Bowen ratio and closed chamber carbon dioxide flux measurements over sagebrush steppe vegetation

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Abstract

Measurement of carbon dioxide (CO_2) fluxes over sagebrush steppe ecosystems has received little attention, and seasonal dynamics of CO_2 uptake are not known for most portions of this expansive ecosystem. We utilized two techniques — Bowen ratio/energy balance (BREB) and closed chamber (CC) — to measure CO_2 fluxes during eight 24 h sampling periods throughout the 1997 growing season on ungrazed sagebrush steppe communities at the US Sheep Experiment Station near Dubois, ID and the Northern Great Basin Experimental Range near Burns, OR. Instantaneous CC measurements generally agreed with 20 min average CO_2 fluxes measured by BREB instrumentation, except later in the season at Burns when soil moisture was depleted. Maximum mid-day CO_2 assimilation occurred in June at both locations, with rates up to 0.4 and 0.5 mg CO_2 m^{-2} s^{-1} at Burns and Dubois, respectively. In August, mid-day assimilation was low, at about 0.1 mg m^{-2} s^{-1} at both locations. Slopes of CC fluxes as a function of BREB were not different between locations, so data were combined across locations. A significant, positive correlation was observed between CC and BREB ($R = 0.82$, $n = 190$). These two independent measurements of CO_2 flux showed good agreement, except during extremely hot and dry periods in late summer. This suggests that both BREB and CC are valid techniques and can be used in concert to obtain reliable estimates of CO_2 flux on these shrub-dominated communities, although caution is advised for CC during periods when temperatures are high and soil moisture is low. The BREB technique is appropriate for large-scale, continuous measurements of CO_2 flux, and compares well with the CC technique, which can partition flux estimates between shrub canopy and interspace, thereby providing a measure of spatial variability. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The world's temperate deserts and semi-deserts are important ecosystems and occupy about 5.85×10^8 ha worldwide (West, 1983). More than 10% of the

worldwide total, about 7.8×10^7 ha, is located in North America and more than 50% of the North American total is classified as the Western Intermountain sagebrush steppe ecosystem (4.5×10^6 ha). Although, these ecosystems have relatively low annual aboveground net primary production (West, 1983), these extensive areas are important as watersheds, wildlife habitat, and animal forage. Modeling studies suggest that natural grasslands are sensitive to climatic variations and

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management practices. Tans et al. (1990) indicated that annual carbon (C) flux to the oceans was probably less than previously thought, and there was evidence for a terrestrial sink in North America (Ciais et al., 1995). Northern temperate forests are probably not as great a C sink as previously thought (Nadelhoffer et al., 1999), suggesting that other North American terrestrial ecosystems may be important C sinks. Research is needed to document the role of North American steppe ecosystems in the global carbon budget, because as Schindler (1999) points out, the missing sink may actually be several smaller sinks rather than one large one.

Little information is available concerning the seasonal dynamics of carbon dioxide (CO_2) fluxes over the Western Intermountain sagebrush steppe ecosystem. Some consider that these temperate deserts and semi-deserts represent a small portion of the terrestrial C sink, because they are relatively less productive than other North American ecosystems. Fan et al. (1998) even suggested that these ecosystems are sources for atmospheric CO_2. Research is needed to determine the role the sagebrush steppe ecosystem plays in the global carbon cycle, and what effect land management practices may have on annual carbon cycles. Research concerning CO_2 fluxes was initiated on rangelands at numerous locations in the central and western US (Svejcar et al., 1997), and the present study is part of that effort.

Two common approaches for measuring CO_2 fluxes are micrometeorological techniques and chamber methods. Bowen ratio/energy balance (BREB) and eddy-covariance (EC) are the two primary micrometeorological systems used to measure surface scalar fluxes (Dabberdt et al., 1993). EC provides direct measurement of sensible (H) and latent (λE) heat fluxes, whereas BREB is an indirect approach wherein H and λE are calculated from other measurements. In this study, we used the BREB method, which has been used by many researchers in evapotranspiration and CO_2 flux studies (e.g. Baldocchi et al., 1981; Denmead et al., 1993; Dugas, 1993; Dugas et al., 1999; Prueger et al., 1997; Tanner, 1960; Todd et al., 2000; Verma and Rosenberg, 1975). Gradient-based methods such as BREB are not well suited to very rough surfaces (e.g. forest), because vertical velocity fluctuations are large and the vertical gradients of scalars are correspondingly small (Verma

et al., 1990). In such cases, EC is preferred over BREB.

Gradient-based methods assume equality of turbulent diffusivity for water vapor (K_v), heat (K_h), and CO_2 (K_c) which is generally valid except under extremes of atmospheric stability (Rosenberg et al., 1983). The BREB method relies on several assumptions (Fritschen and Simpson, 1989). Transport of heat, water vapor, and CO_2 are assumed to be one-dimensional and further, the sensors which measure the vertical gradients are assumed to be located within the equilibrium sublayer. Fluxes within this layer are also assumed to be constant with height. These assumptions are not usually violated if measurements are made at an appropriate height and adequate upwind fetch is present. Rosenberg et al. (1983) established a 100:1 fetch/height-above-surface ratio as a rule of thumb. Steduto and Hsiao (1998) concluded that the assumption of one-dimensional transport, which underlies the technique, is justified. Advection, the "transport of energy or mass in the horizontal plane in the downwind direction" (Rosenberg et al., 1983) can be present under certain conditions. Sensible heat advection can result in underestimation of latent heat flux (Blad and Rosenberg, 1974).

Measurement precision is of concern, and errors in estimating λE are propagated in the calculation of CO_2 flux (Sinclair et al., 1975) and can lead to bias. However, Dugas et al. (1999) successfully employed the BREB method to measure CO_2 fluxes over plant canopies, and the validity of the method has been demonstrated in several earlier studies (Dugas et al., 1991; Held et al., 1990; Malek and Bingham, 1993). Closed chamber (CC) techniques can also be used to measure CO_2 fluxes, although they have limitations because they modify the chamber environment relative to ambient conditions. However, Held et al. (1990) and Chan et al. (1994) found good agreement between BREB and CC techniques. Limited work has been reported for arid and semi-arid ecosystems such as those described here.

Our objective in this study was to compare BREB and chamber techniques for quantifying CO_2 fluxes over sagebrush steppe vegetation at two widely separated sites. Because chamber and BREB measurements utilize different methodologies, they provide a valuable comparison.

2. Materials and methods

2.1. Site details

The sites utilized in this study were located near Dubois, ID, and Burns, OR. They support typical sagebrush steppe species common to the northern extent of the Great Basin region of North America. While both sites can be characterized as sagebrush steppe, the locations differ in species composition, climate (average air temperature and precipitation), and soils.

2.1.1. Idaho site description

The Dubois site is located on the US Sheep Experiment Station (46°16′N 112°08′W; 1700 m elevation), about 10 km north of Dubois, ID. The site was excluded from grazing beginning in 1995 by constructing a fence to create a 200 m × 200 m enclosure. Dominant plants are three-tip sagebrush (*Artemisia tripartita* Rydb. spp. *Rupicola* Beetle) (canopy cover = 40%), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A Löve), and arrowleaf balsamroot (*Balsamorhiza sagittata* (Pursh) Nutt.). Other common species include green rabbitbrush (*Chrysothamnus viscidiflorus* (Hook.) Nutt.), gray horsebrush (*Tetradymia canescens* DC.), needle-and-thread grass (*Stipa comata* Trin. and Rupr.), Sandberg's bluegrass (*Poa sandbergii* Vasey.), and junegrass (*Koeleria cristata* L. Pers.), yarrow (*Achillea millefolium* L.), tapertip hawksbeard (*Crepis acuminata* Nutt.), longleaf phlox (*Phlox longifolia* Nutt.), and milkvetches (*Astragalus* spp.). The climate is semi-arid with cold winters and warm summers. Mean annual precipitation (64 years) is 302 mm, and mean annual temperature is 6°C (NOAA, 1999a). Soils are loamy and are classified as a complex of typic calcixerolls, pachic haploxerolls, and pachic argixerolls with slopes of 0–12%.

2.1.2. Oregon site description

The Oregon study was established on the Northern Great Basin Experimental Range (43°29′N 119°43′W; 1380 m elevation), about 64 km west of Burns, OR, in a 65 ha ungrazed Wyoming big sagebrush (*Artemisia tridentata* Nutt., subspecies *Wyomingensis*) community (canopy cover = 10%). Understory species include Thurber's needlegrass (*Stipa thurberiana* Piper), bluebunch wheatgrass (*Pseudoroegneria spicata*

(Pursh) A. Löve), Sandberg's bluegrass (*Poa sandbergii* Vasey.), bottlebrush squirreltail (*Sitanion hystrix* (Nutt.) Smith), prairie lupine (*Lupinus lepidus* Dougl.), hawksbeard (*Crepis occidentalis* Nutt.) and longleaf phlox (*Phlox longifolia* Nutt.). Sagebrush cover on the site is approximately 10%. Domestic livestock have not grazed the community since 1995. Mean annual precipitation (61 years) is 294 mm, and mean annual temperature is 8°C (NOAA, 1999b). Soils are coarse-to-fine sandy loam in texture and classified as aridic duric haploxerolls and orthidic durixerolls in the Holte–Milcan complex with 0–2% slopes.

2.2. Closed chamber measurements

Three and 10 permanent plots (1 m²) were established at Dubois and Burns, respectively, by pressing a 1 m² angle iron frame into the soil. At Dubois, all plots contained a shrub, while at Burns five plots were centered over a shrub, with the rest in an interspace containing only herbaceous species. The frame provided a base on which to mount a CC for measurement of net CO_2 flux between the surface and atmosphere. Chambers were constructed and operated according to methods presented in detail by Angell and Svejcar (1999). For a measurement, the chamber was placed on the frame using closed cell foam for a tight fit. The chamber fan was turned on, and ventilation doors left open to maintain near-ambient conditions within the chamber until datalogging was initiated. To obtain a measurement, the doors were closed and after a 30 s mixing interval, the measurement period commenced and CO_2 concentration was measured for up to 90 s using a portable CO_2 measurement system (LI-COR 6200, LI-COR Inc., Lincoln, NE, USA). Within each measurement period, three measurements of CO_2 concentration were obtained, along with leaf and air temperature, radiation, and humidity. Measurement periods were brief to minimize chamber effects. CO_2 fluxes above the canopy (positive = downward) were calculated from rate of change in chamber CO_2 concentration. At Dubois, CC measurements were initiated at mid-day on 14 May, 17 June, 7 July, and 31 July 1997. Measurements were repeated six–seven times over the following 24 h. At Burns, CO_2 fluxes were measured beginning at 08.00 h PST on 7 May, 5 June, 1 July, and 6 August 1997. Measurements

were repeated at about 4 h intervals for the following 24 h period. Measured fluxes at each interval were averaged across plots to provide one estimate at each interval. Each measurement period spanned about 45 min at Dubois and 1.5 h at Burns.

2.3. Micrometeorological measurements

At both sites, above-canopy 20 min average CO_2 fluxes were measured continuously using BREB instrumentation (Model 023/CO_2 Bowen ratio system, Campbell Scientific, Inc., Logan, UT, USA). Methods for calculating fluxes followed those published previously (Dugas, 1993). As with the CC, positive fluxes are downward, toward the surface. In brief, temperature and humidity gradients were measured every 2 s at 10 and 110 cm above the canopy surface. Concurrently, CO_2 gradients were measured at the same heights using an infrared gas analyzer (LI-6262, LI-COR, Inc.). Other data needed for BREB calculations were obtained from net radiation sensors (model Q*7 net radiometer, REBS, Seattle, WA, USA), soil heat flux plates (model HFT3, REBS), and averaging soil temperature thermocouples (model TCAV, CSI) located above each heat flux plate. Net radiometers were calibrated against a laboratory standard (model 7.2 REBS) above a grass canopy. Bowen ratios were calculated from temperature and humidity data. The turbulent diffusivity, assumed equal for heat, water vapor, and CO_2, was then calculated. Average 20 min CO_2 fluxes were calculated as the product of turbulent diffusivity and 20 min CO_2 gradient, correcting for vapor density differences at the two heights (Webb et al., 1980). Corrections for temperature difference were not applied to fluxes. A test of BREB equipment in Temple, TX determined that the temperature of the air streams from the upper and lower arms did not differ upon entering the IRGA, with an average difference of only 0.002°C (William Dugas, personal communication). Separate tests in Utah (Edward Swiatek, personal communication) and on our equipment in Oregon (unpublished data) also found that temperatures of the two air streams were not different upon entering the cells of the analyzer. In the Oregon tests, air temperatures at the inlet of the IRGA never differed by more than 0.1°C (5-day-period, $n = 1504$), with an average of $0.007 \pm 0.05°C$. Flow rate through the BREB system is less than for EC systems (0.4 dm³ min⁻¹,

about 1% of the flow rates typical of EC), and the upper and lower tubes are routed together for 2 m prior to entering the BREB enclosure. These factors provide time for the small initial gradient between upper and lower air streams to equilibrate prior to entering the IRGA.

Fluxes for the BREB method are most suspect at night when the temperature/humidity gradients are small and may have signs opposite to the flux (Ohmura, 1982). When this occurs, BREB cannot be used to calculate turbulent diffusivity. At these times, we followed techniques described by Dugas et al. (1999) to calculate diffusivity. On the four dates reported here, <5% of the 20 min BREB data required such treatment. Also, when the Bowen ratio nears −1, the method can indicate erroneous fluxes. This generally occurs at sunrise or sunset, during times when CO_2 fluxes are low. When that occurred, we estimated flux rate by linear interpolation.

Regression analysis was conducted on datasets from both locations using standard procedures (SAS, 1989). Regression slopes for the two locations were compared following the method outlined by Cody and Smith (1997).

3. Results and discussion

3.1. Weather

Burns and Dubois provide two different expressions of the sagebrush steppe, resulting in part from climatic differences. Average annual temperature and precipitation are similar at Burns and Dubois; however, there are important differences in monthly average temperature and precipitation between Oregon and Idaho (Fig. 1). December, January, and February are colder in Dubois than Burns, while summer temperatures are comparable. These cooler temperatures in February and March typically delay the start of growth at Dubois compared to Burns.

Precipitation at Burns exceeds that at Dubois from November through March. Also, more precipitation is received as rain at Burns than Dubois (NOAA, 1999a; NOAA, 1999b), which influences early season soil water content. Later, in the May–August period, average rainfall at Dubois exceeds that at Burns, which can extend the summer growth period at Dubois.
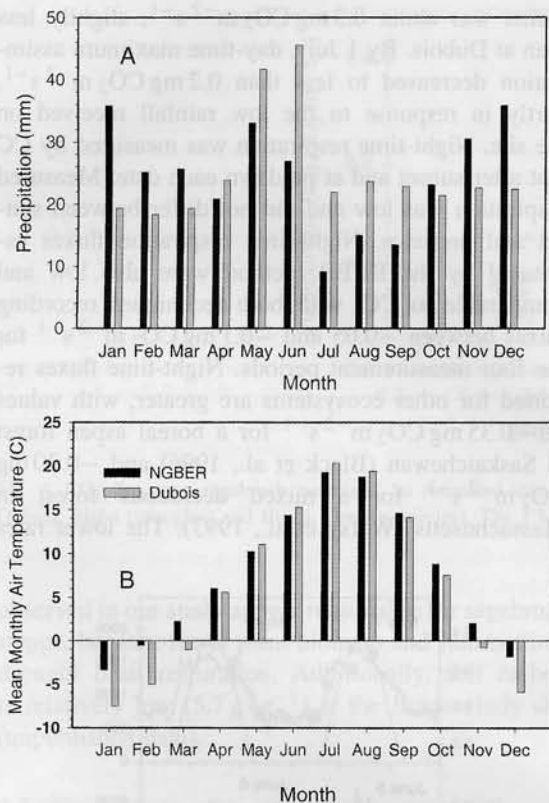
Fig. 1. Long-term monthly precipitation and temperature averages for the US Sheep Experiment Station, Dubois, Idaho, and the Northern Great Basin Experimental Range (Burns), Burns, Oregon. Panel A illustrates the precipitation differences between the two locations, and panel B contrasts the monthly average air temperatures at each site.
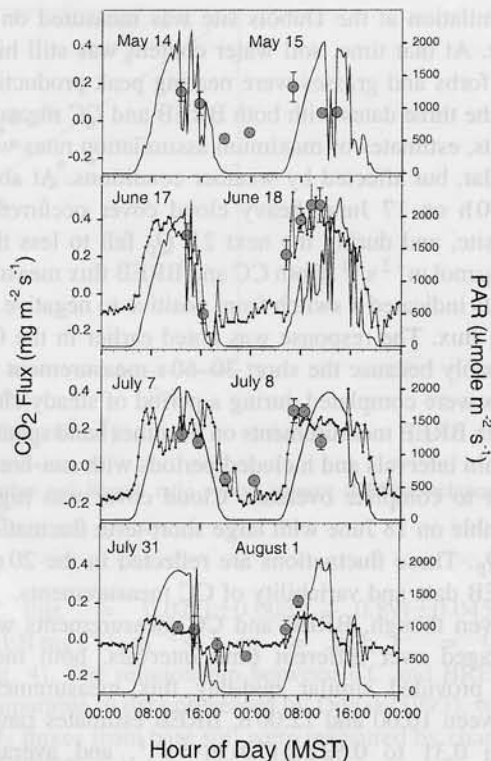

Fig. 2. Estimates of CO_2 flux on sagebrush steppe rangeland at the US Sheep Experiment Station, Dubois, Idaho, on four dates in 1997. Fluxes toward the surface are positive, indicating sequestration. Fluxes were measured using closed chambers (dots) and Bowen ratio energy balance (dotted lines). Solar radiation (lines) for each day is also presented. Data for May are incomplete, because Bowen ratio equipment failed.

Weather at both sites was close to the long-term average. August was the hottest sampling period at both sites, with mid-day air temperature above 33 and 25°C at Burns and Dubois, respectively. As temperatures increased from May to August, soil water decreased during the study. May, June, July, and August gravimetric soil moisture (0–8 cm) was 0.24, 0.23, 0.08, and 0.19 $m^3\,m^{-3}$ at Dubois, and 0.18, 0.12, 0.08, and 0.09 $m^3\,m^{-3}$ at Burns, respectively.

3.2. Dubois flux measurements

Estimates of 20 min CO_2 fluxes were obtained during four monthly 24 h periods for CC and BREB, except in May, when equipment failure precluded

BREB measurements (Fig. 2). Clouds periodically reduced photosynthetic photon flux density (Q_p) at the Dubois site during the May, June, and August sampling dates. On May 15, broken cloud cover was persistent and reduced Q_p to less than 250 μmol $m^{-2}\,s^{-1}$ at 12.20 h MST. During the remainder of the day, broken cloud cover periodically reduced Q_p. Soils were near field capacity in May, but temperatures were still cold, and grass and forb growth remained in the vegetative stage of growth. At that time, maximum assimilation measured by CC was about 0.2 mg $m^{-2}\,s^{-1}$ in full sun. Variability of CC estimates of assimilation was greatest in May and June while plants were actively growing, and was probably influenced by both intermittent cloud cover and variation in leaf area among plots. Maximum

assimilation at the Dubois site was measured on 18 June. At that time, soil water content was still high, and forbs and grasses were nearing peak production. On the three dates with both BREB and CC measurements, estimates of maximum assimilation rates were similar, but affected by weather conditions. At about 16.00 h on 17 June, heavy cloud cover occurred at the site, and during the next 2 h Q_p fell to less than 200 μmol m^{-2} s^{-1}. Both CC and BREB flux measurements indicated a switch from positive to negative net CO_2 flux. The response was noted earlier in the CC, probably because the short 30–60 s measurement periods were completed during a period of steady cloud cover. BREB measurements on the other hand spanned 20 min intervals and included periods with sun-breaks prior to complete overcast. Cloud cover was highly variable on 18 June with large short-term fluctuations in Q_p. These fluctuations are reflected in the 20 min BREB data and variability of CC measurements.

Even though, BREB and CC measurements were averaged over different time intervals, both methods provided similar mid-day flux measurements. Between 10.00 and 12.00 h, BREB estimates ranged from 0.31 to 0.52 mg CO_2 m^{-2} s^{-1}, and averaged about 0.46 $\pm$ 0.03 mg CO_2 m^{-2} s^{-1}. CC measurements taken during that same period indicated an uptake of about 0.48 $\pm$ 0.13 mg CO_2 m^{-2} s^{-1} with a range of 0.25–0.69 mg CO_2 m^{-2} s^{-1}. As the season progressed, both BREB and CC flux estimates decreased and followed similar trends.

CC measurements obtained at midnight 7 July and 31 July were compared to BREB values. In early July, night-time CC and BREB flux estimates were -0.07 ± 0.03 and -0.14 ± 0.03 mg CO_2 m^{-2} s^{-1}, respectively, while later in the month CC and BREB estimates were -0.08 ± 0.04 and -0.02 ± 0.05 mg CO_2 m^{-2} s^{-1}, respectively.

3.2.1. Burns flux measurements

Seasonal CO_2 flux patterns at the Oregon site were similar to those observed in Idaho with maximum CO_2 uptake observed in May and June. At Burns, Oregon cloud cover also affected Q_p as clouds typically increased during afternoon hours in June, July, and August. At both locations, mid-day vapor pressure deficit ranged from 0.8 to 1.2 kPa during the four sampling periods. Soil moisture was adequate, and soils were warm. Maximum assimilation rate measured at

Burns was about 0.3 mg CO_2 m^{-2} s^{-1}, slightly less than at Dubois. By 1 July, day-time maximum assimilation decreased to less than 0.2 mg CO_2 m^{-2} s^{-1}, partly in response to the low rainfall received on the site. Night-time respiration was measured by CC just after sunset and at predawn each date. Measured respiration was low and did not differ between sunset and predawn. Night-time respiration fluxes estimated by the BREB method were also low and comparable to CC, with both techniques recording fluxes between -0.05 and -0.1 mg CO_2 m^{-2} s^{-1} for the four measurement periods. Night-time fluxes reported for other ecosystems are greater, with values of -0.35 mg CO_2 m^{-2} s^{-1} for a boreal aspen forest in Saskatchewan (Black et al., 1996) and -0.20 mg CO_2 m^{-2} s^{-1} for a mixed deciduous forest in Massachusetts (Wofsy et al., 1993). The lower rates
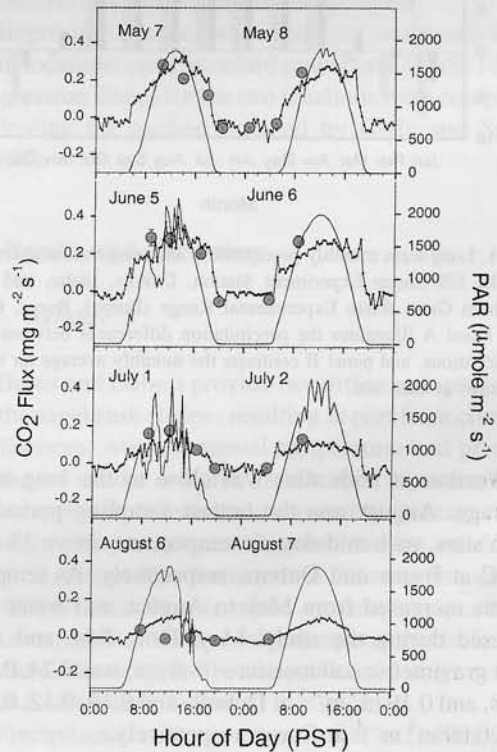

Fig. 3. Estimates of CO_2 flux on sagebrush steppe rangeland at the Northern Great Basin Experimental Range, Oregon, on four dates in 1997. Fluxes were measured using closed chambers (dots) and Bowen ratio energy balance (dotted lines). Solar radiation (lines) for each day is also presented. Fluxes toward the surface are positive, indicating sequestration.
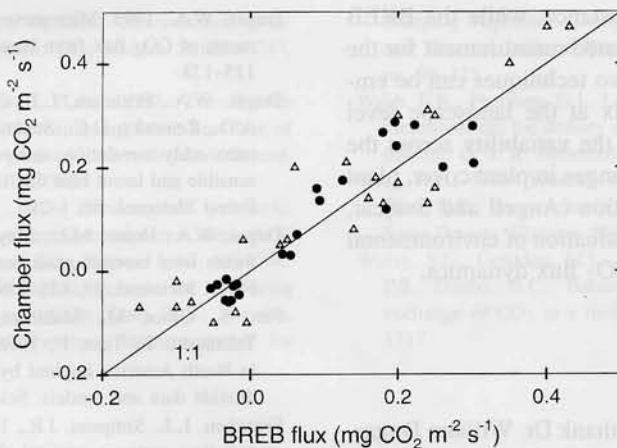
Fig. 4. CO_2 flux over sagebrush rangeland, as estimated using closed chamber and Bowen ratio energy balance (BREB) techniques at Dubois, Idaho (triangles) and Burns, Oregon (circles). The 1:1 line is shown.

observed in our study appear reasonable for sagebrush steppe, because lower plant biomass and summertime drought limit respiration. Additionally, soil carbon is relatively low ($5.7 \, \text{g} \, \text{kg}^{-1}$) at the Burns study site (unpublished data).

3.3. Comparison of canopy chambers and CO_2 Bowen ratio systems

CO_2 fluxes obtained with CC compared well with BREB estimates at both Idaho and Oregon locations. The daily patterns of CO_2 flux were generally similar (Figs. 2 and 3), as were daily maximums and night-time minimums. The greatest difference between the BREB and chamber techniques occurred on 6 August at the Oregon site. That day was quite hot ($45°C$) and surface soil moisture (to $0.1 \, \text{m}$) was low ($0.09 \, \text{m}^3 \, \text{m}^{-3}$). Chamber effects may have increased plant stress enough to initiate stomatal closure. This response was not observed at Dubois, where conditions were less stressful and soil moisture remained above $0.15 \, \text{m}^3 \, \text{m}^{-3}$ most of the season.

Regression analysis indicated that the regression lines for CC versus BREB did not differ between Burns and Dubois ($P < 0.05$), and error variances were equal. We then combined the data across locations. CC was positively correlated with BREB ($R = 0.82$; $P < 0.01$; $n = 190$), and the regression model for pooled data was as follows:

CC flux $= 0.021(\pm 0.008) + 0.89(\pm 0.045) \times$ BREB $\text{mg} \, CO_2 \, \text{m}^{-2} \, \text{s}^{-1}$ ($n = 190$; $r^2 = 0.68$) (Fig. 4). The relationship between CC and BREB is comparable to data presented by Dugas (1993), where CO_2 fluxes from bare soil were measured by chamber and BREB techniques.

4. Conclusions

The BREB and CC techniques employed in this study provided us with independent estimates of CO_2 flux on two widely separated sagebrush steppe ecosystems. Results indicated that CO_2 flux estimates from the two techniques were similar under most conditions. Both of these methods have been compared in more productive ecosystems, however, we are not aware of any documented comparisons in semi-arid ecosystems that have lower CO_2 flux rates.

Because the techniques generally gave comparable results, both methods can be effectively used in combination to address a variety of research questions. During extremely stressful periods, caution is advised because CC may provide unreliable data. The strength of the BREB method is that it provides large-scale, continuous measurements of CO_2 flux, while the CC technique can be used to obtain point measurements across several locations within the treatment area. CC measurements can provide valuable information about

fluxes related to LAI, for instance, while the BREB technique provides an integrated measurement for the entire site. Together these two techniques can be employed to estimate CO_2 flux at the landscape level and also gain knowledge of the variability across the landscape, as affected by changes in plant cover, plant density, or species composition (Angell and Svejcar, 1999). This will allow the evaluation of environmental or management effects on CO_2 flux dynamics.

Acknowledgements

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