranging from 0 to 0.40 mm h⁻¹. Medium and large chamber measured values and mass balance estimated values match the 1:1 line for E fluxes ranging from 0 to 0.85 mm h⁻¹. These laboratory test ranges cover the ranges of chamber ET fluxes in the field plots. The small chamber was used in the field for the measurement of bare soil and small crops during the early growing season, when the ET flux did not exceed 0.30 mm h⁻¹. The medium chamber was used in the field during the middle growing season when ET flux did not exceed 0.55 mm h⁻¹. The large chamber was used in the field for the late growing season when ET flux did not exceed 0.80 mm h⁻¹. Thus, the
Table 1  Regression parameters (slope and intercept) of the instantaneous chamber results and the EC flux tower results with CIs for $\alpha = 0.05$.

<table>
<thead>
<tr>
<th></th>
<th>Slope</th>
<th>Intercept</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn ET 2013</td>
<td>1.12</td>
<td>[0.92 1.32]</td>
<td>0.015 [-0.044 0.073]</td>
</tr>
<tr>
<td>Soybean ET 2014</td>
<td>1.03</td>
<td>[0.94 1.15]</td>
<td>0.04 [-0.01 0.06]</td>
</tr>
</tbody>
</table>

* Significantly different from the intercept value of the 1:1 line (slope = 1; intercept = 0).

Table 2  Regression parameters (slope and intercept) of the daily chamber results and EC flux tower results with CIs for $\alpha = 0.05$.

<table>
<thead>
<tr>
<th></th>
<th>Slope</th>
<th>Intercept</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn ET 2013</td>
<td>0.94</td>
<td>[0.77 1.12]</td>
<td>0.33 [-0.28 0.94]</td>
</tr>
<tr>
<td>Soybean ET 2014</td>
<td>0.97</td>
<td>[0.82 1.13]</td>
<td>0.44 [-0.02 0.89]</td>
</tr>
</tbody>
</table>

Table 3  The cumulative chamber and flux tower results.

<table>
<thead>
<tr>
<th></th>
<th>ET (mm)</th>
<th>Chamber</th>
<th>Flux Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn (DOY 164–206, 2013)</td>
<td>127</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>Soybean (DOY 156–277, 2014)</td>
<td>321</td>
<td>316</td>
<td></td>
</tr>
</tbody>
</table>

laboratory test results indicated that the small, medium and large chambers were able to determine ET accurately.

2.3. Field measurements

Field measurements were performed at the Iowa State University COBS (Comparison of Bio-fuel Systems) research site located in Boone county, IA (41°55′N, 93°45′W). The COBS field was established in 2008, and there are 24 plots (61 m by 27 m) and 6 cropping systems on Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soils. The 6 zero-till cropping systems include corn-soybean, soybean-corn, continuous corn, and continuous corn with winter rye (Secale cereale) cover crop, reconstructed mixed prairie (C3 grasses, C4 grasses, legumes, and multi-functional group mixtures), and fertilized reconstructed mixed prairie (Daigh et al., 2015; Dietzel et al., 2015b; Jarchow et al., 2015). Measurements were made in 4 replications of 3 cropping systems (corn and soybean in corn-soybean rotation system, and reconstructed mixed prairie). In 2013, for corn and soybean, the planting date was DOY 137, and the harvesting dates were DOY 282 and DOY 274, respectively. In 2014, the planting date for corn and soybean was DOY 140, and the harvesting date was DOY 287. The perennial mixed prairie was seeded in 2008, and the biomass harvest date in 2013 was DOY 301, and in 2014, it was DOY 318. Canopy chamber measurements were made on 18 days during the 2013 growing season and on 15 days during the 2014 growing season. In 2014, a sap-flow system and micro-lysimeters were used as complementary measurements for the chamber in the corn plots when the height of the corn plant exceeded the height of the large chamber (1.6 m). Sapflow and micro-lysimeter measurements extended the ET determination in corn to the end of the growing period (Baker and van Bavel, 1987). The sapflow systems were installed in one row near the canopy chamber footprints, with five SGB19 sapflow gages (Dynamax, 2005). Sapflow measurements were taken every 30 min from 4:00 a.m. to 10:00 p.m. every day. The correction from Wang et al. (2017) was used to determine corn T from the sapflow data. The micro-lysimeters were installed in the same row as the sapflow measurement system in each corn plot. Five micro-lysimeters were used in each plot, and the mass changes represented the daily E flux (Boast and Robertson, 1982).

The EC flux tower measurements were made at Brooks field site No.10 located in Boone County, IA (41°58′N, 93°41′W). The site has a corn-soybean rotation on Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls), Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) and Clarion (Fine-loamy, mixed, superactive, mesic Typic Hapludolls) soils. The EC technique relies on the fact that the fluctuations of vertical wind speed are correlated to the fluctuations of water vapor density.

$$ET = \rho \overline{\text{w}C' \text{C}}$$  (2)

where $\rho$ is the molar density of the air, and $\overline{\text{w}C' \text{C}}$ is the covariance of wind speed and mole fraction of water vapor. The Webb et al. (1980) correction was applied to calculate the ET.

The EC flux tower measurements were used to estimate ET of corn in 2013 and soybean in 2014. In 2013, the corn planting and harvesting dates were DOY 139 and DOY 298. In 2014, the soybean planting and harvesting dates were DOY 138 and DOY 291. The flux tower instruments were positioned 250 cm above the ground surface for soybean and 500 cm above the ground surface for corn. The EC flux tower results are used to evaluate the performance of the chamber method.

The field water balance method uses soil moisture, precipitation and drainage data to estimate crop ET. The soil water content in each field plot was measured with 5TE or 5TM sensors (Decagon Devices Inc., Pullman, WA). Soil moisture sensors were installed in each plot at depths of 5, 10, 18, 30, and 50 cm, and the soil water storage in the 0–60 cm soil layer was computed. Weather data, including wind speed, solar radiation, air temperature, air humidity and precipitation, were collected at the COBS site weather station (Campbell Scientific Inc., Logan, UT). Subsurface drains installed about 1 m deep along the center of each plot emptied into a sump (Daigh et al., 2015). The volumes of drainage water were measured by T-10 flow meters (Neptune Technology Group Inc., Tallassee, AL). The field water balance method is based on the following equation

$$P - D - R - \Delta \theta \times L = ET$$  (3)

where $P$ (mm) is the precipitation, $D$ (mm) is the drainage, $R$ (mm) is the surface runoff (the plots have low slope, so the surface runoff is assumed to be zero); $\Delta \theta \times L$ (mm) is the change of soil water storage, where $\theta$ (m$^3$ m$^{-3}$) is the volumetric soil water content and $L$ (mm) is soil layer thickness (Allen et al., 1998). The aim of the field water balance method is to quantify all water balance components on the left hand side of Eq. (3) to compute ET. Accurately monitoring short time changes in soil moisture is one of the challenges of this method. Timlin et al. (2007) reported that low time resolution and time-lag are two potential drawbacks for the field water balance method, due to the soil-root interaction and soil and plant water capacity, which can buffer instantaneous variations of ET. Thus, the field water balance will compare with chamber results over a long time period.

2.4. Cumulative ET fluxes estimation

Daily cumulative ET values are calculated by integrating the instantaneous ET values with the trapezoid rule, i.e.,

$$ET_d = \sum_{i=0}^{n} \frac{ET_i + ET_{i+1}}{2} (t_{i+1} - t_i)$$  (4)

where $ET_d$ is the daily cumulative ET, $ET_i$ is the instantaneous ET at time $t_i$, and $ET_{i+1}$ at $t_{i+1}$ (Parkin and Kaspar, 2004). Because the canopy chambers did not provide continuous measurements, the daily ET values between two chamber measuring days and the cumulative ET throughout the measurement period was calculated based on a recurrent neural network model (RNN). A RNN model is
ETd chamber applied, a special version of artificial neural network models including historical information (Kurková, 1992; Katsuura and Sprecher, 1994), and it has been used in other cropping and environmental studies (Kim and Kim, 2008; Chai et al., 2012). The RNN models are formulated by using the ET on previous days and the radiation on the current day to calculate the daily cumulative ET. In order to implement the RNN model, we first use linear interpolation based on the chamber measured daily ET from Eq. (4) to provide the first predictions to the daily ET when the chamber measurements were not applied, i.e., \( \hat{E}T_{d(i)} \), \( i = 1, 2, 3, \ldots \), and then filter the first prediction with the following RNN model

\[
ET_{d(i)} = p(R_s) + f \left( \hat{E}T_{d(i)}, \hat{E}T_{d(i-1)}, \hat{E}T_{d(i-2)}, \ldots \right)
\]

(5)

where \( p(R_s) \) is the polynomial of the solar radiation \( R_s \); the \( f \) is a artificial neural network model, and \( ET_{d(i)} \) is the output. The RNN was trained with the MATLAB (Mathworks Inc. Natick, MA) neural network toolbox. The degree of the polynomial \( p \) and the time step in \( f \) were selected with cross-validation.

3. Results and discussion

In this section, we first compare the instantaneous, daily, and cumulative ET, over the measurement periods of the canopy chamber with the EC results to evaluate the field performance of the canopy chambers. The instantaneous comparison can directly show the agreement between the chamber and EC results; while the daily and cumulative comparisons indicate the consistency and the stability of the two methods over relatively long periods, which can better reflect the performance of the chamber since they smooth out the instantaneous errors. After that, we make further comparisons between the canopy chamber results, including sapflow and micro-lysimeter results for corn, and the field water balance results.
3.1. Comparison of chamber and EC flux tower methods

Fig. 4 presents a comparison of instantaneous canopy chamber ET with the flux tower ET for corn in 2013 and soybean in 2014. In order to compare the values at the same times, the flux tower results were interpolated with a least squares support vector machine model (Suykens et al., 2002) to provide values at the canopy chamber measurement times. Linear regressions of canopy chamber ET and flux tower ET are presented as the blue lines in Fig. 4. The EC flux tower ET values and the chamber ET values are similar, but they do not match exactly the 1:1 line. The regression results (slopes, intercepts and the Confidence Intervals, CI, with $\alpha = 0.05$) are listed in Table 1.

The regression line slopes were not significantly different from 1. The intercept value of the soybean ET regression was significantly larger than 0, while the corn intercept value was not significantly different from 0. One reason for the difference is that the measurement heights of the two methods differed. The chamber measurements represented the canopy level, while the flux tower measurements were made about 250 cm above the ground, and there could be an unaccounted time-lag between the canopy chamber and flux tower measurements. The physical separation of canopy and flux tower also means that the wind speed could be different. In addition, the chamber measurement is only for 1 min. It would be difficult to match the measurement with the same minute on the EC results due to the oscillation of EC measurements (refer to...
Considering these factors, the measurements were in quite good agreement. The difference between the canopy chamber and EC results can be smoothed out by using daily and seasonal cumulative values for canopy chamber and flux tower measurements (refer to Figs. 6 and 7.)

Before we present the cumulative ET comparisons, it will be interesting to plot the daily patterns of the chamber measured ET and the EC flux tower ET. Fig. 5a and b show examples of daytime chamber and flux tower ET values for corn on DOY 179, 2013, and for soybean on DOY 212, 2014. The diurnal patterns of chamber results and flux tower results were similar for corn and soybean. The canopy chamber ET values matched the daytime flux tower values well, except for some data points near the maxima of the ET fluxes, due to the relative large oscillations in the flux tower data. However, the chamber values were within the oscillation range of the flux tower results. During the morning and late afternoon time periods, the numerical oscillations of the flux tower results were small, and the chamber results agreed well with the flux tower results.

Fig. 6 presents the daytime cumulative chamber and flux tower ET values. The regression lines for the data points are represented by the blue lines, and the regression results (slopes, intercepts and CIs, with α = 0.05) are listed in Table 2. The regression lines are not significantly different from the 1:1 lines. Thus, there is a good match between the chamber daily ET values and the flux tower ET.

The cumulative chamber and cumulative flux tower ET for corn (2013) and soybean (2014) over the chamber measurement period are presented in Fig. 7a and b. The cumulative ET values are listed in Table 3. The patterns of canopy chamber cumulative ET are similar to the flux tower results for both corn and soybean. The RNN interpolations of chamber ET are similar to the continuously measured flux tower ET values. The chamber measurements for corn in 2013 stopped on DOY 206 because the height of corn exceeded the height of the tallest canopy chamber. The differences between cumulative chamber measurements and the flux tower measurements for corn and for soybean are less than 10% throughout the measurement period. The differences of the final cumulative values are less than 5% of the cumulative ET.

In summary, the agreement between canopy chamber results and flux tower ET results indicates that canopy chamber measurements in small plots are able to obtain results similar to the flux tower values obtained in much larger fields for a range of time scales. The results demonstrate the effectiveness and accuracy of the canopy chamber method.

### 3.2. Comparison of chamber ET and field water balance ET

In this section, the chamber ET is compared with water balance ET. The time period for the comparisons between chamber and field water balance results in 2013 was from DOY 164–255. Because the corn outgrew the chamber, the comparison period for corn was from DOY 164–206. In 2014, the comparison period for prairie and soybean was DOY 156–277; and the comparison period for corn ended on DOY 212. However, by including the sapflow and micro-

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**Fig. 10.** Comparisons between canopy chamber ET and water balance ET in 2013 for corn (a), prairie (b), soybean (c), and 2014 for corn (d), include the sapflow and micro-lysimeter results), prairie (e), soybean (f).
lysimeter measurements, corn ET measurements were extended to DOY 261. The cumulative precipitation, change in soil water content, cumulative drainage, and cumulative water balance estimated ET for the 2013 measurement period are presented in Fig. 8. The 27 year (1986–2012) average cumulative precipitation for the measurement period was 326 mm (with standard deviation of 32 mm), while the cumulative precipitation in 2013 was only 149 mm. Thus, the 2013 growing season was noticeably drier than the average growing season.

During the 2013 measurement period, the only two large precipitation events occurred on DOY 203 (16 mm) and DOY 223 (51 mm). Although these precipitation events caused immediate increases in soil water content, overall, the soil water content decreased during the growing season due to the drought-like conditions. ET values were relatively small in 2013, and the cumulative drainage values were less than 20 mm.

The cumulative precipitation, change in soil water content, cumulative drainage, and cumulative water balance estimated ET during the 2014 measurement period, DOY 164–277, are presented in Fig. 9a to d. The 27 year (1986–2012) average precipitation for the measurement period was 408 mm (with standard deviation of 39 mm), while the seasonal precipitation in 2014 was 601 mm. Thus, the 2014 growing season was noticeably wetter than the average growing season.

During the 2014 measurement period, precipitation was evenly distributed throughout the growing season. The water content decreased in the early measurement period and increased by the end of the measurement period. However, due to plentiful precipitation in 2014, the differences between the initial water contents and final water contents for the three crops were small. The cumulative drainage values ranged from 200 to 250 mm.

Comparisons between the chamber measured ET and field water balance estimated ET are shown in Fig. 10 and Table 4. The differences between the field water balance and chamber method were within 10%. Field water balance calculations were influenced by large rainfall events. Thus, the results contained some oscillations. The cumulative chamber ET generally matched well with the field water balance ET as it increased smoothly with respect to time. In 2014, the sapflow and micro-lysimeter measurements extended the chamber measurements for corn and indicated a consistent trend between the chamber ET and sapflow and micro-lysimeter ET values. The pattern of the cumulative ET in corn was similar to the patterns in prairie and soybean for the whole measurement period.

### 4. Summary

In this study, canopy chambers that improved the design of Steduto et al. (2002) were tested under controlled laboratory conditions and under natural field conditions. Field ET measurements were made in corn, soybean and reconstructed mixed prairie field plots in 2013 and 2014, and canopy chamber ET results for corn and soybean were compared with EC flux tower ET results. The instantaneous chamber results were similar to the EC flux tower values. The chamber daily instantaneous ET patterns, the chamber cumulative daily ET values, and the chamber cumulative seasonal ET values were consistent with the EC flux tower results with relative errors less than 10%. Thus, the field performance of the canopy chamber was validated.

Field water balance ET was estimated in 2013 and 2014. Cumulative canopy chamber ET was similar to the field water balance ET in 2013 and 2014. Field water balance is suitable for estimating ET over time periods of several weeks or longer, while the canopy chamber can measure ET from instantaneous to seasonal time scales.

Relative to the EC flux tower method and the field water balance method, an advantage of the canopy chamber method is that instantaneous measurements can be performed on small scale field plots. Moreover, the chamber is easy to set up, and the chamber can be transported rapidly among multiple field plots. Thus, chambers can obtain measurements for several cropping systems during the same time period.

The study provided evidence that the portable canopy chamber is a reliable, efficient and accurate way to measure ET in field plots for a range of time scales (instantaneous, daily, and seasonal) in corn, soybean and reconstructed prairie. We performed and validated chamber measurements in 2013 (a relatively dry season) and 2014 (a relatively wet season), which shows that the chamber method is robust over a range of weather conditions. Future studies should include tests of chamber method over a range of climate conditions. Numerical simulation studies of ET can also be used to further evaluate the chamber method. CO₂ as well as ET exchanges in field plots can also be investigated with canopy chambers to study crop photosynthesis and water use efficiency, which will provide additional information on the usefulness of the canopy chamber.

### Acknowledgment

This work was supported by grants from the Iowa Water Center and the Agriculture and Food Research Initiative of the USDA National Institute of Food and Agriculture (NIFA), grant number 2011-67003-30364, Multi-State Project 3188, and by Iowa State University Department of Agronomy, the Hatch Act, and State of Iowa funds.

### References


