Canopy Gas Exchange Measurements of Cotton in an Open System

Jeffrey T. Baker,* Scott Van Pelt, Dennis C. Gitz, Paxton Payton, Robert Joseph Lascano, and Bobbie McMichael

ABSTRACT

A portable, open transparent chamber system for measuring canopy gas exchanges was developed and tested. Differentials between incoming and outgoing atmospheric H_2O and CO_2 concentrations were used to calculate canopy transpiration (E) and net assimilation (A) at 10-s intervals using solenoid valve actuated sample lines connected to an infrared gas analyzer. A programmable data logger controlled fan speed and air flow rate to control daytime chamber air temperature to within 0.5°C of ambient air temperature. To validate the mass balance equations used to calculate E, the chamber was positioned over sealed soil potted cotton (*Gossypium hirsutum* L.) plants which were placed on a weighing scale. A second scale was used to measure E of cotton plants outside the chamber to quantify potential chamber effects. A wide range of crop canopy leaf areas and soil water contents were created with greenhouse-grown plants for these comparisons. Data analysis indicated agreement between chamber E measurements and the internal weighing scale ($R^2 = 0.93$), as well as comparison between the internal and external scales ($R^2 = 0.88$) across wide ranges of soil water contents and canopy leaf area. Transpiration ranged from near zero at night to 900 g (H_2O) h^{-1} during the day. Bias estimates of E for chamber vs. internal scale and the internal vs. external scale were −6.0 and 4.6 g (H_2O) h^{-1}. With minor chamber effect, the chamber accurately estimates E for many field applications such as comparison of canopy gas exchanges and water use efficiencies among irrigation treatments.

Measurements of CO_2 and H_2O fluxes of crop plants are essential to understand the impacts of environmental variables on crop productivity. As water resources for irrigation become increasingly limited, especially in semi-arid regions, rapid and precise quantification of the degree of drought stress to which a crop is exposed becomes paramount. Both single leaf (Flexas and Medrano, 2002; Medrano et al., 2002; Baker et al., 2007) and whole canopy gas exchange (Marani et al., 1985; Jones et al., 1985; Baker et al., 1997) provide a highly sensitive measure of the degree of drought stress to which a crop is exposed. Furthermore, compared with leaf level measurements of net assimilation, whole canopy net assimilation is more highly correlated with growth and final yield (Nelson, 1988; Peng et al., 2000).

Canopy scale gas exchange has been measured using several approaches, including Eddy Correlation and Bowen Ratio Energy Balance (BREB), as well as weighing lysimeter facilities and a rather wide array of chamber techniques of varying sophistication. Among the more complex and comprehensive chamber systems are outdoor, naturally sunlit Soil-Plant-Atmosphere-Research (SPAR) units that provide precise control of chamber air temperature, humidity, and atmospheric CO_2 concentration while continuously measuring canopy net assimilation (A), nighttime respiration (R_d), and evapotranspiration rates (ET) (Baker et al., 1990, 1992, 1997, 2004; Pickering et al., 1994; Tingey et al., 1996; Jones et al., 1985; Reddy et al., 2001). However, both lysimeter and SPAR facilities are costly and immobile. Accuracy of BREB depends on the validity of the assumptions made (e.g., equality of turbulent diffusivity of heat, H_2O, and CO_2) (Dugas et al., 1997) and also requires a fetch or homogeneous upwind land cover and thus may not always be feasible for use in agronomic field trials.

Portable field chambers can be broadly classified as either open or closed systems. Open or flow through chambers measure canopy gas exchange from the differential between incoming and outgoing gas concentrations. Portable closed system chambers are typically placed over the canopy for brief periods and A and ET are determined from the loss of chamber atmospheric CO_2 and the increase in chamber air H_2O, respectively. Changes in CO_2 for calculation of A have been measured by syringe sampling (Boote et al., 1980; Daley et al., 1984; Garrity et al., 1984) or by cycling air through an infrared gas analyzer (IRGA) (Boote et al., 1980; Ingram et al., 1981; Zur et al., 1983; Pickering et al., 1993). Changes in H_2O for ET calculations have been measured by dew point hygrometer (Zur et al., 1983) or wet-dry bulb psychrometers (Reicosky and Peters 1977; Peterson et al., 1985; Meyers et al., 1987). Currently, instrumentation has advanced to the point where both CO_2 and H_2O concentrations can be accurately and rapidly measured with a single IRGA. Furthermore, memory and

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Abbreviations: A, canopy net assimilation; BREB, Eddy Correlation and Bowen Ratio Energy Balance; CETA, Canopy EvapoTranspiration and Assimilation chamber; E, canopy transpiration; ET, evapotranspiration; IRGA, infrared gas analyzer; NEE, net ecosystem exchange; PAR, photosynthetically active radiation; SPAR, Soil-Plant-Atmosphere-Research chamber.

processing speeds for off-the-shelf programmable data loggers now permit rapid data acquisition and process control.

Placing a transparent field chamber over a crop canopy causes changes to several environmental variables that can potentially cause canopy gas exchange inside the chamber to differ from that outside the chamber. For example, chamber wall materials can alter the quality and quantity of light entering the chamber (Kim et al., 2004) while internal air temperatures in open top chambers can increase by as much as 3°C compared with outside ambient air (Leadley and Drake, 1993). Nonetheless, good agreement has been reported between ET measured with closed system chambers compared with ET determined from water balance, Bowen BREB, or lysimeter measurements (Reicosky et al., 1983; Pickering et al., 1993; Steduto et al., 2002; McLeod et al.,2004).

Several types of open chamber systems have been previously described in the literature (Nijs et al., 1989; Garcia et al., 1990; Brooks et al., 2000; Burkart et al., 2007). In an open system, accurate measurement of canopy gas exchange depends on the ability to measure entry vs. exit gas concentration differentials as well as air flow rate through the chamber. Typically, at a constant air flow rate, these gas concentration differentials are higher during the day (e.g., photosynthetic CO_2 uptake) than at night (e.g., respiratory CO_2 loss). The same diurnal trend usually also holds for transpiration (E) and ET. A low fan speed and low air flow rate will increase the magnitude of the gas concentration differentials due to the increased residence time of air through the system. We reasoned that it would be desirable to have lower air flow rate at night to increase the size of the gas concentration differentials and thus improve the precision of nighttime gas exchange measurements; while a faster flow rate during the day would help minimize heat build up due to solar heat load via a more rapid removal of latent energy from the system.

Our objectives were: (i) develop an open chamber system that could be left in the field for extended periods while simultaneously monitoring canopy CO_2 and H_2O fluxes; (ii) test this open system's calculations of E against a weighing scale using sealed soil potted plants across a wide range of canopy leaf areas and soil water contents; (iii) test the ability of a control algorithm to operate a variable speed fan to limit chamber air temperature increases to 0.5°C during the day due to solar heat load.

MATERIALS AND METHODS

Chamber Construction and Operation

The Canopy EvapoTranspiration and Assimilation (CETA) chamber was constructed of aluminum framework covered in transparent 10 mil LEXAN (GE Polymershapes, Coppell, TX).[1] Chamber dimensions were 0.75 by 1 m in cross-section and 1 m in height (Fig. 1). An antechamber, for mixing inlet air, covered in LEXAN and measuring 0.2 by 0.75 m in cross-section and 1 m tall was attached to the front of the main CETA chamber. Inlet air entered the top duct of this antechamber and passed through a perforated LEXAN sheet before entering the main CETA chamber containing potted cotton plants. This LEXAN sheet was perforated with 2.5 cm diam. holes arranged logarithmically with height to create turbulence and provide a realistic wind speed profile with height. A cone shaped exit duct, also covered in LEXAN, was attached to an aluminum exhaust port (Fig. 1) 0.15 m in diameter, attached to flexible ducting and connected to a variable speed, squirrel cage type air blower (Model 2C938, Dayton Electric Manufacturing, Niles, IL) that pulled air through the entire system. The motor (DMS 1833B-56C, Dart Controls, Zionsville, IN) and motor controller (253–200E-56G2, Dart Controls, Zionsville, IN) controlled fan speed according to a 0 to 5 VDC input voltage from the data logger (CR-3000, Campbell Scientific, Inc., Logan, UT). Exit air flow was measured in the aluminum exhaust port with a pitot tube and

[1]Mention of this or other proprietary products is for the convenience of the readers only, and does not constitute endorsement or preferential treatment of these products by USDA-ARS.

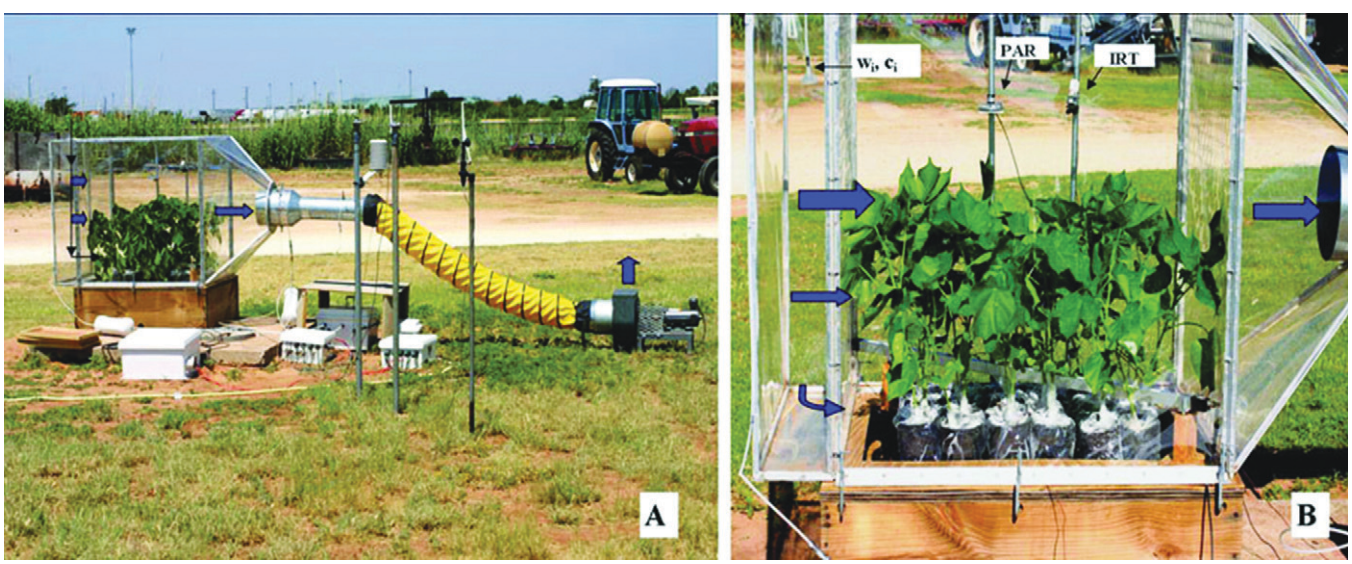

Fig. 1. (A) Wilted cotton plants in the canopy evapotranspiration and assimilation (CETA) chamber at the end of a 4-d run used to tune the fan control algorithm on 21 July 2006. Blue arrows indicate the direction of air flow. (B) Potted cotton plants with sealed soil on the weighing scale used to measure transpiration on 29 Aug. 2006. Also shown is the location of the air inlet port to measure entrance mole fractions of H_2O (w_i) and CO_2 (c_i) as well as the quantum sensor for measuring internal photosynthetically active radiation (PAR) and the infrared thermometer (IRT) for measuring canopy temperature.

static ports connected to a pressure transducer (Serta Systems, Inc., Model 239, Boxborough, MA).

This air flow measurement was calibrated using a micromanometer against a hot wire anemometer of known calibration. Maximum and minimum air flow rates in the exit exhaust port were 18 and 5.5 m s^{-1}, respectively. This corresponds to approximately 26.3 and 8.0 chamber volumes min^{-1}.

To measure entrance and exit gas concentrations, a vacuum pump (Cole-Parmer, Vernon Hills, IL) pulled gas samples at a flow rate of 3 L min^{-1} from the front antechamber and exit exhaust port, respectively, through gas sample lines (Nylotube-12, New Age Industries, Southhampton, PA) 4.6 m in length. A solenoid valve, controlled by the data logger, switched continuously between the entrance and exit air sample streams at 10 s intervals. An infrared gas analyzer (LI-7000, LI-COR, Inc., Lincoln, NE) operating in absolute mode was used to measure both entrance and exit mole fractions of CO_2 and H_2O in the air sample stream. We found that the sample line volume was purged with a new sample by at least 3 s into each 10 s interval. The data logger, operating at a 1 s time step, averaged and recorded the IRGA readings for the last 5 s of each 10 s time interval. The data logger also recorded entrance (T_{in}) and exit (T_{out}) air temperatures with shielded copper/constantan thermocouples averaged over 10 s intervals, located in the entrance antechamber and exit ductwork, respectively. Internal and external chamber photosynthetic flux density (PFD) was measured with quantum sensors (LI-190 SA, LI-COR, Inc., Lincoln, NE) and recorded by the data logger. Diurnal comparison of these two quantum sensors indicated that the chamber wall materials reduced internal chamber PAR by about 10.5% compared with PAR measured external to the chamber. The data logger recorded data from all chamber sensors and controlled the speed (e.g., air flow rate) of the variable speed fan. To prevent excessive heat build up during the day caused by solar heat load, the data logger was programmed with a proportional-integral feedback control algorithm that adjusted the mv signal to the variable speed fan at 10 s intervals. This algorithm was tuned to allow fan speed to increase when $T_{out} - T_{in} > 0.5°C$ and vice versa. This chamber system is sufficiently portable to be transported and put into operation by two people while the list of specific components of the system can purchased from independent vendors for less than $25,000 USD.

Gas Exchange Calculations

Canopy transpiration rate [E, mol (H_2O) m^{-2} s^{-1}] in an open or flow through system is given by LI-COR (1999):

$$sE = u_o w_o - u_i w_i \quad [1]$$

where s is the ground area covered by the chamber (0.75 m^2), u_o and u_i are exit and entrance chamber air flow rates [mol (air) s^{-1}], respectively, and w_o and w_i are exit and entrance mole fractions of water vapor [mol (H_2O) mol^{-1} air], respectively. In our setup, air was pulled through the chamber and air flow rate was measured at the exit (u_o). Because E adds water molecules to the air stream, u_o is > u_i. In this formulation, u_i is given by:

$$u_i = u_o - sE \quad [2]$$

Combining Eq. [1] and [2] and rearranging gives:

$$E = u_o(w_o - w_i)/[s(1 - w_i)] \quad [3]$$

Similarly, canopy net assimilation [A, mol (CO_2) m^{-2} s^{-1}] in an open system that measures air flow at the chamber outlet is given by:

$$A = u_o(c_i - c_o)/s - Ec_i \quad [4]$$

where c_i and c_o are entrance and exit mole fractions of carbon dioxide [mol (CO_2) mol^{-1} (air)], respectively.

Plant Culture

To test the CETA chambers ability to measure canopy gas exchange across wide ranges of canopy leaf area, successive groups of cotton plants were grown in pots in a greenhouse for different periods resulting in plants of different ages and leaf area. The cotton cultivar ('FiberMax RR 960') was seeded in 1.7-L pots filled with artificial media consisting of sphagnum peat and medium-grade vermiculite (Sunshine Professional Growing Mix No. 1, Sungro Horticulture Inc., Bellevue, WA) in the greenhouse. Pots were irrigated daily with an automated drip irrigation system and the plants were fertilized once per week with soluble fertilizer (Peters Professional 15–16–17 Peat-Lite Special) at a rate of about 0.1 g pot^{-1}. To minimize the effects of soil respiration and evaporation of soil water, each pot was placed in plastic bread bags and sealed around the base of the plant stems before taking them outside the greenhouse for chamber testing.

Chamber Tests

Two types of comparisons were made in this study. First, E measured with the CETA chamber was compared with E determined gravimetrically with a weighing scale located inside the chamber. Second, to determine chamber effects on the measurement of E, E was measured with a second weighing scale located outside the chamber. Outside the greenhouse, two concrete pads were poured to provide a level surface for mounting the two weighing scales [Model IS300IGG-H1 (internal scale) and Model IS64EDE-H, (external scale) Sartorius Corp., Edgewood, NY]. In each test with cotton plants with different leaf areas, 18 potted cotton plants were fully watered and placed on each scale. The CETA chamber was then mounted over both the potted plants resting on the internal scale and the internal scale itself. To quantify potential chamber effects on measurement of E, E values determined from the internal and external scales were compared.

Internal scale weight output was monitored with a dedicated laptop computer at 1 s intervals. The external scale lacked an output data port so weights of this scale were recorded manually once or twice per day. Both CETA measurements of canopy gas exchange and internal scale weight were monitored continuously over 2 to 4 d for each set of test canopies. After each 2 to 4 d run, six of the potted plants were destructively sampled and leaf area was measured with a leaf area meter (LI-3100, LI-COR, Inc., Lincoln, NE) and leaf area index (LAI) of each test canopy was calculated.

The ability of the CETA chamber to measure E (Eq. [3]) was evaluated using linear regression analysis from hourly totals of E vs. simultaneous measurement of hourly weight loss from the internal weighing scale. In cases where these regression models were significant ($P < 0.05$) t tests were conducted to determine whether the slope and intercepts were significantly different from 1.0 and 0.0, respectively. Statistical agreement between measured and calculated values was inferred when the regression F value was significant, slope and intercept not significantly different from 1.0 and 0.0, respectively and the linear regression yielded a high coefficient of determination (R^2). Bias and regression root mean square error (RMSE) were calculated to determine overall chamber system performance (Willmott, 1982):

$$\text{Bias} = 1/n\sum_{i=1}^{n}(C_i - S_i) \quad [5]$$

$$\text{RMSE} = [1/n\sum_{i=1}^{n}(C_i - S_i)^2]^{1/2} \quad [6]$$

where C and S are the hourly measurements of E for the chamber and internal scale, respectively, for the ith measurement and n is the total number of measurements. This same procedure was used to compare E determined gravimetrically from measurements made by both the internal and external scale. These tests were conducted to provide potential users of this system with accuracy estimates to determine the suitability of this system for particular applications.

A total of 14 test-canopies or test "runs" were evaluated from May to October 2006 in Big Spring, TX (32°18′ N, 101°27′ W). The first eight of these test runs were used to tune the control algorithm for controlling fan speed and air flow rate throughout the chamber. The last six of these runs, from July to October, were used to compare E measured with the CETA chamber against that determined from the internal scale. Data from all 14 runs were used to compare E measured with the internal vs. external weighing scales. Because the mass of canopy carbon gas exchange is extremely small in comparison to water loss, all changes in weighing scale measurements were attributed to E rather than A.

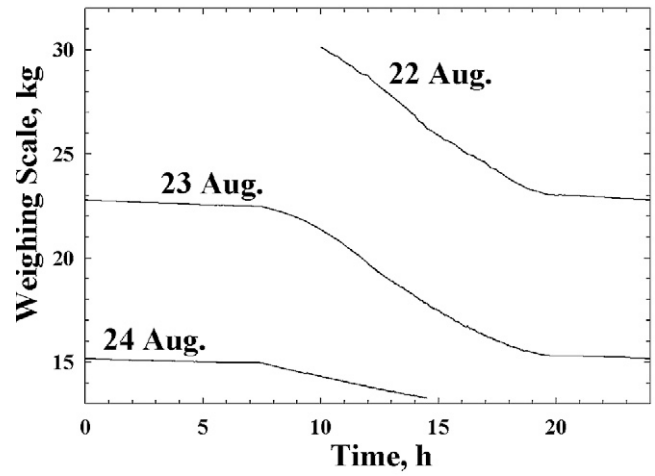

Fig. 2. Example of diurnal trends in internal scale measurements used to calculate hourly transpiration rates for 22 to 24 Aug. 2006. The *y* axis represents the combined mass of the soil media, soil water, pots, and plants

RESULTS AND DISCUSSION

Measured LAI ranged from ~1.4 to 6.0 $m^2\ m^{-2}$ for the last six test runs (Table 1). Due to the limited soil volume, plants at the end of each test run were visibly wilted when they were removed from the CETA chamber and sampled for leaf area. As in all six runs, the rate of water loss as measured by the internal weighing scale during the daylight hours of 22 to 24 Aug. 2006 declined across the 3 d (Fig. 2).

Shown in Fig. 3 are the chamber air flow rate, measured at the exit duct (u_o), photosynthetically active radiation (PAR) and inlet minus outlet air temperature differential along with the target set point of $T_{out} - T_{in} = 0.5°C$ (lower panel). On 22 Aug. 2006 irradiance levels varied rapidly due to high winds aloft and intermittent cloud cover. Here, the proportional-integral control algorithm had difficulty maintaining the target set point of $T_{out} - T_{in} = 0.5°C$ suggesting that a time-step <10 s may have improved the situation. However, some minimum time step is required to obtain a stable measure of air flow rate and to purge the gas sample lines for the next gas concentration measurement. Still, even with highly variable cloud cover, the algorithm maintained the desired set point to within about ± 1°C. At night, the control algorithm set the fan speed to the minimum value since $T_{out} - T_{in} < 0.5°C$, presumably due to small amounts of latent energy loss from the chamber at night and the fact that this chamber was not equipped with resistive heaters to add energy back in the system. The PAR data for 23 Aug. 2006 indicated a nearly cloud-free day and the control algorithm easily maintained the desired set point from daylight until about 1500 h when signs of an impending drought stress became clearly evident based on photosynthesis rates (Fig. 4, described below). After 1500 h on 23 August, as $T_{out} - T_{in}$ drifted > 0.5°C, the control algorithm ran the exhaust fan at its maximum operating speed. The data for 24 Aug. 2006 showed clear signs of drought stress with reductions in both A and E in

Table 1. Leaf area index (LAI) and statistics for the regression ($y = b_0 + b_1x$) of hourly measures of transpiration of cotton by the weighing scale (y) vs. transpiration simultaneously measured with the Canopy Evapotranspiration and Assimilation (CETA) chamber (x) for six comparison date intervals and for all data combined. The last row of the table is the comparison between the internal scale transpiration (x) vs. external scale transpiration (y).

Date	LAI	b_0 ± SE	b_1 ± SE	n	R^2	RMSE	Bias
	$m^2\ m^{-2}$	$g\ h^{-1}$		h		$g\ h^{-1}$	
24–25 July	1.4	0.8 ± 9.6	1.25 ± 0.038*	33	0.97***	35.7	–48.6
22–24 August	6.0	7.1 ± 13.0	1.06 ± 0.031	49	0.96***	64.0	–26.5
29–31 August	3.1	-2.7 ± 8.0	0.89 ± 0.022*	57	0.97***	40.3	33.0
12–14 September	4.9	19.3 ± 19.1	0.94 ± 0.053	47	0.87***	85.6	–2.9
18–20 September	3.9	7.7 ± 8.3	0.91 ± 0.026*	54	0.96***	41.6	13.4
2–4 October	3.6	26.0 ± 11.4*	0.99 ± 0.034	58	0.94***	61.3	–23.3
All data		11.6 ± 5.5*	0.98 ± 0.016	298	0.93***	65.7	–6.0
Internal vs. external scale transpiration 16 May–5 Oct.		8.6 ± 13.6	0.94 ± 0.053	43	0.88***	40.7	4.6

* Significance at the 0.05 level of the t statistic for testing the hypothesis H_o: $b_0 = 0.0$ vs. H_a $b_0 \neq 0.0$ and the hypothesis: H_o: $b_1 = 1.0$ vs. H_a: $b_1 \neq 1.0$.

*** Indicates the regression model was significant at $P < 0.0001$.

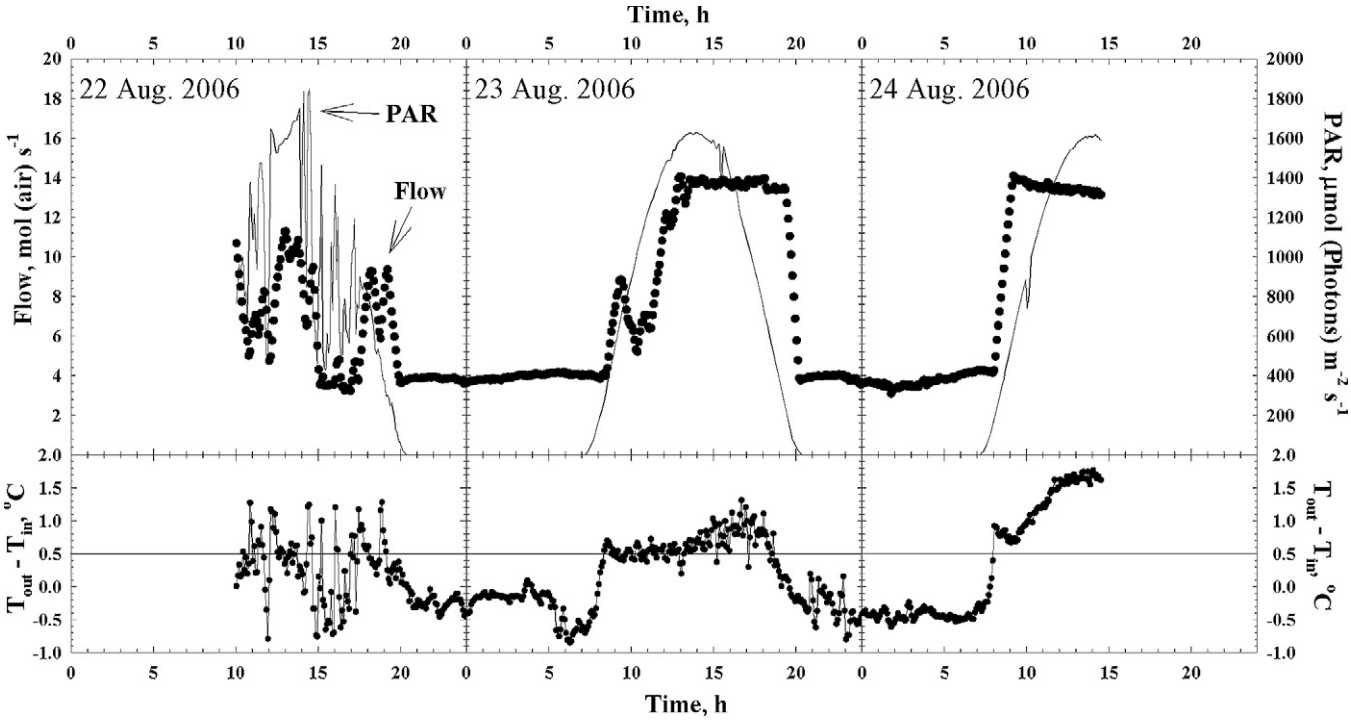

Fig. 3. Time-trend in exit air flow rate (u_o, filled circles, top panel) and photosynthetically active radiation (PAR, solid line, top panel) on 22 to 24 Aug. 2006. Lower panels: differential between exit (T_{out}) and entrance (T_{in}) air temperatures. Desired daytime set-point of 0.5°C is indicated as a horizontal line on the bottom panel.

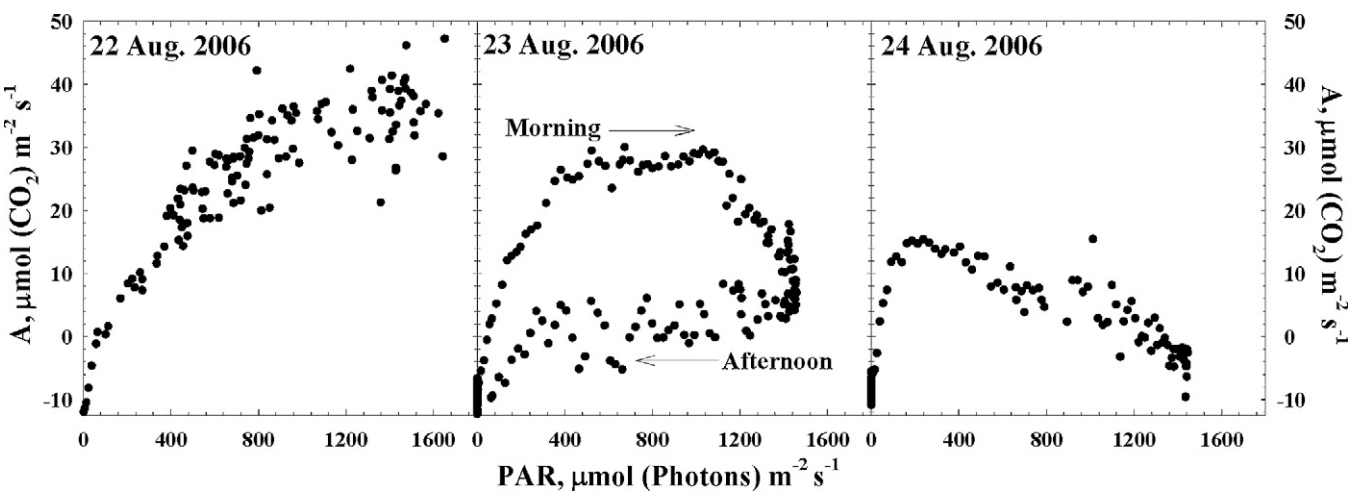

Fig. 4. Response of canopy net assimilation (A) to photosynthetically active radiation (PAR) for 22 to 24 Aug. 2006.

the afternoon. During the daylight hours on 24 Aug. 2006, this reduced latent energy loss via E from the chamber system caused $T_{out} - T_{in}$ to drift above the desired set point and fan speed rapidly reached its maximum operating speed. Based on data from all six runs it is clear that sufficient soil water is required for latent energy removal from the system to counter solar heat load and maintain a desired $T_{out} - T_{in}$ set point.

As expected A declined from 22 to 24 August as soil water was depleted (Fig. 4). Especially evident is the large hysteresis in A on 23 Aug. 2006 with A vs. PAR being much higher in the morning and declining in the afternoon. Comparison of the trends in E (Fig. 5) and A (Fig. 4) on 23 Aug. 2006 indicated that A was decreased earlier and more severely by drought stress and high air temperatures than E. This appears to contrast with Baker et al. (2007) who found that in cotton, leaf level stomatal conductance was reduced by drought stress before reductions in leaf level net assimilation were apparent. However, the CETA chamber does not control humidity or canopy temperature. For example, on 23 Aug. 2006, entrance H_2O measurements (w_i) declined sharply during the day from pre-dawn values of 22 mmol (H_2O) mol^{-1} to 14 mmol mol^{-1} at 1800 h resulting in increasing evaporative demand of the chamber atmosphere during the day. During this time, canopy temperature increased from 27 to >36°C while ambient air temperature increased from 24 to >36°C (data not shown).

Comparisons of E measured with the CETA chamber vs. the internal scale for 22 to 24 Aug. 2006 (Fig. 5) indicated a tendency of the CETA chamber to underestimate E compared with the scale in most cases although the general diurnal pattern matched well. Reasons for this discrepancy are likely either error associated with measuring air flow rate (u_i) or measurements of gas concentration differentials. Regression

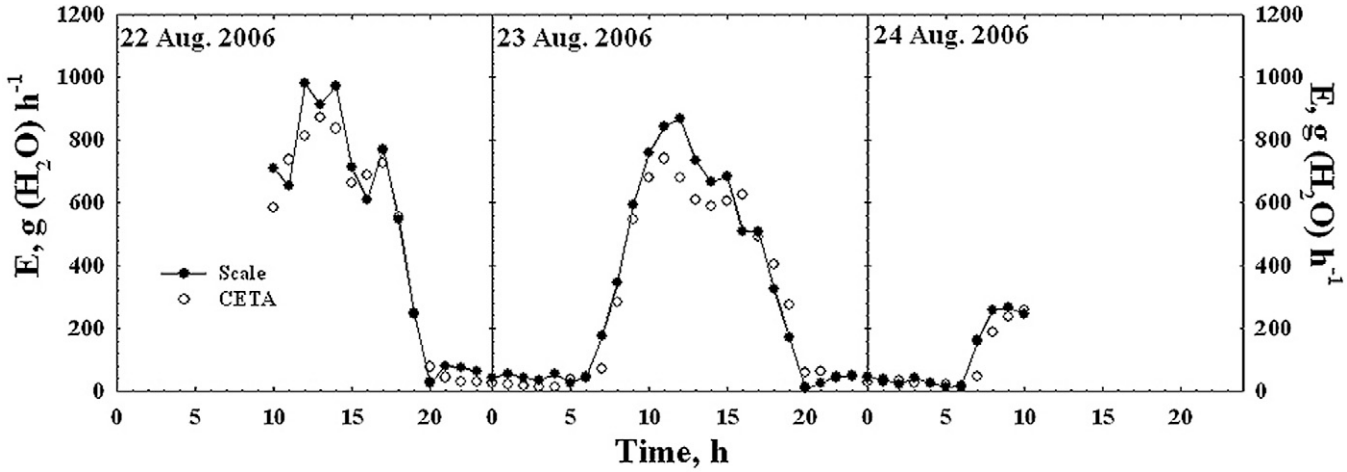

Fig. 5. Diurnal canopy transpiration rate (E) from 22 to 24 Aug. 2006 measured using either the (CETA) chamber (open circle) or the internal scale (closed circle).

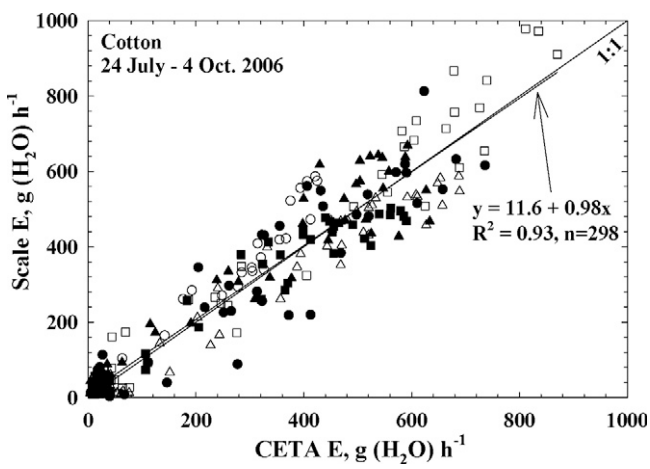

Fig. 6. Transpiration rates (E) measured using the internal scale vs. E measured using the Canopy Evapotranspiration and Assimilation (CETA) chamber and compared to a 1:1 line. Open circles, squares and diamonds are for 24 to 25 July, 22 to 24 Aug. and 29 to 31 Aug. 2006, respectively. Closed circles, squares, and diamonds are for 12 to 14 Sept., 18 to 20 Sept. and 2 to 4 Oct. 2006, respectively.

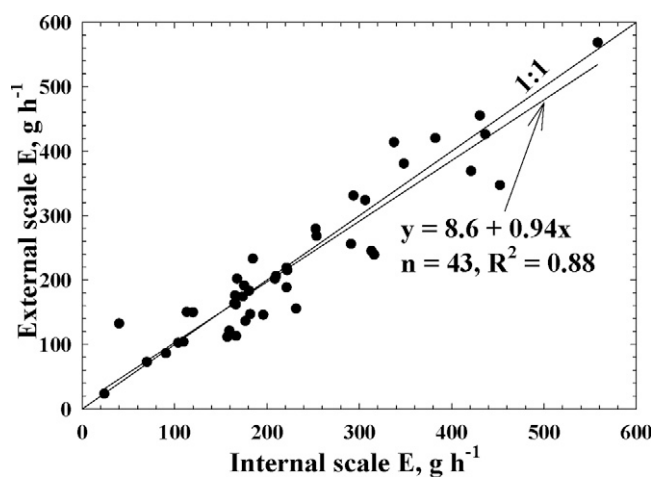

Fig. 7. Transpiration rates (E) measured using the internal vs. external scales to test chamber effects measurement of E and compared with a 1:1 line.

coefficients for the comparison of scale vs. CETA E measurements are given in Table 1 and the data presented in Fig. 6. In all cases, the *F* value for these regressions was significant. Overall for the six runs, the intercept of this regression was positive (Table 1), indicating a tendency for CETA to underestimate low values of E at night. There was no clear pattern in the RMSE estimates among the regression equations indicating little consistent bias among the six runs with different LAI. Bias estimates of E ranged from about −49 to 33 g (H_2O) h^{-1} among the last six test runs, while overall chamber vs. internal scale and the internal vs. external scale Bias estimate were −6.0 and 4.6 g (H_2O) h^{-1}, respectively (Table 1).

For internal vs. external scale estimates of E, the *F* statistic was significant while the intercept and slope were not significantly different from 0.0 and 1.0, respectively (Table 1, Fig. 7). Although it is known that the presence of a transparent chamber can alter a number of environmental variables that can affect E (Kim et al., 2004; Leadley and Drake, 1993; Whiting and Lang, 2001) examination of this regression analysis (Fig. 7) indicated that the CETA chamber can accurately estimate E across different dates and wide ranges of LAI. Because soil respiration is a component of many gas exchange measurements made in the field, some studies use the term net ecosystem exchange (NEE) rather than A. Chamber pressurization effects on soil gas fluxes must be considered for situations where bare soil below the canopy is exposed to the chamber atmosphere. Very small changes in air pressure, either positive or negative, can have large effects on soil respiration measurements (Fang and Moncrieff, 1998; Bremer and Ham, 2005). These effects are also influenced by soil water and properties such as soil texture (Lund et al., 1999). Maintaining neutral chamber pressure in the field has been shown to be extremely difficult (Bremer and Ham, 2005). Most open systems operate with the blower on the inlet side which creates a positive pressure within the chamber that can either partially or completely suppress soil gas fluxes or create an outward leak through the soil if the pressure is sufficiently high. Garcia et al. (1990) noted that if the blower is placed at the chamber outlet, then leakage into the chamber will be amplified due to negative air pressure and that this leakage is essentially unmeasured flow through the system. This is certainly the case for a chamber with the blower at the outlet while measuring air flow at the entrance. However, for the CETA chamber system, the blower was placed at the outlet and

air flow was also measured at the chamber exit, thus minimizing the effects of unmeasured flow through the system caused by leaks of this type. Further, the data presented were from potted plants fitted with plastic barriers in an explicit attempt to exclude gas exchange with the soil. The variable speed fan used to limit heat build up in the chamber described here will also introduce changes in air pressure and thus should be considered when using this system in the field. The most expedient method for suppressing soil gas fluxes would appear to be to seal the soil surface from the chamber atmosphere with a physical barrier. This method should work well with dicots, such as cotton, as was done in this experiment but may be problematic for studies on grasses or turf. This chamber system can be easily modified to push air through the system by reversing the flow direction of the fan and making appropriate adjustments to Eq. [1] to [4] (data not shown). Also, fan speed and air flow rates can be easily set to a constant value, if desired, by a simple modification to the fan control algorithm.

SUMMARY

We developed the CETA open or flow through chamber system for monitoring canopy fluxes of H_2O and CO_2. We used a variable speed fan to alter air flow through the chamber in an attempt to limit heat build up in the chamber to 0.5°C above ambient air temperature. Across wide ranges of canopy LAI for cotton and soil water content, good agreement was obtained between chamber estimates of E and E determined gravimetrically, although there was a tendency of the chamber to underestimate small values of E at night. Comparisons of E measured inside the chamber with E measured outside the chamber indicated a tendency of the chamber to slightly overestimate E at high values of E. The use of a variable speed fan successfully limited heat build up in the chamber during the day provided there was sufficient leaf area and soil water for latent energy removal from the system.

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