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Bowen ratio versus canopy chamber CO_2 fluxes on sagebrush rangeland

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Abstract

Because of their expansiveness, sagebrush (*Artemisia* spp.)-steppe rangelands could contribute significantly to the global carbon budget. However, it is important to determine if there are differences between methods for determining CO_2 fluxes on these rangelands. The objective of this study was to compare the Bowen ratio-energy balance and canopy chamber techniques for measuring CO_2 fluxes in a sagebrush-steppe ecosystem. A Bowen ratio-energy balance system was installed at a sagebrush-steppe site near Dubois, Ida., U.S.A to continuously measure the vertical gradients of air temperature, water vapor, and CO_2 concentration in conjunction with associated micrometeorological characteristics. The canopy chamber technique, which employed a 1-m^2 (1,020 liter) clear plexiglass/plastic film chamber in combination with a portable gas exchange system, was used periodically during May through August across 4 years (1996–1999) to obtain instantaneous measurements of CO_2 fluxes across 3 replicate blocks during a 2-min. measurement period. For the same measurement dates and times across the 4 years of study, CO_2 fluxes ranged from –0.22 to 0.55 mg m^{-2} sec^{-1} for the Bowen ratio-energy balance technique and from –0.18 to 0.48 mg m^{-2} sec^{-1} for the canopy chamber technique. Estimates of CO_2 fluxes by the 2 techniques were not statistically different ($P > 0.05$) for the early (May) and mid-season (June to mid-July) portions of the growing season; however, fluxes measured by the 2 techniques were significantly different ($P < 0.05$) for the late-season period (late-July to late-August). Despite this difference during the hot-dry, late-season period, flux estimates from the 2 techniques were significantly and positively correlated during the early ($r^2 = 0.71$), mid- ($r^2 = 0.88$), and late- ($r^2 = 0.72$) season periods. Thus, both techniques showed similar patterns of CO_2 fluxes at our sagebrush-steppe study site across 4 years of study, although caution should be used when the canopy chamber technique is used during hot, dry conditions.

Key Words: *Artemisia* spp., carbon dioxide fluxes, CO_2 exchange, Bowen ratio, canopy chambers, closed chambers, micrometeorology, rangeland

Resumen

Debido a su expansión, las pastizales de estepa de "Sagebrush" (*Artemisia* spp.) Pudieran contribuir significativamente al balance global del carbón. Sin embargo, es importante determinar si hay diferencias entre métodos para determinar los flujos de CO_2 en estos pastizales. El objetivo de este estudio fue comparar el balance de energía de la relación Bowen y la técnica de cámara de copa para medir los flujos de CO_2 en un ecosistema de estepa de "Sagebrush". Un sistema de balance de energía de la relación Bowen se instaló en un sito de estepa de "Sagebrush" cerca de Dubois, Ida. E.U.A. para medir continuamente los gradientes verticales de temperatura del aire, vapor de agua y concentración de CO_2, en conjunto con las característica micrometerológicas asociadas. La técnica de la cámara de copa, la cual empleó una película plástica transparente de plexiglás de 1m^2 (1,020 litros) en combinación con un sistema portátil de intercambio de gases, se utilizó periódicamente de Mayo a Agosto durante 4 años (1996–1999) para obtener mediciones instantáneas de los flujos de CO_2 a través de 3 bloques de repetición durante un periodo de medición de 2 minutos. Para las mismas fechas y tiempos de medición a través de los 4 años del estudio, los flujos de CO_2 variaron de –0.22 to 0.55 mg m^{-2} sec^{-1} para la técnica de balance de energía de la relación Bowen y de –0.18 to 0.48 mg m^{-2} sec^{-1} para la técnica de la cámara de copa. Las estimaciones del flujo de CO_2 de las 2 técnicas no fueron estadísticamente diferentes ($P > 0.05$) para las porciones de inicios (Mayo) y mediados (Junio a Julio) de la estación de crecimiento; sin embargo, los flujos medidos por las 2 técnicas fueron significativamente diferentes ($P < 0.05$) a fines de la estación de crecimiento (fines de Julio a fines de Agosto). A pesar de la diferencia del flujo durante el período caliente y seco (que es a fines de la estación de crecimiento), las estimaciones obtenidas por las dos técnica estuvieron significativa y positivamente correlacionados durante los periodos de inicio ($r^2 = 0.71$), mediados ($r^2 = 0.88$) y fines ($r^2 = 0.72$) de la estación. A lo largo de los 4 años de estudio, ambas técnicas mostraron patrones similares de flujo de CO2 en nuestro sitio de estudio de la estepa de "Sagebrush", aunque se debe poner cuidado cuando se use la técnica de cámara de copa durante condiciones clientes y secas.

Estimates of C fluxes in ecosystems can be obtained by various methods. Measurement of C stocks can provide estimates of C fluxes across decades or longer (Bliss et al. 1995, Gilmanov and Oechel 1995, Fallon et al. 1998). For shorter time frames, such as within a day or across a growing season, C fluxes must be esti-

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mated with micrometerological techniques such as the eddy covariance and Bowen ratio-energy balance techniques (Rosenberg et al. 1983, Frank and Dugas 2001, Sims and Bradford 2001), or canopy chamber methods (Vourlitis et al. 1993, Angell and Svejcar 1999). A detailed description of micrometeorological techniques and the theories behind them can be found in Moncrieff et al. (1997) and for canopy chamber methods are reported in Reicosky (1990).

The eddy covariance technique is a direct method of determining CO_2 fluxes that measures vertical wind speed, wind direction, and CO_2 concentration of air moving past a sampling point. The eddy covariance method, however, requires expensive and electronically sophisticated equipment, complex data processing and quality assurance procedures, and until recently was not available commercially. In addition, net radiation, sensible heat flux, latent heat flux, and soil heat flux should be determined concurrently with the eddy covariance measurements to correct for lack of energy balance closure (Twine et al. 2000).

The Bowen ratio-energy balance technique is an indirect method of measuring CO_2 fluxes that quantifies the rate of diffusion down a concentration gradient. The Bowen ratio-energy balance method uses relatively simple instrumentation, but the technique has limitations in canopies with small gradients (Raupach 1988). The Bowen ratio-energy balance method also is difficult to apply during periods when net radiation is small, such as at sunrise and sunset. Although eddy covariance and Bowen ratio-energy balance techniques have shown acceptable agreement in semiarid environments (Unland et al. 1996), reliable surface energy fluxes were easier to determine with the Bowen ratio-energy balance method, but the eddy covariance method provided greater accuracy for short time periods. Both eddy covariance and Bowen ratio-energy balance techniques require relatively large areas and considerable labor for calibration and maintenance.

Techniques using canopy chambers are easy to use, equipment for the technique is relatively inexpensive (if a portable infrared gas analyzer is available), and they are adaptable to a wide range of field conditions (e.g., Reicosky 1990); however, canopy chamber methods are labor intensive, particularly for large-sized chambers. Costs associated with labor for the canopy chamber method can be particularly high if frequent measurements are required to provide detailed characterizations of CO_2 fluxes. In addition, high solar radiation can markedly increase air temperature inside chambers compared to ambient conditions unless air conditioning equipment is added to the chambers. As a result, without cumbersome air conditioning, the canopy chamber technique can only be used for brief exposure periods of several minutes so that canopy chamber determinations represent instantaneous flux values. Because canopy chambers are relatively easy to transport, experiments can be more easily replicated compared to experiments that use eddy covariance and Bowen ratio-energy balance techniques. A more detailed discussion of the particular advantages and disadvantages of the various techniques for measuring CO_2 fluxes is presented in Reicosky (1990) and Moncrieff et al. (1997).

Although rangelands occupy about 50% of the total world land surface area (Holechek et al. 1998), only limited data are available concerning CO_2 fluxes in rangeland ecosystems. The USDA-ARS Rangeland CO_2 Flux Network (Svejcar et al. 1997) was established to quantify CO_2 fluxes on rangelands of the western U.S.A. As part of this effort, Angell et al. (2001) found generally good agreement between Bowen ratio-energy balance and canopy chamber measurement techniques at 2 sites dominated by sagebrush (*Artemisia* spp.); however, these measurements were conducted during only 1 growing season. In an effort to evaluate the 2 measurement techniques across a broader range of environmental conditions and to test their agreement across multiple growing seasons, we designed this current study to compare CO_2 fluxes measured with canopy chamber and Bowen ratio-energy balance techniques across 4 growing seasons in a sagebrush-steppe ecosystem in Idaho.

Materials and Methods

Study Site

The field site is at the U.S. Sheep Experiment Station (44° 16' N, 112° 08' W), which is located 10 km north of Dubois on the Upper Snake River Plain of northeastern Idaho. The site is situated in the northeastern portion of the sagebrush-steppe ecosystem (West 1983) at an elevation of about 1,700 m. The dominant shrub, grass, and forb on the study site are 3-tipped sagebrush (*Artemisia tripartita* Rydb.), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A Löve), and arrowleaf balsamroot (*Balsamorhiza saggitata* (Pursh) Nutt.). Other important shrubs include big sagebrush (*Artemisia tridentata* Nutt.), green rabbitbrush (*Chrysothamnus viscidiflorus* (Hook.) Nutt.), and grey horsebrush (*Tetradymia canescens* DC.). Other important grasses at the study site include needle-and-thread grass (*Stipa comata* Trin. & Rupr.), Sandberg's bluegrass (*Poa secunda* J. Presl), and junegrass (*Koeleria pyramidata* (Lam.) P. Beauv.). Other common forbs include yarrow (*Achillea millefolium* L.), tapertip hawksbeard (*Crepis acuminata* Nutt.), milkvetches (*Astragalus* spp.), and longleaf phlox (*Phlox longifolia* L.).

The climate at the site is semiarid with cold winters and warm summers. Mean annual precipitation for the area during a 64-year period was 325 mm, which included 70 cm of snow with a mean annual temperature of 6° C (Anonymous 1993). Temperatures range from 38° C in summer to –34° C in winter with the normal frost-free period of 70 to 90 days (Blaisdell 1958). Soils at the study site are loamy and derived from wind-blown loess, residuum, or alluvium (National Resource Conservation Service [NRCS] 1995). Soils at the experiment station are composed of 3 mollisols on slopes ranging from 0–12%. With increasing depth and degree of development, soils are classified as Typic Calcixerols (Anatolian series), Pachic Haploxerolls (Maremma series), and Pachic Argixerols (Akbash series).

The sagebrush-steppe ecosystem at the U.S. Sheep Experiment Station has been a primary source of forage for sheep in both spring and fall, and the Station has been the site for long-term grazing studies initiated in 1924 (Laycock 1967). In 1995, a relatively undisturbed area (400 x 400 m) was fenced to exclude grazing, and CO_2 flux measurements were initiated. The Bowen ratio-energy balance instrumentation was installed near the center of this enclosure, and 1-m^2 plots for canopy chamber measurements were located about 150 m north of the Bowen ratio-energy balance system. Thus, the site had uniform vegetation and allowed at least 150 m of fetch (upwind distance) from a relatively flat surface from all directions for the Bowen ratio-energy balance method.

Bowen Ratio-Energy Balance Technique

A Bowen ratio-energy balance system was used to obtain continuous measurements of CO_2 fluxes at the study site during the growing seasons of 1996, 1997, 1998, and 1999. The theory and operation of the Bowen ratio-energy balance system (Model 023/CO_2 Bowen Ratio, Campbell Scientific Inc., Logan, Utah) were described in detail by Dugas (1993) and Dugas et al. (1999). Briefly, CO_2 and water vapor concentrations were measured with an infrared gas analyzer (Model LI-6262, Li-Cor Inc., Lincoln, Nebr.) in the differential mode. Air samples from 2 heights (0.8 and 1.8 m above the soil surface) were drawn and routed to the infrared gas analyzer, which measured the concentration gradients between the 2 heights. Height of the vegetation, including grasses, forbs, and sagebrush canopies, ranged from 0.1 to 0.5 m. Thus, the 2 air sampling heights were at least 0.3 and 1.3 m above the vegetation surface, which is required to ensure adequate distance above the plant canopy for determining CO_2 and water vapor gradients.

A low-power pump (Model TD-3LSC, Brailsford and Co., Inc., Rye, N.Y.) aspirated the air through 1-μm teflon filters (Model Acro 50, Gelman Sciences, Ann Arbor, Michigan), which prevented dust and liquid water contamination in the air tubes and infrared gas analyzer. A solenoid valve (Model 236-102B, Numatics Inc., Highland, Mich.) was programmed to reverse the air drawn through the infrared gas analyzer every 2 min. Another solenoid valve was programmed to control the air stream at the beginning of each hour; thus, the infrared gas analyzer sample cell was scrubbed to determine absolute concentrations of CO_2 and water vapor. The air temperature gradients at the 2 heights were simultaneously measured with fine-wire, chromel-constantan thermocouples. The CO_2, water vapor, and temperature gradients were measured every second, and the average gradients were calculated and stored every 20 min. with a datalogger and storage module (Models 21X and SM192, Campbell Scientific Inc.).

Fluxes of CO_2, water vapor, and energy were calculated using these 20-min. averages. Bowen ratios were calculated from temperature and water vapor gradients. Sensible heat flux was calculated from the Bowen ratio, net radiation (Model Q*7.1 net radiometer, REBS, Seattle, Wash.), soil heat flux (Model HFT3, REBS), and soil temperature (Model TCAV, Campbell Scientific Inc.) measured above the soil heat flux plates. The eddy diffusivity, which was assumed equal for heat, water vapor, and CO_2, was calculated from sensible heat flux and temperature gradients. The eddy diffusivity may not be valid when the direction of sensible/latent heat flux is opposite the sign of temperature/water vapor gradient, or when the Bowen ratio approaches –1.0 (Ohmura 1982). Under such conditions, the eddy diffusivity was calculated using wind speed, atmospheric stability, and canopy height (Dugas et al. 1999). This alternate method for calculating eddy diffusivity was applied at sunset, sunrise, and sometimes at night when fluxes and gradients were small; these instances occurred for about 14% of the 20-min. averages. The CO_2 flux was calculated as the product of the eddy diffusivity and CO_2 gradient, and corrected for vapor density gradients at the 2 heights (e.g., Webb et al. 1980). Fine-wire thermocouple measurements indicated that temperatures were the same for the air entering the sample and reference chambers of the infrared gas analyzer so corrections for temperature differences were not applied (Angell et al. 2001). Means for CO_2 fluxes for the Bowen ratio-energy balance method were averaged from 3 to 6, 20-min. measurements that coincided with the time periods when the canopy chamber measurements were obtained.

Canopy Chamber Technique

A chamber, which had a volume of 1,020 liters and covered a 1-m^2 area, was used to obtain instantaneous measurements of CO_2 fluxes at select times during the growing seasons of 1996, 1998, and 1999. We used an identical chamber design and measurement protocols as described by Angell and Svejcar (1999). Three, 1-m^2 plots were permanently identified by pressing 1-m^2 angle-iron frame into the soil surface at the beginning of the 1995 growing season. Each plot included a 3-tipped sagebrush plant canopy, plus associated grasses and forbs within the 1-m^2 frame. A canopy chamber measurement was initiated by placing the chamber on top of the frame. A layer of 0.6-mm thick, closed-cell foam mounted under the canopy chamber provided an air-tight seal between the canopy chamber and the plot frame. Circulation and mixing of air in this closed gas exchange system was achieved by a generator-powered fan (rated at 11 m^3 min^{-1}), which routed the trapped air from duct openings near the ground surface to duct openings near the top of the chamber. The canopy chamber measurements were conducted at least 150 m away from the Bowen ratio-energy balance system. A portable generator was used to operate the mixing fan within the canopy chamber, and depending on the wind direction for the particular measurement day, the generator in conjunction with a long extension cord was positioned in a downwind direction from the Bowen ratio system. This minimized the effects that periodic CO_2 emissions from the generator had on the Bowen ratio-energy balance measurements. Air mixing and circulation were allowed for at least 15 seconds before actual canopy chamber measurements were initiated. The canopy chamber was interfaced with a portable photosynthesis system (Model LI-6200; Li-Cor Inc., Lincoln, Nebr.), which was programmed to obtain measurements every second. A total of about 2 min. was required to complete a canopy chamber measurement. Means of CO_2 fluxes (± 1 SE) for the canopy chamber method were obtained from 3, 1-m^2 plots.

Statistical Procedures

Net ecosystem CO_2 fluxes measured with the canopy chamber and Bowen ratio-energy balance techniques were calculated on various dates during the 4 growing seasons (1996–1999). Following the tradition used in ecophysiology, positive CO_2 flux values indicated a net positive flux from the atmosphere to the earth's surface (photosynthesis exceeds ecosystem respiration), while negative values indicated release of CO_2 from the earth to the atmosphere (ecosystem respiration exceeds photosynthesis). Data for 1997 were published in Angell et al. (2001) to compare CO_2 fluxes across locations, but are also included here to provide a complete analysis of all available data from Dubois for comparing the 2 measurement methods. As a result, a total of 16 measurement periods were available for direct comparisons between the 2 techniques; the canopy chamber measurements were not obtained on 20–21 July and 23–24 August in 1996, 23–24 August in 1997, and 24–25 May in 1998. Data were grouped into 3 time periods: early (14 to 25 May), mid- (15 June to 21 July), and late- (26 July to 25 August) seasons. Mean CO_2 fluxes (± 1 SE) for the canopy chamber technique were calculated from 3, 1-m^2 plots, while the CO_2 fluxes for the Bowen ratio-energy balance technique were calculated from CO_2 gradients and eddy diffusivities averaged across 3 to 6, 20-min. values for the time period required to conduct the canopy chamber measurements. Paired mean comparisons between the 2 techniques were conducted with PROC TTEST (SAS System). The paired comparisons also were analyzed for normal distribution with PROC UNIVARIATE (SAS System) using the Shapiro-Wilk test. The REG procedure (SAS System) was used to test whether the combined slopes and intercepts of the regression lines were statistically different from the 1:1 relationship for the early, mid-, and late-season periods.

Results and Discussion

Values of CO_2 fluxes were obtained by the canopy chamber and Bowen ratio-energy balance techniques during late-May to late-August across 4 growing seasons (Fig. 1). The 24-hour patterns for both canopy chamber and Bowen ratio-energy balance measurements of CO_2 fluxes were characterized by uptake of CO_2 (positive values) during sunrise to sunset and efflux of CO_2 (negative values) during the nighttime period. Variations in CO_2 fluxes within a day largely depend on photosynthetic photon flux density (Frank and Dugas 2001, Sims and Bradford 2001), whereas the dynamics of nighttime CO_2 efflux are usually dominated by belowground respiration (Kim et al. 1992), which generally depends on soil temperature and water content (Dugas 1993, Wagai et al. 1998, Mielnick and Dugas 2000). Across 4 growing seasons of measurement, values of CO_2 fluxes determined with the canopy chamber ranged from a maximum CO_2 efflux of –0.18 mg m^{-2} sec^{-1} on 15 June 1999 to a maximum CO_2 uptake of 0.48 mg m^{-2} sec^{-1} on 16 June 1999, which was near the seasonal peak of vegetation activity. Values of CO_2 fluxes measured with the Bowen ratio-energy balance technique for the same measurement dates and times across the 4 years of study ranged from a nighttime maximum CO_2 efflux of –0.22 mg m^{-2} sec^{-1} to a daytime maximum CO_2 uptake of 0.55 mg m^{-2} sec^{-1}.

Differences between CO_2 fluxes measured with the Bowen ratio-energy balance and canopy chamber techniques were normally distributed ($P > 0.05$), as indicated by the Shapiro-Wilk test ($P > 0.05$, Table 1), with the paired comparisons for the late-season period nearly significant ($P = 0.06$). As indicated by paired t-test comparisons, values of CO_2 fluxes obtained by the 2 techniques were not statistically different ($P > 0.05$) for the early and mid-season portions of the growing season. However, CO_2 fluxes measured by the 2 methods differed statistically ($P = 0.01$) for the late-season period, with the canopy chamber method showing lower CO_2 fluxes than the Bowen ratio-energy balance method. A statistical test for evaluating whether combined slopes and intercepts for the regression line were different from

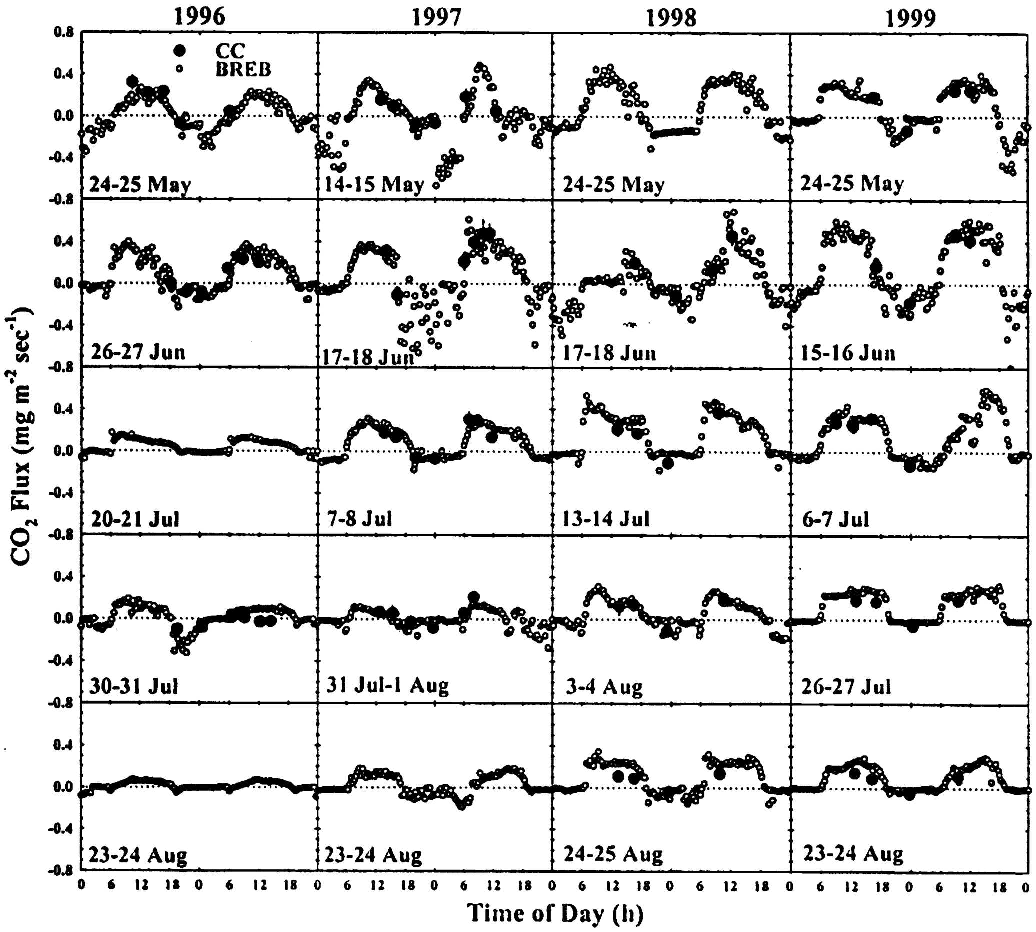

Fig. 1. Net ecosystem CO_2 fluxes in a sagebrush-steppe ecosystem measured with the canopy chamber (CC) and Bowen ratio-energy balance (BREB) techniques on various dates during 4 growing seasons. The average CO_2 fluxes (± 1 SE) for the canopy chamber technique were obtained from 3, 1-m^2 plots, while the CO_2 fluxes for the Bowen ratio-energy balance technique were calculated from CO_2 gradients and eddy diffusivities averaged every 20 min. The canopy chamber measurements were not obtained on 20–21 July and 23–24 August in 1996, 23–24 August in 1997, and 24–25 May in 1998. Positive CO_2 flux values indicate a net positive flux from the atmosphere to the earth's surface (photosynthesis exceeds ecosystem respiration), while negative values indicate release of CO_2 from the earth to the atmosphere (ecosystem respiration exceeds photosynthesis).

Table 1. Statistical analyses with the PROC TTEST (SAS System) that utilized the paired comparisons of means (using data shown in Fig. 2) of net ecosystem CO_2 flux measured with the Bowen ratio-energy balance (BREB) and canopy chamber (CC) techniques (n-number of observations; df-degrees of freedom). The paired comparisons (Difference = BR CO_2 Flux–CC CO_2 Flux) were analyzed for normal distribution using PROC UNIVARIATE (SAS System). Data across the 4 growing seasons of measurements (1996–1999) were grouped into 3 time periods: early (14 to 25 May), mid (15 June to 21 July), and late (26 July to 25 August). Positive CO_2 flux values indicate a net positive flux from the atmosphere to the earth's surface (photosynthesis exceeds ecosystem respiration), while negative values indicate release of CO_2 from the earth to the atmosphere (ecosystem respiration exceeds photosynthesis).

		Statistics				
Season	n	Variable	Mean	Std Err	Minimum	Maximum
		(mg CO_2 m^{-2} sec^{-1})				
Early	15	BREB CO_2 Flux	0.073	0.042	-0.248	0.312
		CC CO_2 Flux	0.108	0.037	-0.133	0.320
		Difference	-0.035	0.022	-0.181	0.065
Mid	35	BREB CO_2 Flux	0.182	0.035	-0.218	0.551
		CC CO_2 Flux	0.172	0.034	-0.176	0.478
		Difference	0.010	0.012	-0.161	0.131
Late	28	BREB CO_2 Flux	0.090	0.024	-0.184	0.267
		CC CO_2 Flux	0.054	0.018	-0.112	0.209
		Difference	0.036	0.013	-0.086	0.127
Paired Comparisons (t-tests for Difference)						
Season	df	t Value	P > |t|			
Early	14	-1.53	0.15			
Mid	34	0.80	0.43			
Late	27	2.84	0.01			
Test (Shapiro-Wilk) for Normal Distribution						
Season	n	W Value	P < W			
Early	15	0.90	0.10			
Mid	35	0.96	0.25			
Late	28	0.93	0.06			

the 1:1 relationship indicated that the regression lines for the early and late-season periods were not statistically different ($P < 0.05$) from the 1:1 line. The slopes and intercepts for the regression line for the late-season period, however, were statistically different ($P > 0.05$) from the 1:1 relationship.

A similar difference during late summer was observed by Angell et al. (2001) at their Oregon study site where they found lower CO_2 fluxes with the canopy chamber technique compared to the Bowen ratio-energy balance method, which they attributed to possible chamber effects. Because of the mixing required within canopy chambers, air turbulence inside canopy chambers is typically greater than ambient conditions outside the chamber, which may alter the gradients of temperature, CO_2, and water vapor within enclosed chamber canopies compared to ambient canopy conditions (Held et al. 1990). In our study, we initially thought that air temperatures in the canopy chamber may have been higher than those in the ambient environment so that resulting vapor pressure deficits might have been greater inside the canopy chamber, resulting in greater stomatal closure and subsequently lower CO_2 fluxes for plants inside than outside the canopy chamber. However, examination of our data showed that calculated vapor pressure deficits were the same inside and outside the canopy chamber. Other factors that could contribute to these late-season differences include differences in spatial scales of the 2 techniques with the Bowen ratio-energy balance technique integrating measurements across a much larger area (and possibly areas subjected to less water stress) than the 1-m^2 canopy chambers. Despite these differences during the hot, dry late-season period, CO_2 fluxes measured by the 2 techniques in our study were significantly ($P < 0.05$) and positively correlated for the early ($r^2 = 0.71$, n = 15), mid- ($r^2 = 0.88$, n = 35), and late-season ($r^2 = 0.72$, n = 28) periods (Fig. 2).

Given the wide range of environmental conditions across our measurement dates and 4 growing seasons, the spatial heterogeneity present in sagebrush-steppe ecosystems, and the inherent differences in the 2 CO_2 techniques, r^2 values ranging from 0.71 to 0.88 between the 2 methods are probably quite reasonable and acceptable. Although differences between the canopy chamber and Bowen ratio-energy balance methods were observed during the late-season period, our results showed that CO_2 fluxes obtained with the 2 techniques similarly characterized the patterns of daily and seasonal CO_2 fluxes in the sagebrush-steppe ecosystem at Dubois. The canopy chamber and Bowen ratio-energy balance techniques have been compared in field crops and more mesic systems (e.g., Held et al. 1990), but comparisons between these 2 techniques are limited in arid and semiarid environments (e.g., Angell et al. 2001). As a result, generalizations cannot be made concerning extrapolations to other rangeland ecosystems. The results of our study support the findings of Angell et al. (2001), and provide comprehensive data across multiple growing seasons and a greater range of environmental conditions.

Similar to the eddy covariance technique, the Bowen ratio-energy balance method is advantageous because it can be used to provide continuous measurements of CO_2 fluxes. In addition, these techniques can detect rapid, short-term changes in CO_2 fluxes, which are difficult to observe with the canopy chamber method because frequency of measurements is limited by available human resources. The initial cost of a Bowen ratio-energy balance system and an eddy covariance system, however, exceeds $25,000, whereas the canopy chamber method is relatively inexpensive to set up (less than $1,500), if a portable photosynthesis system (about $14,000) is available to the project. Bowen ratio-energy balance systems and eddy covariance systems require large, relatively uniform areas which can make locating treatments difficult. In addition, the canopy chamber technique can be used in conjunction with soil respiration chambers (Norman et al. 1992) to partition CO_2 fluxes into above and belowground components, and to obtain estimates of spatial variability across the landscape. The canopy chamber method, however, is labor-intensive and does not provide continuous measurements of CO_2 fluxes. Frequent sampling with the canopy chamber to assess CO_2 fluxes requires considerable labor to transport the canopy chamber from plot to plot and obtain the required measurements.

Results from our study indicated that the canopy chamber and Bowen ratio-energy balance technique gave similar results; however, differences were observed during the hot, dry summer period. Despite differences during this period, data values for the 2 techniques were still positively correlated ($r^2 = 0.72$) at this period and the other 2 periods ($r^2 = 0.71$ and 0.88). As a result, depending on the specific experimental objectives and resources available for the particular project, data from our

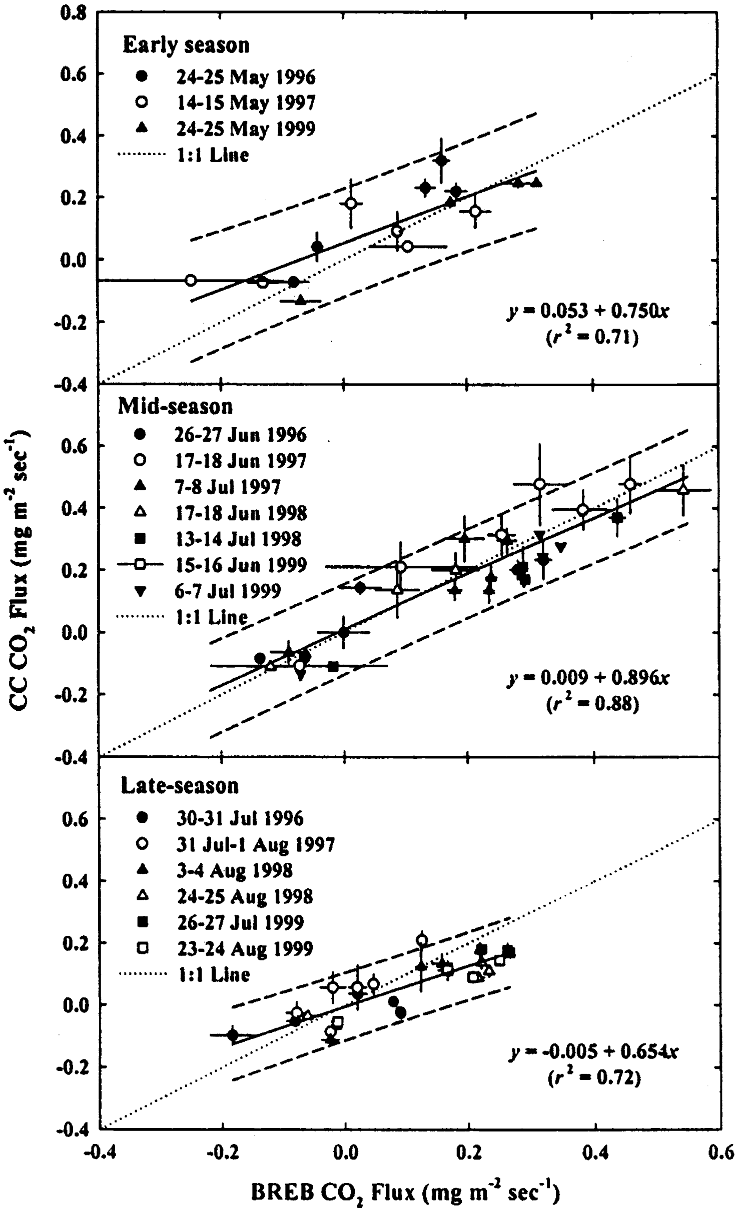

Fig. 2. Net ecosystem CO_2 fluxes measured with a canopy chamber (CC) technique compared to those measured with a Bowen ratio-energy balance (BREB) technique for early season (14 to 25 May), mid-season (15 June to 21 July), and late-season (26 July to 25 August) periods during 4 growing seasons (1996-1999). Data from different dates are represented by different symbols. Means of CO_2 fluxes (± 1 SE) for the canopy chamber method were obtained from 3, 1-m^2 plots, while means for CO_2 fluxes (± 1 SE) for the Bowen ratio-energy balance method were averaged from 3 to 6, 20-min. measurements that coincided with the time periods when the canopy chamber measurements were obtained. Positive CO_2 flux values indicate a net positive flux from the atmosphere to the earth's surface (photosynthesis exceeds ecosystem respiration), while negative values indicate release of CO_2 from the earth to the atmosphere (ecosystem respiration exceeds photosynthesis). The dashed lines represent the prediction interval for the regression line at 95% confidence, whereas the fine-dotted lines represent the 1:1 relationship. The REG procedure (SAS System) indicated that the combined slopes and intercepts of the regression lines were not statistically different ($P < 0.05$) from the 1:1 relationship for the early and mid-season period, but they were different for the late-season period.

study indicate that both the canopy chamber and Bowen ratio-energy balance methods would likely give similar patterns of CO_2 fluxes in sagebrush-steppe ecosystems; however, caution should be used with the canopy chamber during hot, dry conditions.

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