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Core Ideas

- Canopy chambers were used to measure CO_2 exchange rates (CER) in corn and soybean plots.
- Daytime and cumulative CER fluxes were calculated from measured instantaneous CER fluxes.
- Chamber CER fluxes were consistent with eddy covariance flux tower CER fluxes.

Canopy Chamber Measurements of Carbon Dioxide Fluxes in Corn and Soybean Fields

Zhuangji Wang, Chenyi Luo,* Thomas J. Sauer, Matthew J. Helmers, Liukang Xu, and Robert Horton

Crop canopy CO_2 exchange rate (CER) includes crop photosynthesis and soil/plant respiration. A portable canopy chamber is effective in determining crop CER values at a relatively small spatial (m^2) scale. The objectives of this study were to use a canopy chamber to measure CO_2 fluxes in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Chamber measurements were performed for 18 and 15 d in 2013 and 2014, respectively. The canopy chamber measures instantaneous CER fluxes, and daily and daytime cumulative CO_2 values were calculated from the instantaneous CER. The chamber CER results were compared with nearby eddy covariance (EC) flux tower measurements at a variety of time scales, i.e., instantaneous, daily, and daytime cumulative (multiple months). The daily and daytime cumulative chamber CER values were within 5% of the EC results, providing evidence for the effectiveness of the portable canopy chamber method. In conclusion, the portable canopy chamber provides reliable CO_2 flux measurements despite the small size of field plots.

Abbreviations: CER, carbon dioxide exchange rate; DOY, Day of the Year; EC, eddy covariance; ET, evapotranspiration; RNN, recurrent neural network; SCE, soil carbon dioxide efflux.

Carbon dioxide exchange rate (CER) at the crop canopy level includes plant photosynthesis, aboveground plant respiration, and soil CO_2 efflux (SCE), where SCE is the sum of soil respiration and root respiration (Angell and Svejcar, 1999; Reicosky, 1990). The CER is a critical component in the field C budget (Wagner and Reicosky, 1992; Dugas et al., 1997), and it can be related to plant growth under specific field or greenhouse management (Leonardos et al., 1994). Micrometeorological and chamber methods have been used to measure CER fluxes. Canopy chambers sample atmospheric gases at the crop canopy level and measure the variation of CO_2 concentrations with respect to time to estimate the instantaneous CER (Pérez-Priego et al., 2010). Canopy chamber techniques include two categories: steady-state systems and non-steady-state systems (Rochette and Hutchinson, 2005). Steady-state chambers can actively compensate for microclimate changes induced by the chamber, and such chambers are usually designed to measure CER at a specific location continuously for relatively long time periods. Non-steady-state chambers rely on rapid measurements for brief periods (~1 min) to minimize chamber-induced microclimate changes (Wagner and Reicosky, 1992). The non-steady-state chambers are usually designed to be portable, which allows the chamber to be transported among multiple sampling locations.

Non-steady-state chamber results can be cross-validated with micrometeorological measurements, and they can be combined with other gas flux measurements, such as evapotranspiration (ET) or SCE (Dugas et al., 1997; Angell and Svejcar, 1999). Multiple studies regarding chamber design and data interpretation have been published. For example, Steduto et al. (2002) reported comprehensive observations of chamber-induced meteorological changes and their potential effects on measurements.

The objectives of this study were to use the portable canopy chamber reported by Luo et al. (2018) to obtain and evaluate field CER measurements on corn and soybean. To evaluate the canopy chamber performance, the chamber CER values were compared with flux tower EC results at a variety of time scales, i.e., instantaneous, daily (from sunrise to sunset), and daytime cumulative (multiple months).

Z. Wang, USDA–ARS, Adaptive Cropping Systems Lab., Beltsville, MD 20705; Z. Wang, Dep. of Plant Science and Landscape Architecture, Univ. of Maryland, College Park, MD 20742; C. Luo and R. Horton, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011; T.J. Sauer, USDA–ARS, National Lab. for Agriculture and the Environment, Ames, IA 50011; M.J. Helmers, Dep. of Agricultural and Biological Engineering, Iowa State Univ., Ames, IA 50011; L. Xu, LI-COR Biosciences Inc., Lincoln, NE 68504.*Corresponding author (cyluo@iastate.edu).

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Materials and Methods

Figure 1 shows the design of the portable canopy chamber. It was constructed with aluminum framing and covered with 0.08-mm-thick Mylar film (Luo et al., 2018). The chamber had a footprint area of 1.5 m^2 and an adjustable height (0.6, 1.0, and 1.6 m) to match the crop size. An LI-7500 CO_2/H_2O analyzer was installed inside the chamber for gas concentration measurements. Auxiliary sensors, including copper-constantan thermocouples, LI-190SB quantum sensors (LI-COR Biosciences), SB-100 barometers, and IRT-111 infrared thermometers (Apogee Instruments) were mounted to ensure that the air temperature, leaf temperature, radiation, and air pressure were similar inside and outside of the chamber during measurements (Luo et al., 2018). Quadratic regressions of the CO_2 concentration (c, mmol m^{-3}) from the LI-7500 measurements (20 Hz) during a 1-min period were used to calculate CER fluxes (Luo et al., 2018; Wagner et al., 1997; Zhao et al., 2018). The regression models are

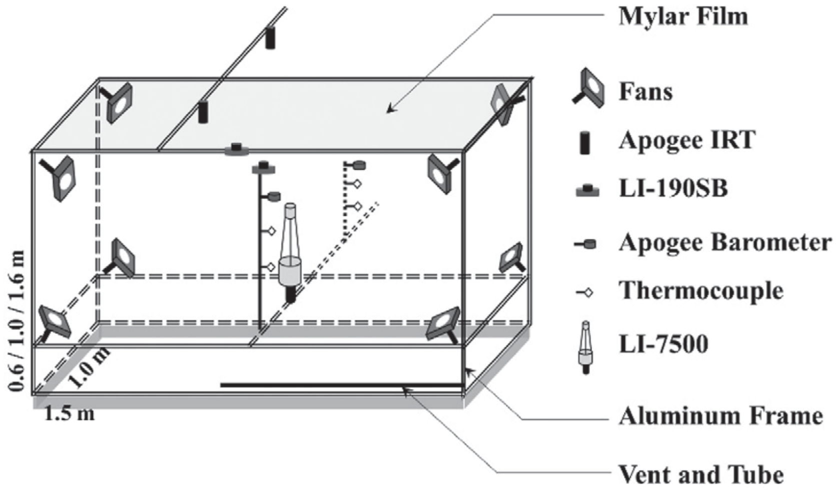

Fig. 1. The design of the portable canopy chamber (Luo et al., 2018). An LI-7500 Open Path CO_2/H_2O Analyzer was mounted at the center of the chamber. Apogee infrared radiometers (IRTs), LI-190SB quantum sensors, Apogee barometers, and thermocouples were mounted inside and outside the chamber. Fans were mounted to mix the air inside the chamber, while a vent tube was placed at a bottom corner of the chamber. The length of the chamber is 1.5 m, the width of the chamber is 1.0 m, and the height of the chamber varies among 0.6, 1.0, and 1.6 m.

$$c = a_c t^2 + b_c t + c_c \quad [1]$$

where t is time, and a_c, b_c, and c_c are fitting parameters for the CO_2 concentration. The slope of the regression curve at $t = 0$ was used to determine the instantaneous CER (µmol m^{-2} s^{-1}):

$$\mathrm{CER} = \frac{\mathrm{d}c}{Et}\bigg|_{t=0} \frac{V}{A} = b_c H \quad [2]$$

where V (m^3) is the chamber volume, A (m^2) is the chamber footprint area, and H (m) is the chamber height.

Field experiments were completed at an Iowa State University study site in Boone County, IA (41°55′ N, 93°45′ W). The soils in the field plots were Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Measurements were made on corn and soybean plots in a corn–soybean rotation system with four replications. The planting date in 2013 was Day of the Year (DOY) 137, and the harvest dates were DOY 282 for corn and DOY 274 for soybean. In 2014, the planting date was DOY 140 and the harvest date for both crops was DOY 287. Chamber measurements were taken on 18 and 15 d during the 2013 and 2014 growing seasons, respectively.

The flux tower EC measurements were made at the Brooks field site no.10 located in Boone County, IA (41°58′ N, 93°41′ W, and 9.0 km away from the chamber study site), with weather conditions similar to the study site. The soils at the field site were Webster, Nicollet, and Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls). The EC measurements were performed continuously on the corn and soybean fields in a corn–soybean rotation system in 2013 and 2014 (Hernandez-Ramirez et al., 2011; Dold et al., 2017). The planting and harvest dates were DOY 139 and DOY 298 in 2013 for corn, and DOY 138 and DOY 291 in 2014 for soybean. The EC instruments were placed 250 cm above the ground for soybean and 500 cm above the ground for corn. The procedures of Webb et al. (1980) were applied in the data analysis.

Daily CER values (from sunrise to sunset) are calculated by cumulating the instantaneous CER during a daytime measurement period with the trapezoid rule:

$$\mathrm{CER_d} = \sum_{i=0}^{n-1} \frac{\mathrm{CER}_i + \mathrm{CER}_{i+1}}{2} \left(t_{i+1} - t_i\right) \quad [3]$$

where $\mathrm{CER_d}$ is the daily CER, CER_i is the instantaneous CER value at time t_i, and CER_{i+1} is the instantaneous CER at time t_{i+1} (Parkin and Kaspar, 2004). During a daytime measurement period, chamber measurements were completed seven or eight times in each plot. Thus, the time intervals between two consecutive chamber measurements were 1.5 to 2 h.

A recurrent neural network (RNN) was used to interpolate the daily CER when chamber measurements were not made, and the interpolated daily CER was used to calculate the daytime cumulative CER throughout the measurement period (Luo et al., 2018; Kůrková, 1992; Katsuura and Sprecher, 1994). The measured daily CER values and the time series of solar radiation are the input data for the RNN model. To implement the RNN, linear interpolations based on the measured daily chamber CER values from Eq. [3] provide the first prediction of CER values on days without measurements, i.e., $\widetilde{\mathrm{CER}}_{\mathrm{d}(i)}$, i = 1, 2, 3, ..., then the first prediction is filtered with the following autoregression model (Luo et al., 2018):

$$\mathrm{CER}_{\mathrm{d}(i)} = p\left(R_s\right) + f\left[\widetilde{\mathrm{CER}}_{\mathrm{d}(i)}, \widetilde{\mathrm{CER}}_{\mathrm{d}(i-1)}, \widetilde{\mathrm{CER}}_{\mathrm{d}(i-2)}, \ldots\right] \quad [4]$$

where $p(R_s)$ is a polynomial of the time series of the solar radiation R_s, f is a regression function, and $CER_{d(i)}$ on the left-hand side is the interpolation result. In this RNN model, the polynomial $p(R_s)$ indicates that solar radiation is the critical energy source for the CO_2 fluxes. The CER values estimated on previous days, i.e., $\widetilde{CER}_{d(i)}$, carry the information on the CO_2 flux measurements into the RNN model. Based on the idea of the Kalman filter, $\widetilde{CER}_{d(i)}$ can be considered as a "correction" for the final CER interpolation. The daily CER values calculated with chamber measurements are related to the crop growth patterns. By including the $\widetilde{CER}_{d(i)}$ values from previous days, we partially include plant information into the RNN model. Cross-validation is used to determine the degree of the polynomial p and the time steps in f. The RNN model can be implemented conveniently with the MATLAB artificial neutral network toolbox (Mathworks).

To verify the effectiveness of such a data interpretation model, the RNN model was trained on the EC CER datasets separately. A comparison of the estimated and measured daily CER is shown in Fig. 2. The interpolated daily EC CER matches the measured daily EC CER, similar to the 1:1 line. In general, the daily error between the interpolated EC CER and measured EC CER is about 10%, while errors in the daytime cumulative CER are <5%. Thus, for the calculation of the cumulative CER, the RNN model can be used to interpolate the missing CER values.

The RNN interpretation is a data-driven model, and the artificial neural network is fitted adaptively to an individual dataset. Thus, potential errors can occur for a specific dataset, and the predicted data may not be able to well represent large daily CER variations under unstable weather conditions. One reason is that the chamber-measured daily CER values are essentially sparse in the time domain, while the representation of large daily CER variations requires measurements with a relatively high time resolution. However, an average of multiple trainings on a relatively large dataset can enhance the accuracy and stability of this RNN interpolation models for specific fields and crops.

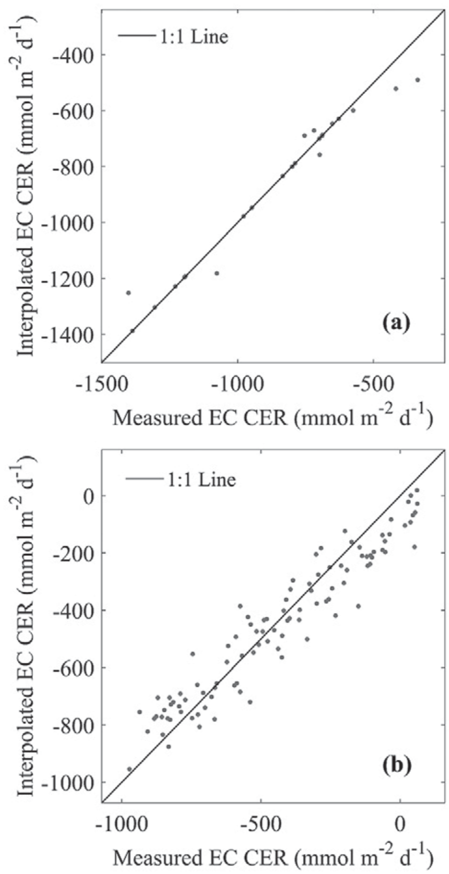

Fig. 2. Comparisons of the measured daily eddy covariance CO_2 exchange rate (EC CER) and the predicted daily EC CER for (a) corn, 2013, and (b) soybean, 2014.

Results

Figures 3a and 3b present comparisons of the instantaneous chamber CER values and the instantaneous EC CER values for corn and soybean in 2013 and 2014, respectively. To enable the pointwise comparison at the same times, a least squares–support vector machine (LS-SVM) model (Suykens et al., 2002) was used to estimate the EC CER values at the times of the chamber measurements. Figure 3c and 3d present the daily chamber CER and EC CER values. The range of instantaneous CER values reported in this study was between 0 and 40 μmol m^{-2} s^{-1}. Reicosky (1990) reported CER values between 5 and 40 μmol m^{-2} s^{-1} under various plant populations and cloud coverages; Steduto and Hsiao (1998) reported corn CER values for multiple humidity conditions that had a range of 10 to 30 μmol m^{-2} s^{-1}; Rochette et al. (1995) reported soybean CER values from a greenhouse study in Ottawa, Canada, that ranged from 0 to 35 μmol m^{-2} s^{-1}; and Hernandez-Ramirez et al. (2011) reported instantaneous CER values for corn and soybean that ranged from 0 to 46 μmol m^{-2} s^{-1} at the Iowa State University site. Thus, the chamber results from this study are comparable to literature results.

The blue lines in Fig. 3a to 3d represent the linear regressions between chamber CER and EC CER values, and the regression results are listed in Table 1. The slopes of the regression lines are not significantly different from the 1:1 line, except for the instantaneous soybean CER in Fig. 3b. One reason for that is the numerical instability of the regression when the range of the instantaneous soybean CER values is relatively small. However, for the daily CER values, the regression lines do not differ significantly from the 1:1 line. Therefore, the chamber CER results statistically match the EC CER results, which was consistent with the literature results, e.g., Wang et al. (2010) and Zamolodchikov et al. (2011).

Figures 3e and 3f present the cumulative daytime chamber CER and EC CER for corn in 2013 and for soybean in 2014 during the chamber measurement periods. The chamber daytime cumulative CER values are 289 g C m^{-2} for corn in 2013 from DOY 164 to 206 and 647 g C m^{-2} for soybean in 2014 from DOY 156 to 277, while the EC daytime cumulative CER values are 278 g C m^{-2} for corn and 678 g C m^{-2} for soybean. The daytime cumulative CER value is 300 g C m^{-2} below the gross primary production

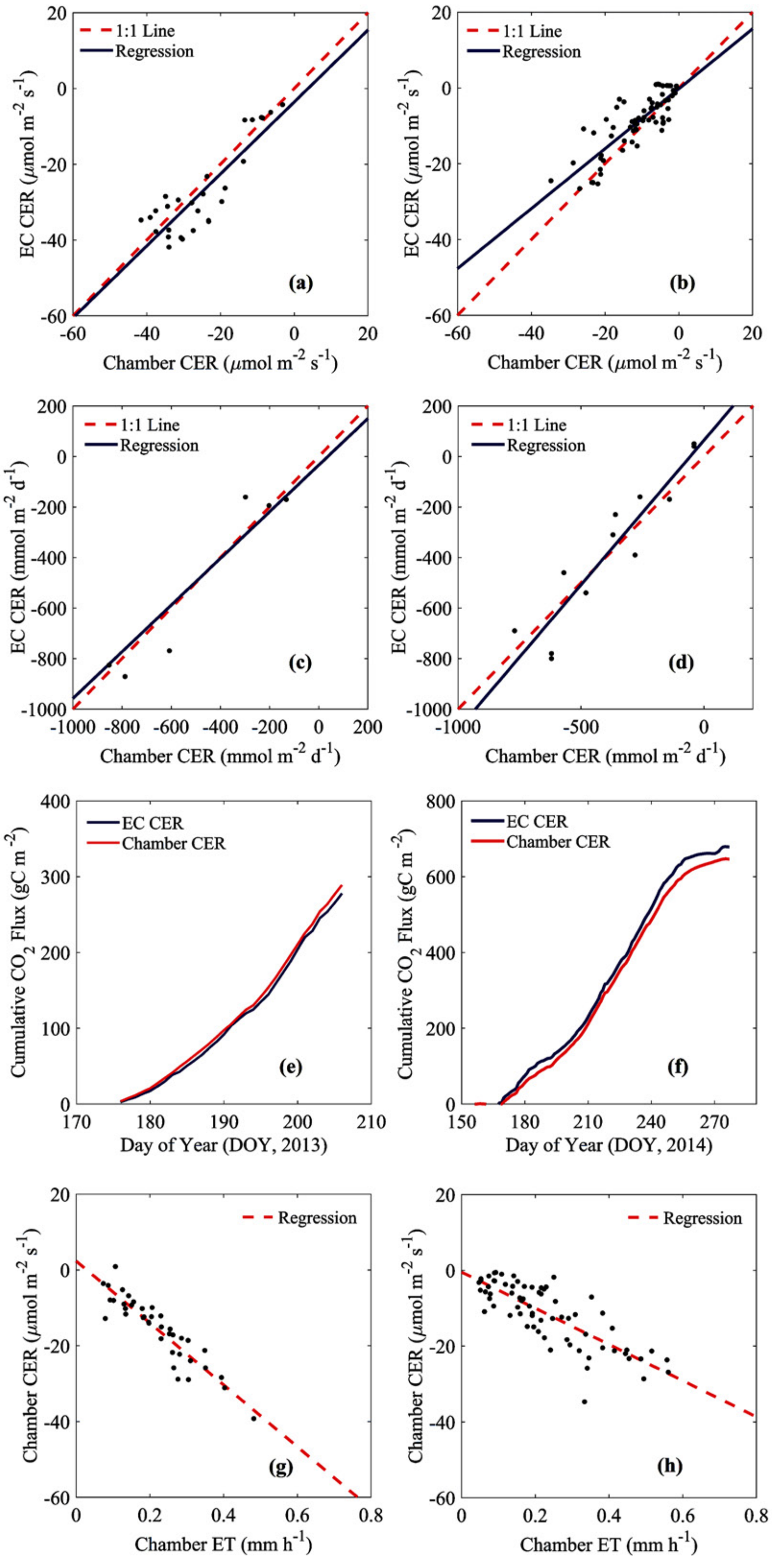

Fig. 3. A comparison between canopy chamber and eddy covariance (EC) measurements of CO_2 exchange rate (CER) for corn in 2013 and soybean in 2014, including instantaneous CER for (a) corn and (b) soybean, daily CER for (c) corn and (d) soybean, cumulative CER for (e) corn and (f) soybean, and the linear correlations between evapotranspiration (ET, data are from Luo et al., 2018) and CER for chamber measurements for (g) corn and (h) soybean. In 2013, six daily measurements were made for corn, shown in (c), due to the crop size; in 2014, 11 daily measurements were performed after the emergence of soybean (d).

of soybean reported by Suyker and Verma (2010). The reason for the smaller value is that plant and soil respiration is included in the chamber measurements.

The trends of canopy chamber daytime cumulative CER are similar to the EC results for both corn and soybean. At the end of the measurement periods, the differences between cumulative daytime chamber values and cumulative daytime EC values were about 5%. However, for the flux tower EC measurements, large uniform fields are required for stable and valid results (Baldocchi et al., 1988). Although the canopy chamber measurements are obtained on small uniform areas, the chamber results match the larger scale EC values well. Thus, the effectiveness and accuracy of the crop canopy chamber method for small-scale field plots are demonstrated.

For further comparison, Fig. 3g and 3h cross-validate the instantaneous chamber CER and ET results for corn and soybean. The ET values are taken from Luo et al. (2018) and represented in millimeters per hour. Linear correlations can be observed, with correlation coefficients (R) >0.8. Although the daytime CER is dominated by crop photosynthesis, and the daytime ET is mostly from transpiration, which are parallel processes, they each rely on solar radiation as the energy source. Thus, positive correlations are expected between CER and ET, which is consistent with the results reported by Held et al. (1990) and Steduto and Hsiao (1998).

The chamber technique can be combined with other measurements. For example, if the chamber CER and SCE are measured on the same field plot, the difference between the CER and SCE represents the daytime C assimilation in the aboveground crop parts, and that can serve as the C source pool for plant root growth or shoot growth. Crop and soil models, such as GLYCIM (Acock and Trent, 1991), leverage the shoot growth and root growth by separating such C source pools based on plant water uptake and transpiration. Moreover, the combination of CER and ET can also represent the field water use efficiency, such as in Abraha et al. (2016).

Summary

In this study, canopy chambers reported in Luo et al. (2018) were used to make field CO_2 flux measurements. The CER measurements were made in corn and soybean in 2013 and 2014. To evaluate the performance of the canopy chamber, the results were compared with EC flux tower results for corn and soybean in a nearby field. The good agreement between chamber and EC results indicated the effectiveness of the canopy chamber CO_2 flux measurements. In conclusion, the portable canopy chamber is a reliable, efficient, and accurate way to measure CER in relatively small field plots at a variety

Table 1. Regression parameters (slope and intercept) of the instantaneous chamber results and eddy covariance flux tower results with confidence intervals (CI) for $\alpha = 0.05$.

Measurement	R^2	Slope	CI	Intercept	CI
Instantaneous					
Corn CER 2013	0.76	0.95	[0.73, 1.17]	−3.6	[−9.4, 2.3]
Soybean CER 2014	0.71	0.79*	[0.66, 0.92]	−0.2	[−2.0, 1.5]
Daily cumulative					
Corn CER 2013	0.93	0.92	[0.66, 1.19]	−34.5	[−230, 161]
Soybean CER 2014	0.87	1.14	[0.83, 1.46]	63.7	[−75.1, 202]

* Significantly different from slope and intercept values of 1:1 line (slope = 1, intercept = 0).

of time scales. Future studies should include the applications of this chamber for diurnal (24-h) measurements among multiple cropping systems, and the combination of the chamber CER and other gas fluxes, such as SCE and ET.

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