

Carbon dioxide fluxes over a grazed prairie and seeded pasture in the Northern Great Plains

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“Capsule”: Annual CO₂ flux over temperate grasslands differed, the magnitude depending on dormant season flux.

Abstract

Temperate grasslands are vast terrestrial ecosystems that may be an important component of the global carbon (C) cycle; however, annual C flux data for these grasslands are limited. The Bowen ratio/energy balance (BREB) technique was used to measure CO₂ fluxes over a grazed mixed-grass prairie and a seeded western wheatgrass [*Pascopyrum smithii* (Rybd) Löve] site at Mandan, ND from 24 April to 26 October in 1996, 1997, and 1998. Above-ground biomass and leaf area index (LAI) were measured about every 21 days throughout the season. Root biomass and soil organic C and N content were determined to 110 cm depth in selected increments about mid-July each year. Peak above-ground biomass and LAI coincided with peak fluxes and occurred between mid-July to early August. Biomass averaged 1227 and 1726 kg ha⁻¹ and LAI 0.44 and 0.59, for prairie and western wheatgrass, respectively. Average CO₂ flux for the growing season was 279 g CO₂ m⁻² for prairie and 218 g CO₂ m⁻² for western wheatgrass (positive flux is CO₂ uptake and negative flux is CO₂ loss to the atmosphere). Using prior measured dormant season CO₂ fluxes from the prairie sites gave annual flux estimates that ranged from -131 to 128 g CO₂ m⁻² for western wheatgrass and from -70 to 189 g CO₂ m⁻² for the prairie. This wide range in calculated annual fluxes suggests that additional research is required concerning dormant season flux measurements to obtain accurate estimates of annual CO₂ fluxes.

These results suggest Northern Great Plains mixed-grass prairie grasslands can either be a sink or a source for atmospheric CO₂ or near equilibrium, depending on the magnitude of the dormant season flux. Published by Elsevier Science Ltd.

Keywords: Carbon dioxide uptake; Global carbon cycle; Rangeland; Bowen ratio; Natural ecosystems

1. Introduction

Changes in land-use management and increased burning of fossil fuels have increased atmospheric CO₂ concentrations (Watson et al., 1996). Researchers have identified both natural- and human-influenced sources and sinks for atmospheric carbon (C) (Rastetter et al., 1992; Schimel, 1995; Fan et al., 1998). The largest terrestrial biomass sink for C are the tropical forest ecosystems, which contain about 40% of the total C stored in terrestrial ecosystems (Dixon et al., 1994). Temperate grassland ecosystems, which comprise 32% of the earth's natural vegetation (Adams et al., 1990), may also be a significant C sink (Batjes, 1998; Sundquist,

1993). Temperate-region natural grassland ecosystems have extensive fibrous root systems and may be important C sinks for balancing the global C budget (Rastetter et al., 1992; Gifford, 1994; Schimel, 1995; Keeling et al., 1996; Fan et al., 1998).

Short-term studies have shown that grasslands may be a sink for atmospheric CO₂ during their peak biomass accumulation period, but annual data are limited. Kim et al. (1992) reported average daily CO₂ fluxes for a prairie site dominated by warm-season tallgrasses of 4.1 g CO₂ m⁻² day⁻¹ from May through October. During plant senescence, the ecosystem CO₂ budget was in balance with the atmosphere, but during droughts and after plant senescence, fluxes were about -3 g CO₂ m⁻² day⁻¹. Dugas et al. (1999) reported an annual CO₂ flux for a tallgrass prairie site of 0.7 g CO₂ m⁻² day⁻¹. Frank and Dugas (2001) estimated an annual CO₂ flux

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for a nongrazed mixed-grass prairie of $167 \text{ g CO}_2 \text{ m}^{-2}$. The generally low productivity of grassland soils may limit the potential of grassland ecosystems to capture and store C (Cole, 1996; Houghton et al., 1999). Also, the large vegetation diversity in grasslands and annual climatic variability requires that CO_2 fluxes be measured across a wide range of grasslands typical of the varied environments in which they occur.

The objectives of this research were to determine the CO_2 fluxes for a grazed prairie site that is typical of the Northern Great Plains mixed-grass prairie region and a grazed western wheatgrass site that was seeded in 1986, and to estimate annual CO_2 fluxes for these two sites.

2. Materials and methods

The two study sites, a Northern Great Plains mixed-grass prairie and a seeded western wheatgrass pasture, are located about 700 m apart at the Northern Great Plains Research Laboratory, Mandan, ND (latitude $46^\circ 46' \text{ N}$, longitude $100^\circ 55' \text{ W}$, elevation 518 m). Vegetation at both sites was characterized using point frame procedures (25 frames, 50 hits/frame) in 1995 and 1997. The prairie is typical of a Northern Great Plains mixed-grass prairie ecosystem dominated by blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Griffiths], needle-and-thread (*Stipa comata* Trin. and Rupr.), Carex (*Carex* spp.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], side-oats grama [*Bouteloua curtipendula* (Michx.) Torr.], western wheatgrass [*Pascopyrum smithii* (Rybd) Löve], and Kentucky bluegrass (*Poa pratensis* L.). The western wheatgrass pasture is 76% western wheatgrass with minor components of Kentucky bluegrass, crested wheatgrass [*Agropyron desertorum* (Fisch. Ex. Link) Schult.], and broadleaf forbs. The soil at both sites is a Werner–Sen–Chama complex (loam, silt loam, and silty clay loam Entic and Typic Haploborolls). The prairie has never had fertilizer or herbicide applied and has been grazed at 2.6 ha per steer from mid-May to October each year since 1916. The western wheatgrass was seeded in 1986, has never had fertilizer or herbicides applied, and has been grazed since 1987 at 2 ha per steer.

Green biomass and leaf area were measured at each site by clipping four representative 0.25-m^2 quadrats within 40 m of the instrument towers about every 21 days beginning in mid-April through mid-October each year. Leaves were manually separated from stems, and leaf area was measured using a belt-driven photoelectric area meter. Leaves and stems were oven-dried (70°C) and weighed to obtain total above-ground biomass. Plant height was measured at least three times each growing season and was occasionally used in calculation of turbulent diffusivity (Dugas et al., 1999).

Root biomass was measured on 15 July 1996, 18 July 1997, and 21 July 1998 by taking four soil cores (6.6 cm

diameter) to 110 cm depth within 40 m of the towers. Cores were cut into depth segments of 0–10, 10–20, 20–30, 30–60, 60–90, and 90–110 cm. Root mass was obtained by elution with water, oven-dried (70°C), and weighed. No attempt was made to separate live and dead roots.

Soil organic carbon and nitrogen contents were determined by taking three cores (3.2 cm diameter) about 15 cm apart within 40 m in each direction from the towers on the same dates as root sampling. Cores were cut into depth increments to match the root sampling. Soil from the three cores was composited for each depth increment and processed by removing all visible root material. Bulk density and soil water content was determined for each composite sample. Each sample was dried at 31°C for 72 h, crushed to pass a 2-mm sieve, ground to $200 \mu\text{m}$, and stored in glass bottles until analysis.

Total carbon and nitrogen contents were determined by dry combustion using a Carlo Erba model NA1500 automatic carbon-nitrogen analyzer (Fisons Instruments, Valencia, CA) as described by Schepers et al. (1989). A separate subsample was acidified to determine inorganic carbon content (Loeppert and Suarez, 1996), which was subtracted from the total carbon content to obtain total organic carbon.

Fluxes of CO_2 were measured during the growing season every 20 min from 24 April through 26 October in 1996, 1997, and 1998 using Bowen ratio/energy balance (BREB) instrumentation (Model 023/ CO_2 Bowen ratio system, Campbell Scientific, Inc., Logan, UT, USA) located centrally in a 12-ha, nearly square fenced area that provided at least 200 m of fetch in all directions from the tower. Fluxes were calculated using methods described by Dugas (1993) and Dugas et al. (1999). Bowen ratios were calculated from temperature and humidity gradients measured every 2 s at 1 and 2 m above the canopy. Sensible heat flux was calculated from the Bowen ratio, average net radiation (Model Q*7.0 and 7.1 net radiometer, REBS, Seattle, WA, USA), and soil heat flux calculated from two soil heat flux plates (Model HFT, REBS) with soil temperature measured by thermocouples above the plates. Net radiometers were calibrated against a laboratory standard (Model 7.1, REBS) over grass each year before use. Sensor sensitivities were constant. The turbulent diffusivity, assumed equal for heat, water vapor, and CO_2 , was calculated using the 20-min sensible heat flux and temperature gradient measurements. Twenty-minute averages of CO_2 flux, corrected for vapor density differences at the two heights (Webb et al., 1980), were calculated as a product of turbulent diffusivity and the 20-min average CO_2 gradient measured every 2 s at 1 and 2 m above the canopy. When the BREB method for calculating turbulent diffusivity was not valid because of differences in the sign of the flux and the gradient,

diffusivity was calculated using wind speed, atmospheric stability, and canopy height (Dugas et al., 1999).

This alternate method of calculation of diffusivity was used almost exclusively at night and occurred in approximately 10% of the calculations. Carbon dioxide and water vapor concentration gradients between the two heights were measured with infrared gas analyzers (Model 6262, Li-Cor, Inc., Lincoln, NE, USA) that were calibrated weekly. Fluxes were not corrected for temperature differences in the two air streams because in a separate test, fine-wire thermocouples indicated air temperatures from the two heights did not differ when entering the gas analyzer (unpublished observations). Soil water content was measured at 8 cm depth with time-domain reflectometry methods (Model CS615 Water Content Reflectometer, Campbell Scientific, Inc.) every 20 min and averaged daily. All data generated from the BREB system were stored in a model 21X data logger (Campbell Scientific, Inc.). Growing season fluxes were calculated from BREB measurements across the 24 April–26 October period. Annual fluxes for each year were estimated by subtracting dormant season or winter period (27 October–23 April) flux from growing season flux. Dormant season flux estimates were those reported by Frank et al. (2000) and Frank and Dugas (2001) for a prairie site similar to the prairie site in this study.

3. Results

The long-term (85 year) annual precipitation total at Mandan is 404 mm, but during this study annual precipitation varied from 345 to 517 mm (Fig. 1). Unusually high amounts of precipitation were received in single-day, high-intensity events during August and October 1998. Precipitation during the flux measurement period was 381, 230, and 405 mm in 1996, 1997, and 1998, respectively,

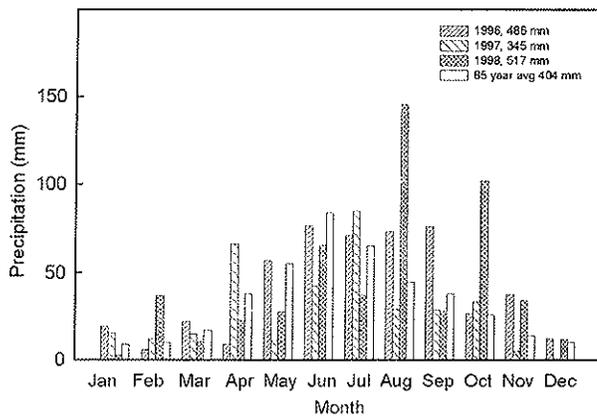


Fig. 1. Monthly total precipitation during 1996, 1997, 1998, and the 85-year average. Annual and long-term average precipitation totals are shown with the bar legends.

and 1998, respectively, compared to the long-term average of 320 mm.

Environmental conditions for the prairie site in 1997 are representative of the other 2 years of the study and are typical of the semiarid climate for this region (Fig. 2). Cloud cover often reduced net radiation to less than 100 w m^{-2} causing decreased C uptake. Soil water decreased rapidly prior to day-of-year (DOY) 182 due to low precipitation. From DOY 180 to 300, soil water varied with precipitation received.

Peak above-ground green biomass for both sites occurred during July to early August depending on precipitation and year (Fig. 3). Peak biomass averaged 1227 and 1726 kg ha^{-1} and LAI averaged 0.44 and 0.59 during the three years for prairie and western wheat-grass, respectively.

Root biomass for both sites was two to three times greater in the top 0–10 cm depth than at any other depth

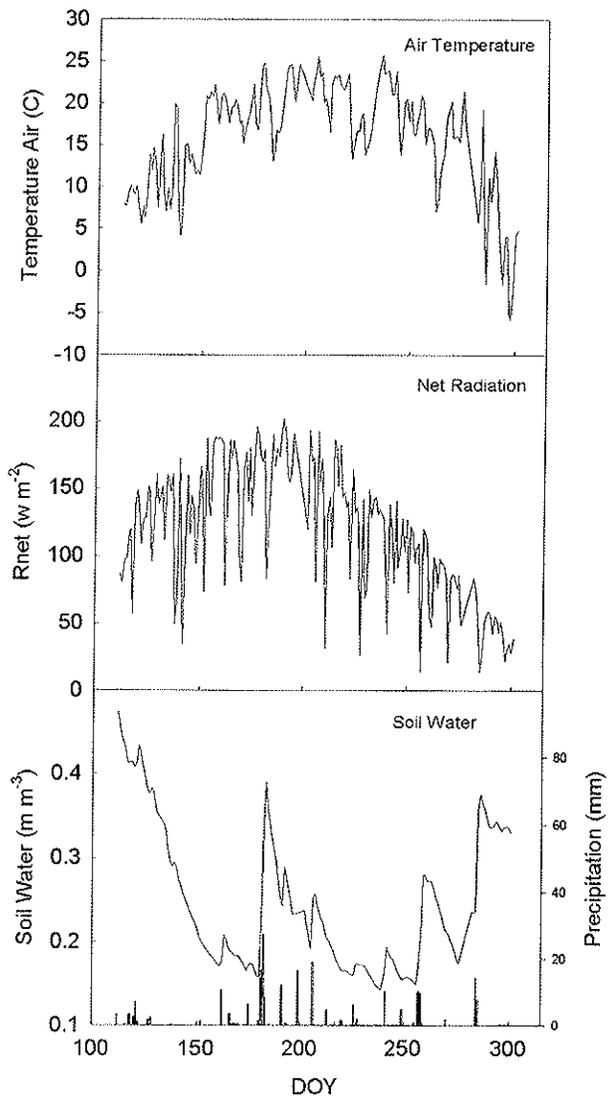


Fig. 2. Seasonal trends in air temperature, net radiation, and soil water to 8-cm depth during 1997 for the prairie site.

(Fig. 4). Nearly 80% of root biomass was in the upper 30 cm for prairie compared to 69% for western wheatgrass. Root biomass decreased rapidly below 20 cm. Total root biomass averaged across years was 12,170 kg ha⁻¹ for prairie and 9750 kg ha⁻¹ for western wheatgrass.

Soil organic C and N content decreased at each successive increment from the 0 to 110 cm depth (data not shown). Soil C content in the prairie at the depth of greatest root biomass (0–30 cm depth) was 6.5 kg C m⁻² or 39% of the total organic C in the 0–110 cm depth compared to 7.2 kg C m⁻² and 42% for western wheatgrass. Total N content for the prairie at the 0–30 cm depth was 0.5 kg N m⁻² or 46% of the total N in the 0–110 cm depth compared to 0.63 kg N m⁻² or 49% for western wheatgrass.

Daily CO₂ fluxes were near zero or slightly negative at the beginning of the measurement period on 24 April, became positive (i.e. CO₂ uptake) during the spring and summer as LAI increased, and returned to near zero or negative during late autumn with plant senescence (data not shown). Diurnal CO₂ flux patterns for nearly clear days in 1997 were similar for the two sites during the growing season (Fig. 5). A marked increase in canopy CO₂ uptake activity was evident on 25 June compared to 24 April, followed by a gradual decline in capacity to

capture C on 8 September and 18 October. This decline is evident from daylight period fluxes, which were 0.61, 5.65, 3.37, and 0.05 g CO₂ m⁻² day⁻¹ for prairie and 0.87, 4.79, 4.10, and 0.66 g CO₂ m⁻² day⁻¹ for western wheatgrass for 24 April, 25 June, 8 September, and 18 October respectively. Night-time ecosystem respiration was greater for prairie, (-0.34, -4.27, -2.02, and -4.13 g CO₂ m⁻² d⁻¹) than western wheatgrass, (-0.07, -3.30, -0.59, and -1.16 g CO₂ m⁻² day⁻¹), on 24 April, 25 June, 8 September, and 18 October, respectively. These data suggest that night-time respiratory losses can significantly affect the magnitude of net annual fluxes.

Growing season fluxes were 237, 328, and 273 g CO₂ m⁻² for prairie and 81, 194, and 380 g CO₂ m⁻² for western wheatgrass in 1996, 1997, and 1998, respectively (Fig. 6). Average daily CO₂ fluxes for each month during the growing season (Fig. 7) generally followed LAI and biomass production (Fig. 5). Maximum fluxes occurred 1 month earlier for western wheatgrass in 1996 and 1997 than for prairie.

Dormant season fluxes are necessary for calculating annual CO₂ fluxes. However, dormant season fluxes were not measured during the 1996–1998 period of canopy flux measurements. Dormant season fluxes reported by Frank et al. (2000) of 0.5 g CO₂ m⁻² day⁻¹, and by Frank and Dugas (2001) of 2.2 and 1.7 g CO₂ m⁻² day⁻¹ as measured by BREB methods and soil CO₂ flux, respectively, were used in calculating annual fluxes. Using these values gives annual fluxes ranging from -131 to 128 g CO₂ m⁻² for western wheatgrass to -70 to 189 g CO₂ m⁻² for prairie.

4. Discussion

Some reports suggest that C budgets of grassland ecosystems are near equilibrium (Sims and Singh, 1978;

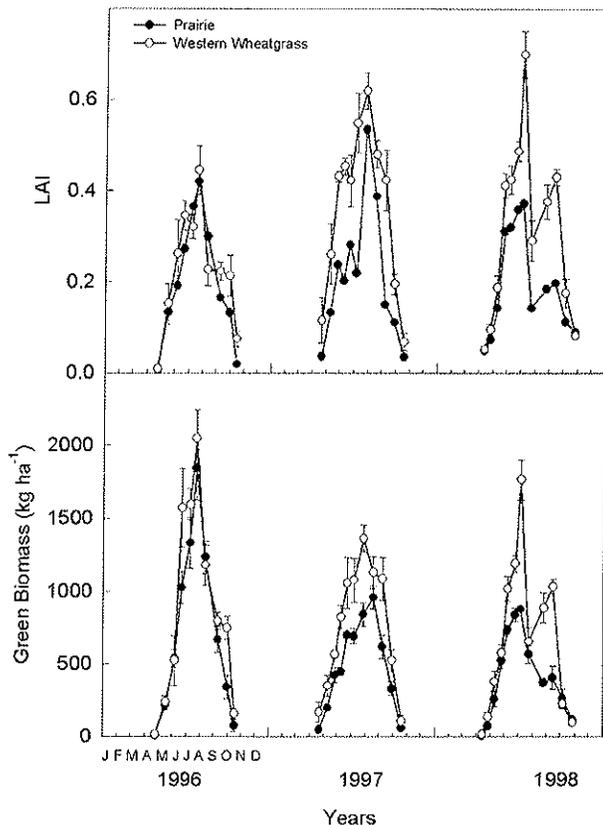


Fig. 3. Leaf area index (LAI) and above ground green biomass during 1996, 1997, and 1998 for the western wheatgrass and prairie sites. Data points correspond to samples taken about every 21 days beginning in mid-April each year.

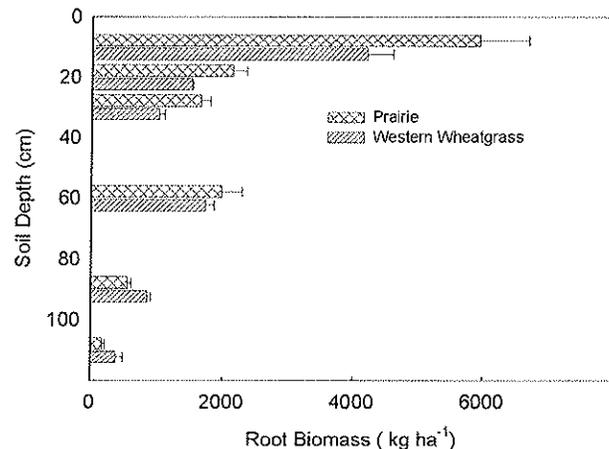


Fig. 4. Mid-season mean root biomass at 0–10, 10–20, 20–30, 30–60, 60–90, and 90–110 cm depths in 1996, 1997, and 1998 for the western wheatgrass and prairie sites. Horizontal bars are standard error of the mean.

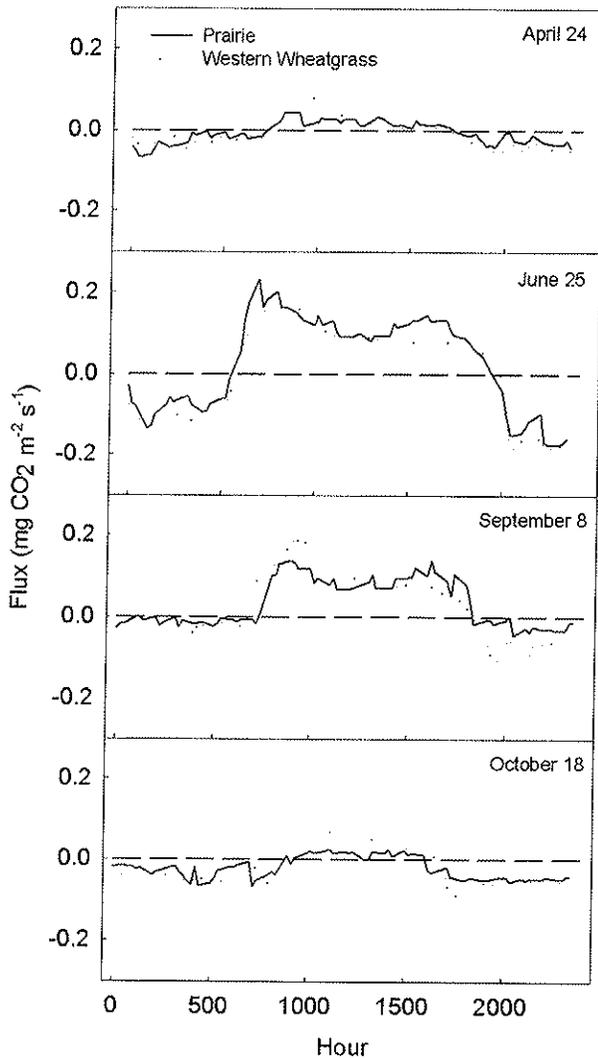


Fig. 5. Diurnal CO_2 fluxes over prairie and western wheatgrass for four representative clear days in 1997. Time is Central Standard Time.

Bruce et al., 1999). Dugas et al. (1999) found an average annual flux of $239 \text{ g CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ for a tallgrass prairie site in the Southern Great Plains and interpreted that this site was in approximate equilibrium, given that estimated annual fluxes were 10 times greater for an adjacent newly established perennial grass pasture. Kim et al. (1992) reported that a tallgrass prairie site in the Central Great Plains fixed $750 \text{ g CO}_2 \text{ m}^{-2}$ from May through October, but only $250 \text{ g CO}_2 \text{ m}^{-2}$ from late June to August 2 years later. The average growing season flux of $279 \text{ g CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ for prairie and $218 \text{ g CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ for western wheatgrass in this study is within the range reported by Kim et al. (1992) and Dugas et al. (1999).

The growing season CO_2 fluxes in our study were measured during a 185-day period. For most of the remaining 180 days of the year the two sites were assumed to be sources of CO_2 because of soil respiratory

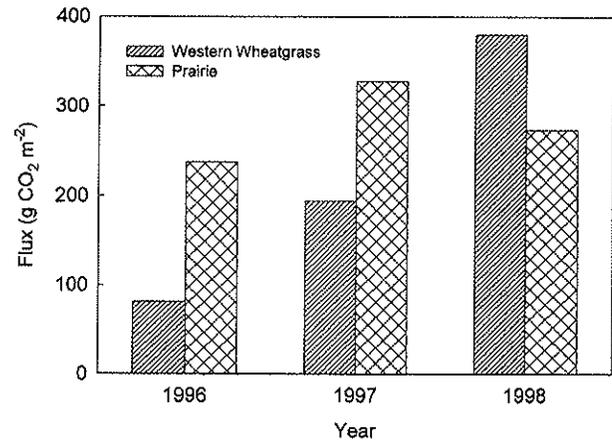


Fig. 6. Growing season, dormant season (estimated from soil temperature), and annual CO_2 fluxes for prairie and western wheatgrass in 1996, 1997, and 1998.

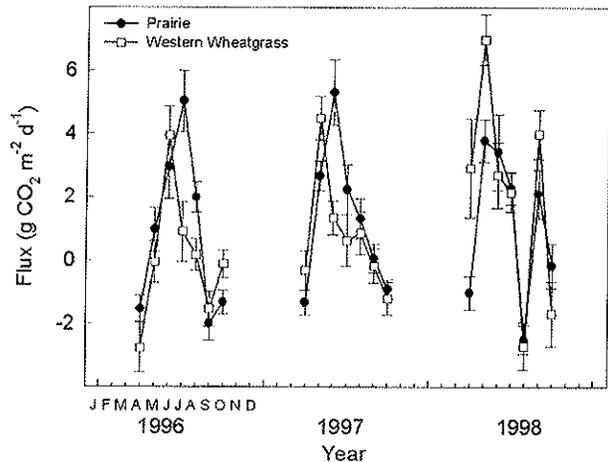


Fig. 7. Average daily carbon dioxide flux each month for April through October in 1996, 1997, and 1998. Solid symbols are growing season fluxes measured using the Bowen ratio system and open symbols are dormant season fluxes estimated from soil temperatures. Vertical bars represent standard errors of the mean.

losses to the atmosphere. Consequently, accurate estimates of annual CO_2 flux depend on obtaining precise estimates of dormant season fluxes. Using the previous estimate of dormant season CO_2 flux from early winter BREB measurements of $-0.5 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$ (Frank et al., 2000), $-2.2 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$ for dormant season BREB measurements, and $-1.7 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ for soil CO_2 respiratory measurements (Frank and Dugas, 2001) gives annual fluxes 128, -47 , and $-131 \text{ g CO}_2 \text{ m}^{-2}$ for western wheatgrass and 189, 14, and $-70 \text{ g CO}_2 \text{ m}^{-2}$ for prairie. This is equivalent to an average loss of -14 g C m^{-2} for western wheatgrass and a gain of 36 g C m^{-2} for the prairie. The storage of plant C as stable soil C was not measured in this study; however, if 10% of the annual C fixed by plants was stored in soils as humus, as suggested by Follett et al. (1997) for crop residues, then over the range of CO_2 flux values given

above an average of about $4 \text{ g C m}^{-2} \text{ year}^{-1}$ would be stored in the prairie and about $1 \text{ g C m}^{-2} \text{ year}^{-1}$ in western wheatgrass. Using these dormant season flux estimates suggest that the prairie and western wheatgrass sites are probably near equilibrium for C sequestration. The large difference in annual fluxes calculated using documented dormant season fluxes indicated the importance of obtaining accurate estimates of dormant season fluxes.

Growing season CO_2 fluxes were more variable for western wheatgrass than prairie across the 3 years of flux measurements (Fig. 6). The greater species diversity in the prairie than western wheatgrass may have reduced flux variability in the prairie. Also, the variation in annual precipitation, short-term drought periods, and temperature stress effects on CO_2 uptake are factors that contribute to inter-annual flux variability. The large variation in green biomass across years is typical in the Northern Great Plains where precipitation and temperature often vary widely across years. Rogler and Haas (1947) showed that antecedent soil water along with precipitation amount and distribution were important factors controlling grassland biomass production. The inter- and intra-annual variability in fluxes and the precipitation observed in our study underscores the need for extended measurements across several years to accurately assess ecosystem CO_2 fluxes.

Respiratory losses during the night-time and the dormant season are critical to obtaining accurate estimates of annual CO_2 fluxes. The BREB method has difficulties in measuring night-time CO_2 fluxes, especially when atmospheric conditions are stable and diffusivities for heat and water vapor are not equal. However, Frank et al. (2000) showed that CO_2 fluxes measured at night by the BREB method only slightly underestimated the sum of the night-time plant and soil respiratory losses. A challenge of any method for measuring dormant season CO_2 fluxes is the difficulty in operating the instrumentation during the cold, dormant season common to the Northern Great Plains. Additional research needs to be conducted to determine accurate estimates of dormant season CO_2 flux based on soil temperature and/or other measurements routinely obtained at weather stations.

The prairie ecosystem in this study is typical of the Northern Great Plains mixed-grass prairie region. The seeded western wheatgrass was located on land that was tilled and reseeded to grass numerous times prior to 1986. Both sites were grazed by livestock, which reduces biomass and LAI compared to ungrazed sites. Although the CO_2 flux data presented are for only a 3-year period, which included highly variable precipitation amounts and dormant season flux estimates, it was anticipated that the annual flux would be near zero, as suggested for other grasslands (Sims and Singh, 1978; Cole 1996; Dugas et al., 1999). Data from our study indicate that

both sites may be either in C balance or serve as a net C sink depending on the value of dormant season flux used in calculating annual fluxes. Increasing atmospheric CO_2 would probably increase photosynthesis and improve plant water-use efficiency, both of which could increase biomass C and possibly soil C (Gifford, 1994; Morgan et al., 1994; Schimel, 1995; Batjes, 1998).

5. Conclusions

The CO_2 fluxes measured in our study on grazed prairie and seeded western wheatgrass suggest that these Northern Great Plains grasslands are probably not a significant sink for atmospheric CO_2 . The effects of highly variable amounts of precipitation and biomass accumulation resulted in seasonal fluxes that differed by more than four-fold, which suggests the need for long-term flux measurements. Grazing is the normal use of these grasslands, but grazing can reduce the potential of grasslands to capture CO_2 through reduction in above-ground biomass. The vegetation diversity in prairie grasslands partly compensates for the low biomass production, low soil productivity, and variable precipitation that reduces CO_2 sequestration. Carbon dioxide flux measurements suggested that both the prairie and western wheatgrass do sequester significant amounts of CO_2 during the growing season. Prairie sequestered an average of $279 \text{ g CO}_2 \text{ m}^{-2}$ and western wheatgrass $218 \text{ g CO}_2 \text{ m}^{-2}$ over a 3-year period. However when accounting for CO_2 losses through mainly respiration during the plant dormant season total carbon sequestered was reduced to about 36 g C m^{-2} for prairie while there was a loss of -14 g C m^{-2} for western wheatgrass. The variability in CO_2 flux within each site and across years suggests the importance of having accurate dormant season losses estimates and the need for continued long-term flux measurements.

The Northern Great Plains mixed-grass prairie region is located near the northwestern edge of the region in North America that Fan et al. (1998) identified as a large terrestrial sink for atmospheric CO_2 . They estimated that 70–100% of the terrestrial sink in North America was located in the broadleaf plant (forests) regions south of 51° N latitude. The results of our study suggest that Northern Great Plains grasslands may be contributing to this North American sink. Whether these grasslands operate as a sink or source for atmospheric CO_2 depends on the particular land use, grazing intensity, and climate, especially precipitation.

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