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Abstract

Accurate measurements of surface fluxes of carbon dioxide (CO_2) and water (H_2O) are important for several reasons and can be made using several types of instrumentation. For three C_4 grasses—bermudagrass (*Cynodon dactylon* (L.) Pers.), a mixed species native tallgrass prairie, and sorghum (*Sorghum bicolor* (L.) Moench.)—we measured evapotranspiration (ET) using a canopy chamber (CC) and Bowen ratio/energy balance (BREB) instrumentation and we measured leaf CO_2 uptake using a leaf chamber (LC), and, after accounting for soil CO_2 fluxes, we calculated leaf uptake using a CC and BREB instrumentation. In addition, soil CO_2 fluxes from bare soil were measured using a CC and soil chamber (SC). Measurements were made on 4 and 5 May 1994 at the Blackland Research Center, Temple, TX. Flux of CO_2 into the leaf was considered positive and was expressed per unit ground area. Half-hour CC ET measurements were consistently and substantially greater than BREB measurements for all grasses, perhaps because of increased soil evaporation due to greater turbulence inside the CC. Leaf CO_2 uptake measured using the three methods showed similar diurnal trends for all grasses (responding, primarily, to changes in photosynthetic photon flux density), but consistently tended to be greatest for BREB measurements. The regression equation for LC CO_2 uptake as a function of BREB uptake had a slope not statistically different from 1.0, with large scatter likely because of limited leaf area sampled. CC CO_2 uptake was consistently the least, partly because we may have underestimated soil CO_2 flux in the CC. Half-hour soil CO_2 fluxes from the CC were significantly greater ($P < 0.05$) than those from the SC for about two-thirds of the day on bare soil, perhaps because of

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large chamber ventilation rates. Differences of daytime soil CO_2 fluxes averaged 0.07 $mg\,m^{-2}\,s^{-1}$ (1.0 $mg\,m^{-2}\,s^{-1} \approx 22.7\ \mu mol\,m^{-2}\,s^{-1}$). These results show the consistency, repeatability and, we believe, accuracy of leaf CO_2 uptake and soil CO_2 flux measurements made using all methods.

1. Introduction

Accurate flux measurements of carbon dioxide (CO_2) and water (H_2O) over vegetative surfaces are important to understand the effects of the environment on biological processes, develop an accurate global carbon balance, validate crop growth models, and identify soil management and cropping systems that improve water use efficiency.

Several methods can be used to measure these fluxes and they vary in both spatial and temporal sampling aspects (Goel and Norman, 1990). Micrometeorological methods generally calculate or measure fluxes using measurements of atmospheric elements above a surface. Unlike several other methods, they usually do not modify the surface microenvironmental conditions and provide a spatially- (LeClerc and Thurtell, 1990; Schuepp et al., 1990) and temporally-integrated measurement. They may, however, be unreliable at selected times of the day, especially early-morning and early-evening (Verma and Rosenberg, 1975), and may not apply in all situations, e.g. within forest canopies (Denmead and Bradley, 1985). One micrometeorological method, the Bowen ratio/energy balance (BREB) method, has been used extensively and successfully for measurement of H_2O fluxes (e.g. Malek and Bingham, 1993), herein termed evapotranspiration (ET), and, to a lesser extent, CO_2 fluxes (Brown and Rosenberg, 1971; Verma and Rosenberg, 1975; Baldocchi et al., 1981, 1983; Held et al., 1990; McGinn and King, 1990; Denmead et al., 1993). The accuracy of CO_2 fluxes calculated using the BREB method is limited by the validity of the assumptions made (e.g. equality of turbulent diffusivity of heat, water vapor, and CO_2) and measurement errors of required inputs (e.g net radiation and temperature and humidity gradients).

Chambers of various sizes also can be used to measure these fluxes, although measurements with chambers are usually non-continuous and are subject to several problems, including altering the temperature, radiation, and wind conditions inside the chamber relative to that outside (Denmead, 1984; Monteith, 1990; Leuning and Foster, 1990). This may result in nonrepresentative measurements. Chambers vary in volume from those that measure the gas exchange for individual leaves ($\approx 10^{-5}$ m^3) to those that measure it for an entire soil/plant canopy ($< 10^3$ m^3). Despite these limitations, chambers can be useful for making replicated measurements in small plots.

There have been several studies comparing CO_2 and H_2O fluxes measured using BREB or other micrometeorological methods and chambers. Held et al. (1990) showed that diurnal measurements of net CO_2 flux for alfalfa (*Medicago sativa* L.), maize (*Zea maize* L.), and sunflower (*Helianthus annuus* L.) were similar for BREB and a canopy chamber. The BREB method was more responsive to short-term environmental changes, especially radiation. Chan et al. (1994) suggested chamber measurements were better suited to characterize the spatial variability of fluxes, while the BREB method was more sensitive. Norman and Polley (1989) made a similar comparison for a Kansas grassland and found that chamber CO_2 fluxes were consistently smaller, perhaps because of reduced radiation inside the chamber. Denmead et al. (1993) showed that ET for Eucalypt trees measured by BREB and chamber methods was similar, but CO_2 uptake was different between the two methods under clear skies because of differences in the relative contribution of direct and diffuse radiation on different portions of the tree canopy inside the chamber. They suggest long-term placement of a chamber on vegetation can alter daily water use efficiency by 50%.

For ET, a representative lysimeter can be used to evaluate the accuracy of ET measurements from other methods. However, there are no readily-available standards for determining the accuracy of field measurements of CO_2 fluxes, whether by micrometeorological or chamber methods. Often, then, one needs to consider the magnitude of differences between methods and the comparative advantages and disadvantages associated with the use of a method for a particular application.

In this study, we compared ET measured using a CC and BREB instrumentation and leaf CO_2 uptake measured using a leaf chamber (LC), and, after accounting for soil CO_2 fluxes, calculated using a CC and BREB instrumentation. In addition, soil CO_2 fluxes from a bare soil measured using a CC and soil chamber (SC) were compared.

2. Materials and methods

2.1. Measurement techniques

Daytime measurements of H_2O and CO_2 flux from leaves of plant canopies were made for three C_4 grasses—bermudagrass (*Cynodon dactylon* (L.) Pers.); a native tallgrass prairie whose main species are little bluestem (*Schizachyrium scoparium* (Michaux) Nash), johnsongrass (*Sorghum halepense* (L.) Pers.), Texas thistle (*Cirsium texanum* Buckl.), Illinois bundle flower (*Desmanthus illinoensis* (Michx.) MacM.), and annual forbs; and sorghum (*Sorghum bicolor* (L.) Moench.). Flux measurements were made using a CC, a LC, and BREB instrumentation. For a direct comparison with LC measurements, the soil CO_2 flux, measured using a SC, was combined with CC and BREB measurements. Fluxes of CO_2 into the leaf were positive and were expressed on a per unit ground area basis.

In a related study, bare soil CO_2 fluxes measured using a CC and SC were compared. Flux of CO_2 away from the soil surface was positive.

2.1.1. Canopy chamber (CC)

The CC measured the change of CO_2 and H_2O in an air volume that covered a plant canopy and soil surface and was open to the soil but closed to the atmosphere. The CC used in this study (Reicosky, 1990a; Reicosky et al., 1990) had a volume of 3.3 m^3, covered a land area of 2.8 m^2, had four mixing fans (each delivering 0.22 $m^3 s^{-1}$ from upward-directed outlets located 0.46 m above the soil), and was mounted on a rough-terrain forklift that carried it into a field and set it on the ground. Measurements using the CC were made at the same locations in each field during each visit in this study.

Measurements of concentration of CO_2 and H_2O inside the CC were made using a Li-Cor 6262 (Li-Cor Corp., Lincoln, NE) [1] infrared gas analyzer. Chamber air temperature also was measured. Concentration and temperature measurements were made every second for 60 s after the chamber was placed on the soil surface. After the appropriate lag time, the CO_2 uptake, which included soil respiration, and ET were calculated (Wagner et al., 1996) from the rate of change of CO_2 and H_2O inside the CC for a 30 s period while it was on the surface. The ET measured from a CC of this type has been shown to be close to that measured by a weighing lysimeter for alfalfa (Reicosky et al., 1983) and corn (Peterson et al., 1985). Fluxes of CO_2 calculated using this CC have not been compared with those measured using other methods.

2.1.2. Leaf chamber (LC)

Similar to the CC, the LC measured the uptake of CO_2 by vegetation in a sample of air. Leaf CO_2 uptake was measured using a CI-301PS portable photosynthesis system operated in an open mode with a 4.5×10^{-5} m^3 leaf chamber (CID, Inc., Vancouver, WA). Outside air was drawn through the chamber at 8×10^{-6} $m^3\,s^{-1}$. Air was drawn from 4.2 m above the soil surface to stabilize the CO_2 concentration.

Measurements of CO_2 uptake were made on leaves in the upper, middle, and lower third of each canopy, with leaves maintained at their original inclination and angle. Leaves too small to fill the chamber area (90 by 25 mm) were clipped after measurement and their leaf area was measured; otherwise chamber area was used for calculation of leaf area and leaf uptake rates. The chamber was left on a leaf for at least four consecutive uptake measurements to obtain a stable set of measurements. Each leaf uptake measurement required 30 s. The photosynthetic photon flux density ($\boldsymbol{Q}_p$) was measured for each leaf in the same plane as the leaf section measured, 18 mm from the section.

To compare LC measurements of CO_2 uptake with those calculated from CC and BREB instrumentation, we scaled LC measurements up to a unit ground area. Several models, often involving such factors as canopy geometry, vertical leaf area distribution, sunlit and shaded fractions of total leaf area, and radiation transfer, have been proposed for scaling leaf gas exchange measurements to a canopy (e.g. Norman and Welles, 1983; Kim and Verma, 1991; Baldocchi and Harley, 1995).

In this study, leaf CO_2 uptake, per-unit-ground-area, was calculated as the product of leaf uptake, per unit leaf area as measured by the LC, and the leaf area index (LAI). We sampled leaves at three representative levels within the canopy, and at different angles and inclinations to quantify the uptake for the entire canopy. We presumed all leaf area was sunlit due to the low leaf area indices (Campbell, 1977).

2.1.3. Bowen ratio / energy balance (BREB)

The flux of CO_2 above the vegetation (positive = downward) was calculated from BREB measurements. Similar to the CC, the soil CO_2 flux measured with the SC was added to this measurement for comparison with LC measurements.

[1] Trade names are given for clarification and do not imply endorsement.

The BREB instrumentation (Model 023/CO_2 Bowen ratio system, Campbell Scientific, Inc., Logan, UT, USA) and methods of calculating CO_2 flux used in the current study have been described by Dugas (1993). Briefly, half-hour Bowen ratios were calculated from the average temperature and humidity gradients, measured every 2 s at two heights above the canopy. The sensible heat flux was calculated from the Bowen ratio and half-hour averages of net radiation and soil heat flux. Net radiation was measured using a Model Q*6 net radiometer (REBS, Seattle, WA, USA) and soil heat flux was calculated from heat flux measured by plates (three per field) buried at 50 mm (Model HFT, REBS) and from soil temperatures above the plate. The turbulent diffusivity, assumed equal for heat, water vapor, and CO_2, was calculated using the average half-hour sensible heat flux and temperature gradient. Half-hour averages of the CO_2 flux, corrected for vapor density differences at the two heights (Webb et al., 1980), were calculated as a product of the turbulent diffusivity and half-hour average CO_2 gradient that also was measured for the same two heights by the BREB instrumentation. Three CO_2 BREB systems were used, one each in the bermudagrass, native prairie, and sorghum.

For intercomparison, the three BREB systems were operated adjacent to one another for 7 d in a bare soil field in March 1994. For the 7-d period, the average half-hour CO_2 gradient between the lower arm positioned at 0.3 m above the soil surface and the upper arm at 1.3 m for the three systems was 0.67, 0.70, and 0.67 $\mu mol(CO_2) mol^{-1}$ (dry air), respectively, while the root mean square difference (RMSD) [2] between CO_2 gradients from the three sets of two systems, i.e. system 1 vs. 2, 1 vs. 3, and 2 vs. 3, was < 0.07 $\mu mol\, mol^{-1}$ for each set. The average H_2O gradient was 0.09 $mmol(H_2O) mol^{-1}$ (dry air) for all three systems. Thus, the systems all measured approximately the same gradients. Daytime turbulent diffusivities on these days were typically 0.15 to 0.2 $m^2\, s^{-1}$. The three net radiometers used in the current study were all calibrated against a laboratory standard (Model S-1, Swisstecho Instruments, Oberriet, Switzerland) in the spring of 1994. Thus, there was no systematic bias between the three BREB systems.

2.1.4. Soil chamber (SC)

Soil CO_2 flux measurements were used for two purposes. First, SC measurements of CO_2 flux made in the native prairie and sorghum were combined with CC and BREB fluxes for comparison with LC measurements. Second, SC and CC measurements were compared with each other on bare soil.

The SC measurements of CO_2 fluxes were made using instrumentation and procedures described by Dugas (1993). A 10^{-3} m^3 chamber (inside diameter = 0.1 m), attached to Li-Cor 6200 photosynthesis system, was set on the soil surface for about 30 s and the flux was calculated from the rate of change of CO_2 concentration inside the chamber. Measurements of soil CO_2 flux using this type of chamber have been shown to be within 15% of those calculated from a laboratory apparatus (Nay et al., 1994).

[2] $RMSD = [\Sigma(\text{Measurement No. 1} - \text{Measurement No. 2})^2/(n-1)]^{0.5}$.

2.2. Grasses

Leaf CO_2 uptake was measured and calculated on 4 May (native prairie) and 5 May (bermudagrass and sorghum) 1994 at the Blackland Research Center, Temple, TX (31°06′ N, 97°20′ W, elevation = 219 m). The soil in all fields is a fine, montmorillonitic, thermic Udic Pellustert (Houston Black clay) (Godfrey et al., 1960). The CC and SC measurements of bare soil CO_2 flux were made on 5 May.

In all fields, oven-dried standing crop, separated by live and dead components and by species, was measured on 6 May from six quadrats inside or near CC measurement locations (see below). Leaf area, by species, was calculated from live leaf biomass and specific leaf area, the latter calculated from leaf area and biomass measurements on a sample from each quadrat. Leaf area was measured using a leaf area meter.

Volumetric water content was measured on 6 May in each field using three, 0.1-m deep soil cores. The ratio of Q_p below and above the canopy was measured using two cross-calibrated Li-Cor Model 191SA line quantum sensors (Li-Cor, Lincoln, NE). Measurements were made simultaneously above the canopy, and either at the soil surface or at positions 1/3 and 2/3 upward in the canopy at six locations in each field from 1120 to 1300 h CST on 5 May.

2.2.1. Bermudagrass (5 May)

The bermudagrass field was 1.8 ha and was directly adjacent to and southwest of the sorghum. Sprigs of bermudagrass were planted in April 1993 and at the time of these measurements the vegetation was a mixture of bermudagrass and johnsongrass.

The CC measurements were made from 0545 h CST to 1945 h CST at six locations that were 7 m apart on a southwest–northeast transect located west (downwind) of the BREB instrumentation. The first position was 10 m from the southwest field edge. It took 15 min to make the six measurements and CC measurements were repeated in this field about every 60 min throughout the day. The CC measurements were averaged for half-hour periods.

The LC measurements were made on bermudagrass and johnsongrass from 630 to 1445 h CST at a location 50 m south of the BREB instrumentation and 40 m east of the CC transect. Three measurements were made on each species during each visit, each at a different vertical canopy position. Measurements in this field were repeated about every 50 min, and it took 25 min to make the six measurements.

The relationship between leaf CO_2 uptake and Q_p was not different for the two species (results not shown). Therefore, uptake for each measurement on each species was scaled to a unit ground area using the entire community LAI. These per-unit-ground-area leaf uptake measurements were averaged and used as replicates in half-hour averaging periods.

The BREB instrumentation was 30 m south of the northern field edge and, with wind directions from east and southeast, fetch was > 80 m. Measurements arms were 1.13 and 2.13 m above the soil.

The SC measurements were not made in the bermudagrass because of time and personnel constraints and because previous measurements by us have shown SC measurements in sorghum and bermudagrass to be similar at this time of year. The sorghum SC measurements (see below) were combined with CC and BREB measurements in bermudagrass for comparison with LC measurements.

2.2.2. Native prairie (4 May)

The native prairie was a 125 m north–south by 280 m east–west field and was 0.7 km south of the sorghum and bermudagrass. It is a remnant native central Texas tallgrass prairie.

The CC measurements were made continuously on 4 May from 0800 h to 1600 h CST at eight locations, 7 m apart, along a transect that was 10 to 30 m south of the northern prairie edge. It took about 30 min to make the eight measurements. Measurements in each half-hour were averaged, with each measurement being used as a replicate.

The LC measurements were made from 0800 h to 1600 h CST near the prairie center, 50 m southwest of the CC transect. Two or three single leaf gas exchange measurements were made sequentially on little bluestem, johnsongrass, Texas thistle, and Illinois bundle flower, again at three representative vertical canopy levels. It took about 60 min to make a round of measurements on all species. Again, the relationship between leaf CO_2 uptake and Q_p was not different for any of the species (results not shown). Therefore, as with the two species in the bermudagrass, every measurement of leaf uptake for each species in the prairie was scaled up to a unit ground area basis using the community LAI, and all measurements within half-hour periods were averaged. Individual measurements were used as replicates.

The BREB instrumentation was 11 m south of the northern field edge and 20 m west of the CC transect. When winds were from the east to southeast, fetch was > 200 m. Measurements arms were 1.47 and 2.47 m above the soil.

Three SC measurement locations were used. Every 30 min, six measurements were made (two per location), each taking about 1 min. Measurements were made for the same hours as the CC measurements. Soil surface litter, but not green or standing dead vegetation, was included in the surface upon which the SC was placed. The SC measurements for half-hour periods were averaged for combination with CC and BREB measurements. Soil CO_2 fluxes were nearly constant throughout the day, averaging 0.15 $mg\,m^{-2}\,s^{-1}$, with a daytime range of ± 0.03 $mg\,m^{-2}\,s^{-1}$. (Note: 1 $mg\,m^{-2}\,s^{-1} \approx 22.7$ $\mu mol\,m^{-2}\,s^{-1}$.) This average flux was added to each half-hour CC and BREB average. The reduced diurnal variation of soil CO_2 flux in the native prairie, relative to that measured in the sorghum and two bare soil areas (see below), was due to a reduced surface soil temperature range caused by higher surface residue.

2.2.3. Sorghum (5 May)

The 4 ha sorghum field was planted on 16 March 1994 in 0.68 m-wide rows at 14 plants m^{-2}.

The CC measurements were made on 5 May from 0520 h CST to 2010 h CST at four locations that were 5 m apart on an east–west transect located 100 m southwest of the BREB station and 50 m from the nearest field edge. Measurements were repeated in this field about every 60 min. The CC, whose width was 1.53 m, was centered on the mid-row. Two rows of sorghum and an average of 38 plants were under the chamber.

The LC measurements were made from 0620 to 1340 h CST at a location 120 m southwest of the BREB instrumentation. Three measurements were made during each visit, each at a different vertical canopy position. Measurements were repeated about every 40 min. Sorghum was the only species in this field. All measurements within half-hour periods were averaged, and measurements on individual leaves were used as replicates.

The BREB instrumentation was 30 m south of the northern field edge. When wind direction was from the east and southeast, the fetch was > 150 m. Measurements arms were 1.3 and 2.3 m above the soil.

The SC measurements were made at six locations in the sorghum—two each in the mid row, in the row, and midway between these two positions. Measurements were made about every 30 min during the same hours as CC measurements. The SC measurements for half-hour periods were averaged for combination with CC and BREB measurements. Soil CO_2 fluxes were 0.05 $mg\,m^{-2}\,s^{-1}$ at sunrise and sunset and 0.16 $mg\,m^{-2}\,s^{-1}$ at midday. If necessary, half-hour averages of soil CO_2 fluxes, for combination with CC and BREB measurements, were estimated by linear interpolation.

2.2.4. Bare soil (5 May)

Soil CO_2 flux measurements were made on 5 May in two areas, both on the southern edge of the sorghum field, to compare the CC and the SC. There was no above-ground vegetation in either area. The first area, termed bare, was 15 by 15 m and had the sorghum killed by herbicide in early-April. The other area, termed de-topped, was 5 by 20 m and had the above-ground portion of sorghum plants removed on the afternoon of 4 May.

The CC measurements of soil CO_2 flux were made from 0530 h to 2030 h at three locations in each area about every 40 min. Measurements in each area for each half hour were averaged and individual measurements were used as replicates.

The SC measurements were made about every 30 min at six locations each in the two areas from 0530 h CST to 1930 h CST. Measurements in each area for each half hour were averaged and individual measurements were used as replicates. In the de-topped area, CC and SC measurement locations were in the same position with respect to rows as was used in the sorghum.

2.3. Analytical procedures

A t-test procedure (SAS Institute, 1988) was used to compare half-hour averages of ET from CC and BREB instrumentation and half-hour averages of CC and SC soil CO_2 fluxes. Half-hour averages of leaf CO_2 uptake for the CC, LC, and BREB instrumentation were compared using an ANOVA procedure in a general linear model procedure (SAS Institute, 1988). For the purposes of comparison with BREB measurements, we assumed the BREB was the 'correct' uptake. There were no replicates for this measurement. Replicates for the other two methods were the multiple measurements made in each half hour. Because soil CO_2 fluxes were small and less variable (by more than a factor of three) as compared to those measured by the CC and LC (see below), the variance of SC measurements was not included in this analysis.

2.4. Ancillary measurements

Half-hour averages of air temperature and relative humidity at 1.5 m and of wind speed and direction at 2.0 m were measured in the sorghum, and half-hour averages of above-canopy Q_p were measured nearby.

3. Results and discussion

3.1. Weather

On both 4 and 5 May 1994 skies were generally clear until 1100 h CST (Fig. 1). On 4 May, skies became cloudy at 1200 h CST and Q_p was reduced considerably for the remainder of the day. On 5 May, there were a few clouds between 1100 and 1400 h CST and skies were generally clear for the remainder of the day. Maximum temperatures were 22 and 27°C on 4 and 5 May, respectively, wind speeds varied from 1 to 3 $m s^{-1}$, and wind directions were easterly or southeasterly on both days. Maximum midday vapor pressure deficit was only 0.5 kPa on 4 May and 1.2 kPa on 5 May. There was 17 and 19 mm of precipitation on 29 April and 2 May, respectively, and, as a result, surface soils were moist—volumetric water contents were 0.33, 0.39, and 0.27 $m^3 m^{-3}$ in the bermudagrass, native prairie, and sorghum, respectively, and 0.21 and 0.34 $m^3 m^{-3}$ in the bare and de-topped areas, respectively. No precipitation occurred on 4 and 5 May.

3.2. Vegetation measurements

The green leaf LAI in the bermudagrass was 1.42; about 60% of this was johnsongrass and 30% was bermudagrass. Vegetation height varied from 0.2 m for bermudagrass to 0.6 m for johnsongrass, although the majority of johnsongrass leaves was < 0.3

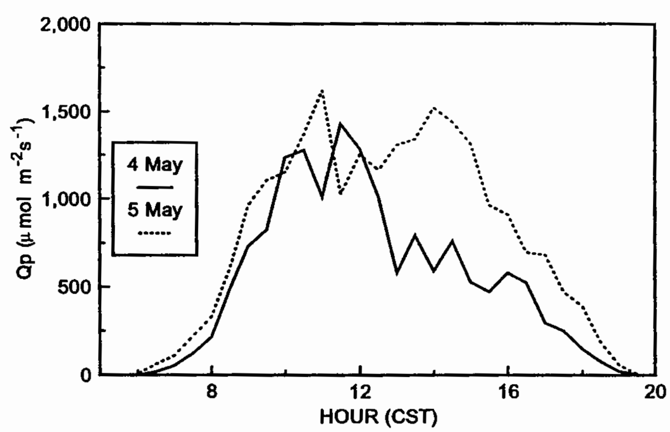

Fig. 1. Half-hour averages of photosynthetic photon flux density (Q_p) on 4 and 5 May 1994 at Temple, TX. Averages are plotted at end of half-hour. CST = Central Standard Time.

m above the soil surface. The below:above canopy Q_p ratio at midday decreased linearly from 1.0 above the canopy to 0.45 at the soil surface. Thus, a significant portion of radiation was incident upon the soil surface. Above-ground biomass was 268 $g\,m^{-2}$. There was no dead biomass.

The green LAI in the native prairie was 1.02, which was equally divided between little bluestem, johnsongrass, and annual forbs. Average vegetation height was 0.6 m, but again the majority of green leaves was < 0.4 m above the soil surface. At the soil surface, the below:above canopy Q_p ratio at midday was 0, while it was 0.3 at a height 1/3 of the way up from the soil surface to the top of the canopy. The low Q_p ratio at the soil surface was due to the large amount of standing dead vegetation on the soil surface. Above-ground, live biomass was 205 $g\,m^{-2}$, while above-ground, dead biomass was 903 $g\,m^{-2}$.

The sorghum LAI was 0.77 and the crop height was 0.3 m. At the soil surface, the below:above canopy Q_p ratio near midday was 0.7 and, thus, again a significant portion of solar radiation was incident upon the soil surface. Midday surface soil heat flux was > 100 $W\,m^{-2}$. Above-ground biomass was 46 $g\,m^{-2}$.

3.3. Evapotranspiration

The CC ET was consistently greater than BREB measurements for all grasses (Fig. 2), but especially in bermudagrass where half-hour ET rates were statistically different between the two methods for most of the day. Statistically significant differences were less common during the middle of the day for all grasses when ET rates were greater.

Total ET was least in the native prairie on 4 May for both methods (Fig. 2) because of reduced radiation (Fig. 1) and vapor pressure deficit on this day, and a shorter period of measurements common to both methods. Both methods measured a decrease in ET in the native prairie after 1300 h associated with reduced Q_p.

Grau (1995) showed that ET measured with a CC was 25% greater than that measured gravimetrically from a potted plant, while Dugas et al. (1991) also showed CC ET measured for irrigated wheat in Arizona to be greater than ET measured by micrometeorological instrumentation, although CC measurements in that study may have been affected by energy advected from a nearby dry soil surface. That situation was not present in this study.

Based upon the results of Wagner and Reicosky (1992) and Pickering et al. (1993) one might expect CC ET to be less than that measured by BREB instrumentation due to suppression of ET caused by increasing vapor densities and reduced radiation intensities inside the chamber. However, we used a quadratic regression equation (e.g. Wagner et al., 1996) that partially corrected for the effects of increasing vapor densities. Reicosky et al. (1983) did show reasonable agreement between measurements of ET by a CC and those from a nearby weighing lysimeter.

In the bermudagrass and sorghum, half-hour averages of CC ET were greater in the morning and late afternoon than potential ET (PET) that was calculated (Priestley and Taylor, 1972) using the measured net radiation and soil heat flux (results not shown). This also suggests CC ET measurements are too large at these times, especially considering that LAIs were < 1.5. The PET on 5 May was 5.4 mm in both the

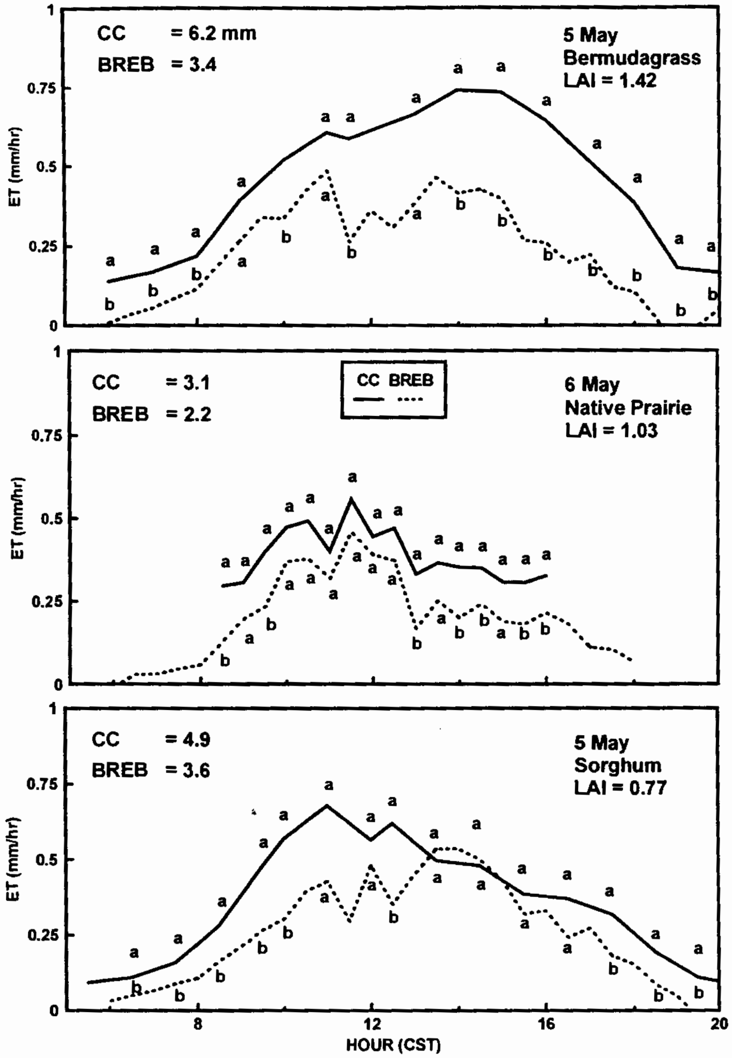

Fig. 2. Half-hour averages of evapotranspiration (ET) for bermudagrass, native prairie, and sorghum measured by canopy chamber (CC) and Bowen ratio/energy balance (BREB) methods. Averages for each grass with same letters are not statistically different ($P < 0.05$). Averages are plotted at end of half-hour. Total ET (mm) for the period common to both methods, the date of measurement, and the leaf area index (LAI) area shown for each grass. CST = Central Standard Time.

bermudagrass and sorghum (net radiation and soil heat flux were essentially equal for these two grasses). This was less than total CC ET (6.2 mm) in bermudagrass.

There may be several reasons for the ET differences in this study. The increased wind speeds inside the CC ($\approx 13\ m\,s^{-1}$ at the midpoint of the fan outlet), which are necessary to adequately mix chamber air to ensure a representative sample for gas concentration measurements, may have increased soil evaporation due to increased boundary layer conductance inside the CC. Soil evaporation was likely a large component of ET because of the wet soil surface and low LAIs. This is supported by the relative large ET rates measured by the CC in the bermudagrass and sorghum fields near sunrise and sunset when transpiration was likely a smaller percentage of ET.

The BREB measurements also may have been in error or non-representative. Average daytime Bowen ratios were 0.8 in the native prairie and 0.5 in both the sorghum and bermudagrass. Thus, ET rates were relatively insensitive to errors in temperature and humidity gradient measurements (Angus and Watts, 1984). Measurements from this type of BREB instrumentation have been shown to be close to energy balance components measured by other types of BREB systems over irrigated wheat (Dugas et al., 1991), to bare soil evaporation measured by a lysimeter (Dugas, 1992), and to latent heat and sensible heat fluxes calculated from eddy correlation instrumentation over rangeland (Dugas, 1992). In this study, fetch in all fields was less than the 100:1 fetch:height ratio often cited as necessary for representative measurements from a surface, although the relatively small Bowen ratios in this study suggest a fetch:height ratio this large may not have been required (Heilman et al., 1989). Regardless, in the bermudagrass, where the fetch:height ratio was least, the sorghum was upwind and surface conditions (canopy height and cover, surface soil moisture, and leaf area) were not markedly dissimilar between the bermudagrass and sorghum. In all cases, there were small differences in the surface conditions of surrounding fields. Plant canopy development and soil moisture conditions immediately upwind (south and east) of BREB instrumentation in all fields were visually similar to that of the field in general and to the areas where CC measurements were made in particular. Thus, we believe BREB measurements were not affected by a nearby surface that was markedly dissimilar to that measured by the CC in any field. The assumption of diffusivity equality for heat and water vapor (typically 0.3 $m^2 s^{-1}$ during the day in all fields) also was likely valid because atmospheric stability was near neutral during these measurements (Lang et al., 1983). Finally, it is unlikely net radiation measurements were substantially in error because all sensors were calibrated against a laboratory standard in the spring of 1994. The reasons for ET differences between BREB and CC instrumentation remain unresolved, but we remain concerned about the effects of microclimatic differences, especially the increased turbulence, inside the CC.

3.4. CO_2 Uptake

Leaf CO_2 uptake rates measured using the three methods in this study were quite similar (Fig. 3), especially considering the difficulty of and assumptions involved in measuring CO_2 fluxes using the BREB and CC methods and the spatial and temporal extrapolation required to scale LC measurements to a value per unit ground area. (Fluxes from the three grasses were combined in Fig. 3 because there was no significant effect of species on the relationship between flux from the CC or LC as a function of the BREB flux.) The regression equation for LC measurements as a function of BREB measurements had a slope not statistically different from 1.0, but the scatter was large, likely due to limited leaf area sampled by the LC. Differences between BREB and CC

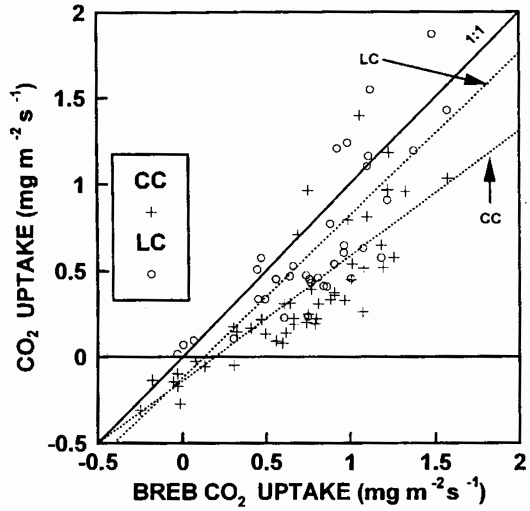

Fig. 3. Half-hour averages of carbon dioxide (CO_2) leaf uptake, per unit ground area, measured by canopy chamber (CC) and leaf chamber (LC) methods versus that measured by Bowen ratio/energy balance (BREB) method. The 1:1 line and linear regression line for each method are shown. Regression equations (with standard errors) are: CC = −0.16(0.06) + 0.73(0.07) × BREB, $n = 46$, $r^2 = 0.68$; and LC = −0.12(0.1) + 0.94(0.12) × BREB, $n = 35$, $r^2 = 0.64$. Positive flux is uptake of CO_2.

measurements were greater and there was a tendency for the BREB measurements to be consistently larger. A portion of the difference between CC and BREB measurements may be related to the greater soil CO_2 flux that occurred under the CC versus that measured by the SC (see below). Soil fluxes measured by the SC were used to calculate leaf uptake for the CC in Fig. 3. This underestimate of soil CO_2 flux in the CC would have reduced the calculated CC uptakes shown in Fig. 3. Uptakes for all three methods were normally distributed (Shapiro–Wilk statistic > 0.93) and had equal variances, and there were no residuals with a significant effect on the regression.

The underestimate of uptake by the CC, relative to that measured by LC and BREB instrumentation, also may be related to chamber leaks, but we ensured a good contact between the soil surface and chamber bottom, and previous analyses (Reicosky, 1990b) suggest this is a small problem with this system.

Norman and Polley (1989) also showed grassland CC uptake to be less than that measured using a micrometeorological method. They suggest this was a result of reduced Q_p inside the chamber. Reicosky et al. (1983) measured an 8–10% reduction in Q_p in a similar chamber, while Denmead et al. (1993) measured a 30% reduction in net radiation in a different chamber.

The RMSD between half-hour BREB and CC uptake (Fig. 3) was 0.41 $mg\,m^{-2}\,s^{-1}$, while that between BREB and LC measurements was 0.31 $mg\,m^{-2}\,s^{-1}$. These differences are 50% of the average CO_2 uptake measured by BREB instrumentation for the three grasses. Total daytime LC CO_2 uptakes for the three grasses were both greater and less than those calculated from BREB measurements, while CC measurements were

Table 1
Leaf uptake of carbon dioxide ($g\,m^{-2}$), per unit ground area, for bermudagrass, native prairie, and sorghum measured by canopy chamber (CC), Bowen ratio (BREB), and leaf chamber (LC) methods. Totals were calculated for periods shown. Positive flux is uptake of carbon dioxide. CST = Central Standard Time

Field	Period (CST)	Method		
		CC	BREB	LC
Bermudagrass	0530–2000	29.5	38.4	
	0600–1430	19.8	30.1	32.3
Native Prairie	0800–1600	9.7	24.4	14.0
Sorghum	0530–2000	6.6	26.4	
	0625–1410	5.5	19.3	10.4

consistently the least (Table 1). For the native prairie and sorghum, differences between methods were substantial.

Leaf uptake was greatest in the bermudagrass (Fig. 4 and Table 1) due to the greater LAI and greater Q_p on 5 May (Fig. 1). This was true for all methods. These leaf uptakes are similar to midday, maximum measurements (1.5 $mg\,m^{-2}\,s^{-1}$) made by Baldocchi (1994) for a partial-cover C_4 crop (maize) in Oregon, but greater than measurements made by Rochette et al. (1995) for soybeans with a comparable LAI in Canada.

Uptake was reduced in the native prairie in the afternoon (Fig. 4) due to reduced Q_p (Fig. 1). These uptakes for a prairie are similar to those shown by Verma et al. (1989) and Moncrieff et al. (1992) for a tallgrass prairie in Kansas in 1986 and 1989, respectively, but are considerably less than those measured in the same prairie in 1987 under well-watered soil water conditions following a spring burning of the prairie (Kim et al., 1992; Verma et al., 1992). The prairie in the current study had not been burned for more than 20 years.

Sorghum uptake measured in this study (Fig. 4) was similar to that measured by Kanemasu and Hiebsch (1975) for sorghum and Rochette et al. (1995) for soybean with an LAI < 1.0, but is considerably less than that measured by Szeicz et al. (1973) for sorghum with an LAI of 2.0.

The consistently smaller CC uptake versus that from BREB measurements in this study (Fig. 4) is different from that shown by Denmead et al. (1993) who found CO_2 uptake for a Eucalypt forest to be greater in a ventilated CC than that measured using BREB instrumentation. Their chamber was continuously over the canopy. Differences of CO_2 uptake between the two methods in their study were often greater than those shown in this study.

There are several possible explanations for differences between uptake measured by the three methods. We believe the precision is least for LC measurements due to the small spatial sampling aspects associated with the method. This is the cause for the large scatter of LC measurements with respect to the other two methods (Fig. 3).

Wagner and Reicosky (1992) estimated that uptake measured by the chamber was 10% below what it would have been at the instant the chamber was placed on the canopy. Some of this underestimate was accounted for by our use of a quadratic regression equation for calculating fluxes (Wagner et al., 1996). Again, most of the

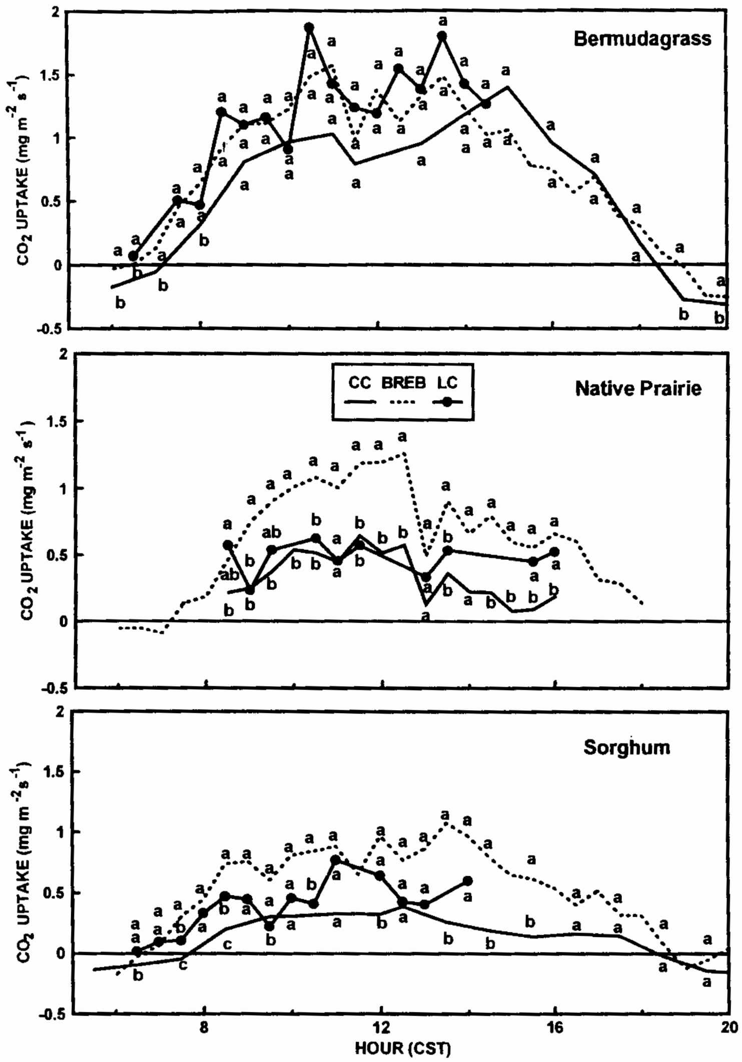

Fig. 4. Half-hour averages of carbon dioxide (CO_2) leaf uptake, per unit ground area, for bermudagrass, native prairie, and sorghum measured by canopy chamber (CC), Bowen ratio/energy balance (BREB), and leaf chamber (LC) methods. Averages for each grass with same letters are not statistically different ($P < 0.05$). Averages are plotted at end of half-hour. Positive flux is uptake of CO_2. CST = Central Standard Time.

differences between BREB fluxes and those from the CC or LC in Fig. 4 and Table 1 are greater than 10%. Denmead et al. (1993) showed a large effect of the ventilated chamber itself on measured CO_2 uptake.

The BREB calculation of CO_2 flux could also be in error due to measurement errors of inputs. Under our conditions, the percentage change in midday CO_2 flux calculated from BREB measurements was about $\pm 10\%$ for a $\pm 10\%$ error in either net radiation or

CO_2 gradient, and was half this for a $\pm 10\%$ error in the temperature and humidity gradients. In addition to the reasons discussed above for ET, the assumption of equality of diffusivities for heat and carbon dioxide may not be valid. Although Dugas (1993) showed soil CO_2 fluxes from this method compared favorably with those measured using a SC, BREB fluxes above the vegetation in the current study are 10 times greater than those from soil measured by Dugas (1993).

Differences in calculated water use efficiency, CO_2 uptake/ET, between CC and BREB instrumentation in this study would have been greater than differences of ET or CO_2 individually because ET was greater (Fig. 2) and CO_2 uptake was smaller (Fig. 3) for the CC.

3.5. Bare soil

Half-hour averages of soil CO_2 flux followed a typical diurnal pattern for both methods (Fig. 5). Soil CO_2 flux was responding primarily to soil temperature. Differences of soil CO_2 fluxes between SC and CC were one-tenth of differences in leaf uptake measured by the CC and BREB methods (Fig. 4). Half-hour soil CO_2 fluxes were significantly greater from the CC for two-thirds of the day on both surfaces. (The anomalous half-hour average at 0800 h from the SC in the de-topped area was because there was only one measurement during that half-hour period and this measurement location consistently had a large flux.)

The difference in soil CO_2 fluxes between CC and SC (Fig. 5) is part of the reason for the consistent underestimate of leaf uptake by the CC relative to that measured by the BREB instrumentation (Fig. 3). We used the SC CO_2 flux in conjunction with CC measurements to calculate leaf uptake in all fields. Results from Fig. 5 suggest CC soil CO_2 fluxes were consistently greater by 0.07 $mg\,m^{-2}\,s^{-1}$. This is a quarter of the difference between leaf uptake measured by CC and BREB instrumentation (Fig. 3).

Due to the presence of roots and higher soil water content in the de-topped area, fluxes were larger for both methods in this area, but especially for the CC (Fig. 5). Fluxes were more variable in the de-topped area—the CV of the six SC measurements was 50% in the de-topped area and 15% in the bare area, likely because of less variation in near-surface roots in the bare area.

The SC average for the de-topped area, 0.09 $mg\,m^{-2}\,s^{-1}$, was 20% of downward CO_2 flux measured in the sorghum by the BREB instrumentation, supporting the statement by Monteith et al. (1964) that a large fraction of CO_2 taken up by leaves is from the soil. Rochette et al. (1995) showed similar percentages of atmospheric and soil CO_2 sources for daytime CO_2 flux measurements throughout the growing season.

Differences between the CC and SC soil CO_2 fluxes may have been a result of higher mixing rate in the CC. The mixing rate inside the CC (16 chamber air volumes per minute) is 10 times greater than that inside the SC (1.6 volumes per minute). Subsequent measurements by us have shown the air movement over a smooth surface placed on the bottom of the chamber reduces the pressure over this surface by an average of 1.5 Pa. We measured this pressure drop, using a differential pressure transducer (Setra Model 264, Acton, MA, USA), at 72 uniformly-spaced locations through a 13-mm thick plywood board that had access holes fitted with rubber stoppers. Corresponding wind

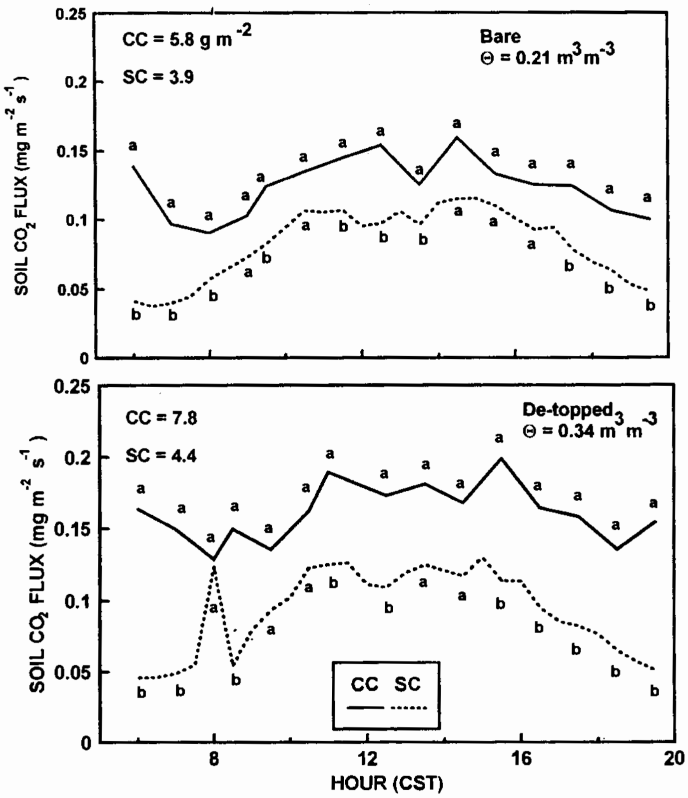

Fig. 5. Half-hour averages of soil carbon dioxide (CO_2) flux from bare and de-topped areas in bare soil field measured by canopy chamber (CC) and soil chamber (SC) methods. Averages for each area with same letters are not statistically different ($P < 0.05$). Averages are plotted at end of half-hour. Total daily CO_2 flux ($g\,m^{-2}$) and surface volumetric water content (Θ) are shown. Positive flux is away from soil surface. CST = Central Standard Time.

speeds, measured using an omnidirectional hot wire anemometer (Davis Instruments, Model 8470, Baltimore, MD, USA), with the sensor midpoint 0.01 m above the board, averaged 1.7 $m\,s^{-1}$. Short-term impacts of dynamic pressures changes due to air flow on the soil flux are being evaluated. Kanemasu et al. (1974) and Nakayama and Kimball (1988) have shown that small pressure differences for extended periods can affect soil CO_2 flux. Hutchinson and Livingston (1993) suggest near-surface gradients (and, presumably, fluxes) are modified by ventilation.

Field measurements of CO_2 fluxes with a CC, thus, present a dilemma of balancing the need for adequate mixing to achieve a uniform and representative gas sample and the need not to use a mixing rate so large such that the flux is enhanced until soil transport properties limit the flux. Measurements from the CC and SC had similar temporal trends and they both can presumably be used for relative treatment comparisons. Results from Nay et al. (1994) and Dugas (1993) suggest measurements are accurate using a chamber similar to the SC.

The CC measurements certainly appear to be too large in the early morning and late-afternoon (Fig. 5). The large early-morning fluxes may be due to the greater CC mixing rate and high near-surface soil CO_2 concentrations at these hours (Reicosky, 1989), although recent measurements by us suggest midday CC flux measurements over a dry soil are insensitive to mixing rates (results not shown). Further studies are planned to examine the effect of mixing rate on fluxes over wet and dry surfaces. The constant soil CO_2 fluxes for both surfaces measured by the SC from 0600 h to 0730 h are typical of constant nighttime CO_2 flux we have measured in these fields using the same instrumentation (results not shown).

4. Conclusions

We compared evapotranspiration (ET) and carbon dioxide (CO_2) fluxes for three C_4 grasses and bare soil using measurements from canopy chamber (CC), leaf chamber (LC), soil chamber (SC), and Bowen ratio/energy balance (BREB) instrumentation.

The CC ET was consistently greater than that measured by BREB instrumentation. Differences were large in some instances and may have been caused by enhanced soil evaporation inside the CC due to increased turbulence or by errors in BREB measurements. The CC ET appeared too large relative to leaf area and calculated potential ET.

Diurnal patterns of leaf CO_2 uptake were similar for the three methods. There was a large variation in half-hour LC fluxes, relative to the BREB fluxes, likely due to spatial extrapolation required to scale up LC measurements. The CC CO_2 uptake was closely related to BREB fluxes, but was consistently smaller. A quarter of this difference may have been related to an underestimate of the soil CO_2 flux under the CC.

In view of the wide differences in spatial and temporal scales for each method, we suggest the similarity of the magnitude and temporal dynamics of these fluxes is encouraging and, if used properly, all methods can provide a viable estimate of CO_2 fluxes depending upon research objectives and availability of resources. Additional research is required to resolve inconsistencies between methods for measurement of ecosystem CO_2 fluxes.

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