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## Carbon dioxide fluxes over a northern, semiarid, mixed-grass prairie

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### Abstract

Temperate grassland ecosystems are an important component of the global carbon (C) cycle. The Bowen ratio/energy balance (BREB) technique was used to measure CO<sub>2</sub> fluxes over a mixed-grass prairie at Mandan, ND from 24 April to 26 October in 1996–1999. Above-ground biomass and leaf area index (LAI) were measured about every 21 days throughout the season. Root biomass and soil organic C and nitrogen (N) contents to 1.1 m depth were measured in mid-July each year. Peak above-ground biomass typically occurred between mid-July to early-August and ranged from 782 kg ha<sup>-1</sup> in 1998 to 1692 kg ha<sup>-1</sup> in 1996. Maximum LAI ranged from 0.3 in 1998 to 0.5 in 1999. Root biomass ranged from 12.7 mg ha<sup>-1</sup> in 1996 to 16.2 mg ha<sup>-1</sup> in 1997. Maximum daily CO<sub>2</sub> fluxes generally coincided with periods of maximum above-ground biomass. Total CO<sub>2</sub> flux for the 24 April to 26 October period ranged from 181 g CO<sub>2</sub> m<sup>-2</sup> in 1998 to 474 g CO<sub>2</sub> m<sup>-2</sup> in 1999 (positive flux is CO<sub>2</sub> movement from atmosphere to plants or soil). The 4-year average flux for this period was 345 g CO<sub>2</sub> m<sup>-2</sup>. Fluxes during the 1999–2000 dormant season were estimated from BREB (–349 g CO<sub>2</sub> m<sup>-2</sup>) and soil flux (–265 g CO<sub>2</sub> m<sup>-2</sup>) measurements and when combined with the growing season fluxes, resulted in estimated annual fluxes in 1999 of 125 and 209 g CO<sub>2</sub> m<sup>-2</sup> for BREB and soil flux dormant season measurements, respectively. These results suggest that the C budget of Northern Great Plains mixed-grass prairie grasslands may be near equilibrium. © 2001 Elsevier Science B.V. All rights reserved.

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

### 1. Introduction

Land use changes and increasing fossil fuel use have contributed to increased atmospheric CO<sub>2</sub> concentrations (Watson et al., 1996). Researchers have identified some natural and human influenced carbon (C) sources and sinks (Rastetter et al., 1992; Schimel, 1995; Fan et al., 1998). Temperate grassland ecosystems comprise 32% of the earth's natural vegetation (Adams et al., 1990), and may have a significant role in uptake of atmospheric CO<sub>2</sub> and in balancing

the global C budget (Batjes, 1998; Sundquist, 1993). Grassland ecosystems have generally been considered to be an example of agriculture systems where soils are marginally productive yet contain high amounts of soil organic C, because the extensive fibrous root system of grasses are effective accumulator of C. Tropical forests are probably the largest terrestrial biomass sink for C and contain about 40% of the total C stored in terrestrial ecosystems (Dixon et al., 1994). Temperate-region ecosystems, of which grasslands are a part, also may be functioning as important C sinks that could contribute to balancing the global C budget (Rastetter et al., 1992; Gifford, 1994; Keeling et al., 1996; Schimel, 1995; Fan et al., 1998).

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Several short-term studies suggest grasslands function as a sink for atmospheric CO<sub>2</sub> during their peak biomass accumulation period, but annual data are limited. Kim et al. (1992) reported average daily CO<sub>2</sub> fluxes for a prairie site dominated by warm-season tallgrass species of 4.1 g CO<sub>2</sub> m<sup>-2</sup> per day from May through October. During the period of plant senescence fluxes were near zero, but during droughts and after plant senescence in late autumn, fluxes were about -3 g CO<sub>2</sub> m<sup>-2</sup> per day. Dugas et al. (1999) reported an annual CO<sub>2</sub> flux for a tallgrass prairie site of 0.7 g CO<sub>2</sub> m<sup>-2</sup> per day. Both studies showed maximum CO<sub>2</sub> flux coincided with maximum leaf area and above-ground biomass accumulation during the growing season.

The perennial nature of grasslands along with the usually low soil productivity of grassland soils raise questions about the potential of grassland ecosystems to sequester and store C (Cole, 1996; Houghton et al., 1999). Measurements of CO<sub>2</sub> fluxes over grasslands provides data to evaluate this issue. The large vegetation diversity and climate variability present in grasslands ecosystems suggest that CO<sub>2</sub> fluxes must be measured across a wide range of grasslands to accurately estimate their role in the global C budget.

The objective of this research was to determine CO<sub>2</sub> flux for a native prairie site that is typical of the Northern Great Plains mixed-grass prairie region. It is hypothesized the C budget for this prairie site is near equilibrium. This research is part of the Agricultural Research Service Rangeland Carbon Dioxide Flux Project (Svejcar et al., 1997), which addresses the role of grasslands in the global C cycle.

## 2. Materials and methods

### 2.1. Site description

The site is a mixed-grass prairie located at the Northern Great Plains Research Laboratory, Mandan, ND (latitude 46°46'N, longitude 100°55'W, elevation 518 m) on slopes of 2–10%. Vegetation, determined by point frame procedures (Levy and Madden, 1933) (25 frames, 50 hits per frame) in 1995 and 1997, was 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.], and Kentucky bluegrass (*Poa pratensis* L.), which are typical of a Northern Great Plains mixed-grass prairie ecosystem. The soil is a Werner-Sen-Chama complex (loam, silt loam, and silty clay loam Entic and Typic Haploborolls). This site has never had fertilizer or herbicides applied, has never been burned, and was last grazed in 1992.

### 2.2. Biomass and leaf area

Plant biomass and green leaf area were measured by clipping four representative 0.25 m<sup>2</sup> quadrats about every 21 days beginning in mid-April through mid-October each year from 1996 to 1999. Quadrats were located within 40 m of the instrument tower (see below). Leaves were manually separated from stems and leaf area was measured using a belt-driven photoelectric area meter. Green leaves, green stems, and dead material were oven dried and weighed to obtain total above-ground live and dead 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, 21 July 1998, and 12 July 1999 by taking four 66 m diameter soil cores to 1.1 m depth. Cores were cut into segments of 0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.1 m depth increments. Roots were washed, oven dried, and weighed. All live and dead roots were included in the sample.

### 2.3. Soil carbon and nitrogen

Soil organic C and N contents were measured by taking three 32 mm diameter cores about 0.15 m apart and 20–40 m in each cardinal direction from the tower on the same dates as root sampling and the same depth increments. Soil from the three cores was composited for each depth increment and processed by removing all visible root material. Subsamples were removed for determining bulk density and soil water content. Samples were dried at 31°C for 72 h, crushed to pass a 2 mm sieve, ground to 200 µm, and stored in glass bottles.

Total C and N contents were determined by dry combustion using a Carlo Erba model NA1500 automatic C–N analyzer (Hake Buckler Instruments Inc.,

Saddle Brook, NJ), as described by Schepers et al. (1989). A separate subsample was acidified to determine inorganic C content (Loeppert and Suarez, 1996), which was subtracted from the total C content to obtain total organic carbon.

#### 2.4. Canopy CO<sub>2</sub> flux

The 20 min averages of carbon dioxide fluxes were measured from 24 April through 26 October in 1996–1999 using Bowen ratio/energy balance (BREB) instrumentation (Model 023/CO<sub>2</sub> Bowen ratio system, Campbell Scientific Inc., Logan, UT, USA) mounted on a tower 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 from arms at 1 and 2 m above the canopy. Sensible heat flux was calculated from the Bowen ratio, average net radiation (Model Q\*7 net radiometer, REBS, Seattle, WA, USA), and average soil heat flux calculated from two soil heat flux plates (Model HFT, REBS) and soil temperatures measured above the plates. The net radiometer was calibrated against a laboratory standard over grass each year before use. Sensor sensitivities were constant. The turbulent diffusivity, assumed equal for heat, water vapor, and CO<sub>2</sub>, was calculated using the 20 min sensible heat flux and temperature gradient measurements. The 20 min averages of CO<sub>2</sub> 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<sub>2</sub> gradient that was measured along with the humidity. When the BREB method for calculating turbulent diffusivity was not valid because of differences in the sign of the sensible/latent heat flux and the temperature/humidity gradient, it was calculated using wind speed, atmospheric stability, and canopy height (Dugas et al., 1999). This alternate method of calculation of diffusivity was used approximately 10% of the time and almost exclusively at night when fluxes and gradients were small. Carbon dioxide and water vapor concentration gradients between the two heights were measured with an infrared gas analyzer (Model 6262, Li-Cor Inc., Lincoln, NE, USA). The air stream from each arm

was switched between the two analyzer cells every 2 min. Analyzers were calibrated weekly using a gas mixture of near ambient CO<sub>2</sub> concentration. Fluxes were not corrected for temperature differences in the two air streams, because in tests described by Angell et al. (2001), fine wire thermocouple measurements indicated air temperatures from the two arms was not different when entering the sample and reference chambers of the analyzer. All data generated from the BREB system were captured with a model 21X data logger (Campbell Scientific Inc.).

During the course of the study instances occurred when equipment calibration or repair caused one to several missing 20 min reading. These missing fluxes were calculated as the average of the before and after flux calculations. Fluxes were not calculated from 5 to 8 May 1999, when the system was shut down due to adverse weather conditions. Average daily CO<sub>2</sub> fluxes for each month were calculated as the average of the daily flux during the month.

Growing season CO<sub>2</sub> fluxes were calculated from measurements made during the 24 April to 26 October period each year. Estimates of annual fluxes for 1999 were calculated from growing season and dormant season fluxes. Dormant season fluxes were measured using the BREB method on an adjoining nearly identical mixed-grass prairie pasture from 27 October 1999 to 1 April 2000.

#### 2.5. Soil CO<sub>2</sub> flux

Dormant season fluxes were also estimated from soil CO<sub>2</sub> flux measurements. Soil CO<sub>2</sub> flux was measured between 13.00–15.00 h CST on 10 and 30 November, and 28 December in 1999 and on 18 and 26 January, 27 February, 1, 16, and 29 March in 2000 using a closed system consisting of a 1259 cm<sup>3</sup> chamber (Li-Cor soil chamber) with a 95 mm diameter opening (Li-Cor, Lincoln, NE), a Li-Cor 6262 infrared gas analyzer, and a Li-Cor model LI-670 gas flow control unit. Six collars (polyvinyl chloride 104 mm diameter by 50 mm deep) were placed about 2.5 cm in the soil in a circular pattern of nearly 80 m diameter from the BREB tower. At the time of soil flux measurements, soil temperature at 30 mm depth was measured using a temperature probe. When the soil was frozen, soil temperatures were measured with copper–constantan thermocouples installed near the tower at 38 mm

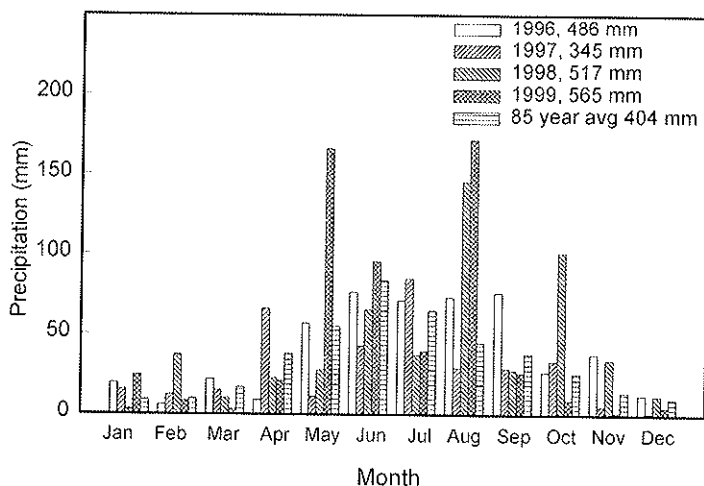


Fig. 1. Monthly total precipitation in 1996–1999. Annual and long-term average precipitation totals are shown with the bar legends.

depth. The soil surface within the collars was kept free of any live vegetation and residue. Soil fluxes during the dormant season were assumed to be net fluxes as soils were often frozen and plants were totally senesced. Soil temperatures ranged from 7.1°C on 10 November 1999 to –5.3°C on 26 January 2000.

### 3. Results and discussion

#### 3.1. Precipitation

Annual precipitation totals varied from 345 mm in 1997 to 565 mm in 1999 (Fig. 1). The long-term (85 years) annual precipitation total at Mandan is 404 mm. Historically, the greatest average monthly precipitation occurs in June, when 21% of the annual precipitation is received. Unusually high amounts of precipitation were received in single-day, high-intensity events in August 1998 and May and August 1999. Precipitation during the growing season flux measurement period (24 April to 26 October) was 381, 230, 405, and 508 mm in 1996, 1997, 1998, and 1999, respectively, compared to the long-term average of 320 mm.

#### 3.2. Biomass and leaf area

Biomass production from prairie grasslands is primarily a function of timing and quantity of precipitation (Rogler and Haas, 1947). Peak green

above-ground biomass typically occurred during the July to early August sampling period (Fig. 2) depending on precipitation and year, and ranged from 782 kg ha<sup>-1</sup> in 1998 to 1692 kg ha<sup>-1</sup> in 1996. Average maximum above-ground biomass over the 4 years was 1192 kg ha<sup>-1</sup>. Maximum LAI tracked green biomass and ranged from about 0.3 in 1998 to 0.5 in 1999 and averaged 0.4 over the 4 years. Peak above-ground standing dead biomass varied widely within years (Fig. 2).

Root biomass was about three times greater in the 0–0.1 m depth than at any increment to 1.1 m depth (Fig. 3). Nearly 64% of the total root biomass was in the upper 0.1 m and 80% was in the upper 0.3 m. Total root biomass varied across years ranging from 12.7 mg ha<sup>-1</sup> in 1996 to 16.2 mg ha<sup>-1</sup> in 1997 (data not shown). These root biomass data are considerably less than the 30 mg ha<sup>-1</sup> reported for both roots and crowns by Sims and Singh (1978a) for an ungrazed North Dakota mixed-grass prairie likely because Sims and Singh included plant crowns whereas our data are for roots only. Total peak green above-ground biomass plus total root biomass was 14.4, 17.0, 13.6, and 15.5 mg ha<sup>-1</sup> for 1996, 1997, 1998, and 1999, respectively.

#### 3.3. Soil carbon and nitrogen

Soil organic C and N contents decreased at each successive increment from 0 to 1.1 m depth (data not

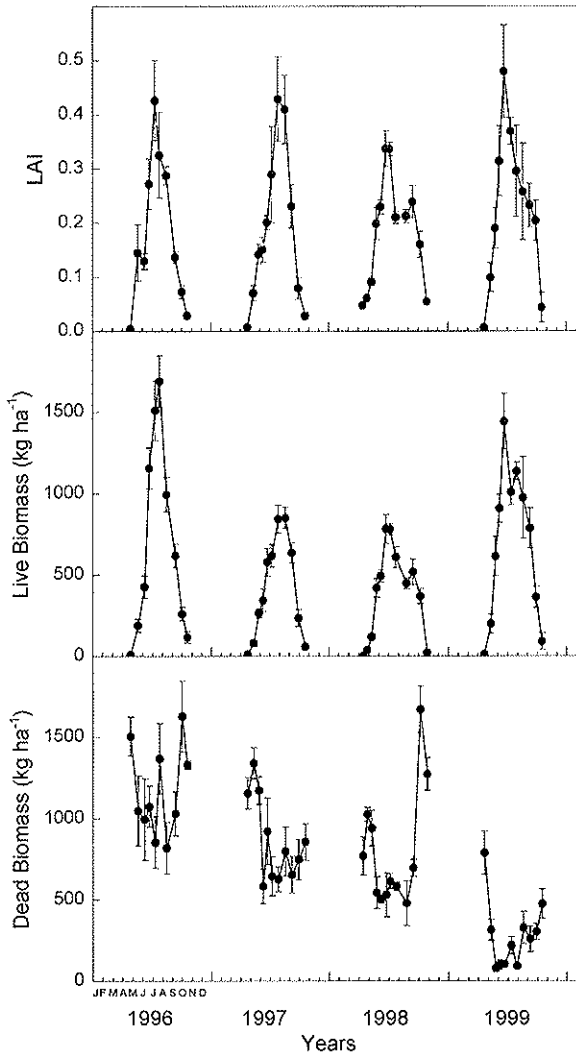


Fig. 2. Leaf area index (LAI) and above ground-green biomass during 1996–1999. Vertical bars are standard error of the mean.

shown). Soil C content in the surface 0–0.3 m depth, the depth of greatest root biomass, was  $6.6 \text{ kg C m}^{-2}$  or 41% of the total organic C in the 0–1.1 m depth. Total N content in the 0–0.3 m depth was  $0.6 \text{ kg N m}^{-2}$  or 60% of the total N in the 0–1.1 m depth.

### 3.4. Canopy CO<sub>2</sub> flux

Daily CO<sub>2</sub> fluxes (Fig. 4) were near zero or slightly negative at the beginning of the measurement period

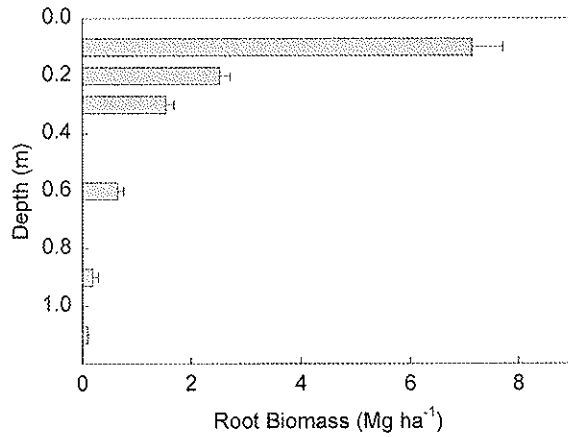


Fig. 3. Mid-season mean root biomass at 0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.1 m depths in 1996–1999. Horizontal bars are standard error of the mean.

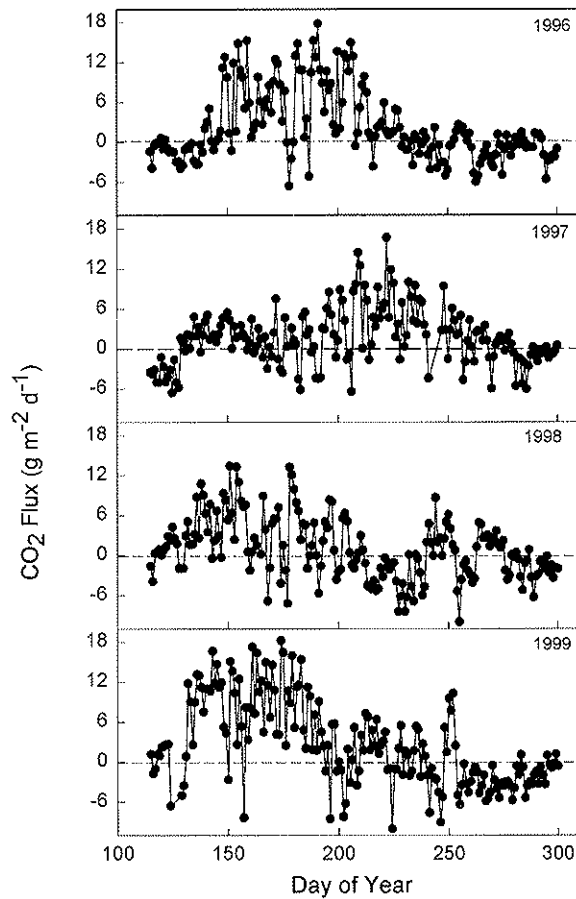


Fig. 4. Daily carbon dioxide fluxes in 1996–1999.

Table 1

Carbon dioxide fluxes for a mixed-grass prairie over 4 years, with estimated dormant and annual fluxes based upon Bowen ratio/energy balance methods and soil flux measurements for 1999

Season	Year ( $\text{g CO}_2 \text{ m}^{-2}$ )				Average ( $\text{g CO}_2 \text{ m}^{-2}$ )
	1996	1997	1998	1999	
Growing season	415	311	181	474	345
Dormant season (soil flux)	–	–	–	–265	–
Annual	–	–	–	209	–
Dormant season (BREB)	–	–	–	–349	–
Annual	–	–	–	125	–

in early spring, became positive (i.e.  $\text{CO}_2$  uptake) during the spring and summer as LAI increased (Fig. 2), and returned to near zero or negative during late autumn. Total growing season  $\text{CO}_2$  fluxes each year during the 24 April (DOY 115) to 26 October (DOY 300) measurement period were 415, 311, 181, and  $474 \text{ g CO}_2 \text{ m}^{-2}$  for 1996, 1997, 1998, and 1999, respectively (Table 1). The average flux for this period was  $345 \text{ g CO}_2 \text{ m}^{-2}$ .

Diurnal  $\text{CO}_2$  fluxes for a 15-day period of active  $\text{CO}_2$  uptake during late June to early July and a 15-day period of reduced  $\text{CO}_2$  uptake during September were remarkably similar for all years (Fig. 5). Nighttime  $\text{CO}_2$  fluxes were more negative during the early period than the late period likely due to increased soil respiration caused by higher temperatures, live biomass, and soil water content in the June–July period.

Average daily  $\text{CO}_2$  fluxes for each year were maximum in July, August, May–June, and June in 1996, 1997, 1998, and 1999, respectively (Fig. 6). The month of maximum flux occurred later in 1996 and 1997 due to lower spring precipitation (Fig. 1) that delayed biomass and LAI development (Fig. 2). The month of maximum flux (Fig. 6) generally corresponded to the time of peak green biomass and LAI (Fig. 2).

### 3.5. Soil $\text{CO}_2$ flux

Soil flux decreased as soil temperature decreased from 10 November 1999 to 26 January 2000 followed by increasing soil flux as soil temperatures increased throughout March (Fig. 7). Carbon dioxide loss from the soil was detected every day of measurements, even for soil temperatures less than  $0^\circ\text{C}$ . The daily average soil flux for the 9 days of flux measurements was  $-1.7 \text{ g CO}_2 \text{ m}^{-2}$ , which is equivalent to

$-265 \text{ g CO}_2 \text{ m}^{-2}$  when scaled to the 156-day dormant season (Table 1).

### 3.6. Seasonal and annual fluxes

Carbon budgets of native grassland ecosystems in semiarid environments are perceived to be near equilibrium (Bruce et al., 1999; Sims and Singh, 1978b).

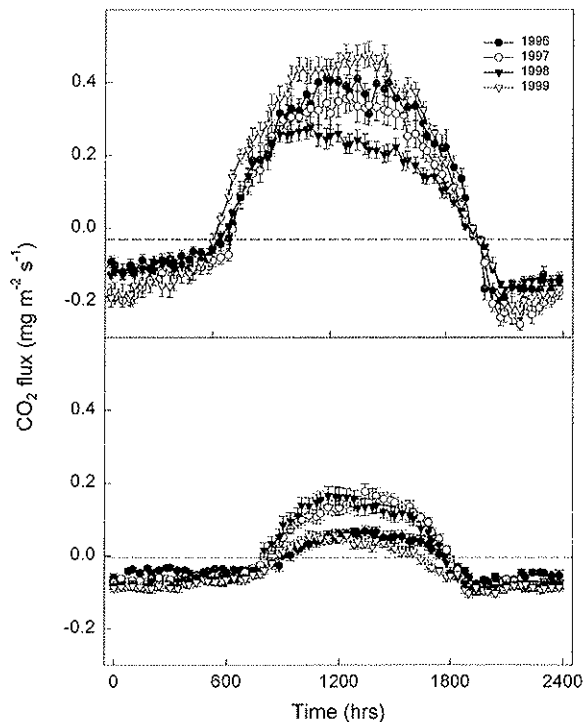


Fig. 5. The 20 min average carbon dioxide flux averaged for 15-day periods in 1996–1999. Fluxes are for late-June to early-July (top) and mid-September (bottom) growth periods. Time is central standard time. Vertical bars are standard error of the mean.

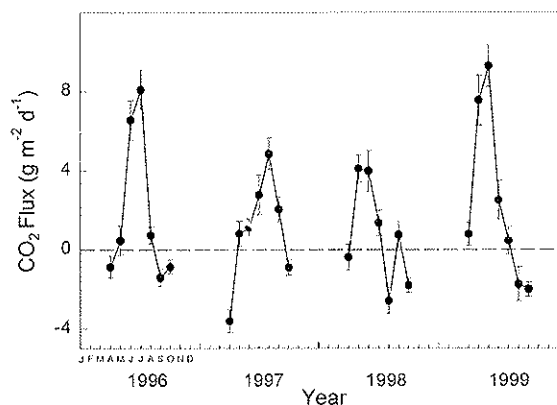


Fig. 6. Average daily carbon dioxide flux each month for April through to October 1996–1999. Vertical bars are standard error of the mean.

However, the dynamics of above- and below-ground biomass, which are generally mediated by climate, may alter the C budget of grasslands. There are limited data on the magnitude of annual CO<sub>2</sub> fluxes on grasslands in the literature. Kim et al. (1992) reported that a tall grass prairie site in the Central Great Plains fixed 750 g CO<sub>2</sub> m<sup>-2</sup> from May through October, but only 250 g CO<sub>2</sub> m<sup>-2</sup> from late June to August 2 years later. The growing season flux average reported here for native prairie grassland of 345 g CO<sub>2</sub> m<sup>-2</sup> (Table 1) compares favorably with results of Kim et al. (1992) and with the 240 g CO<sub>2</sub> m<sup>-2</sup> reported by Dugas et al. (1999) for a Southern Great Plains tallgrass prairie. Dugas et al. (1999) interpreted annual fluxes of 184 and 294 g CO<sub>2</sub> m<sup>-2</sup> per year for a tallgrass prairie in

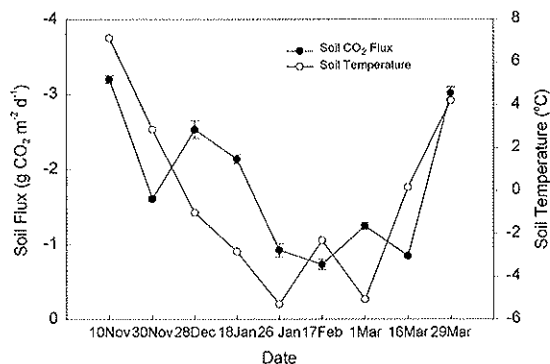


Fig. 7. Daily soil CO<sub>2</sub> flux and soil temperature at 38 mm depth measured between 1300–1500 h during the winter of 1999–2000.

1993 and 1994 as being in approximate C equilibrium, given that annual fluxes were 10 times greater for an adjacent newly established perennial grass pasture.

The average growing season CO<sub>2</sub> flux of 345 g CO<sub>2</sub> m<sup>-2</sup> reported here was measured over a 185 day period. For most of the remaining 180 days of the year the plants at this site were dormant, soil temperatures were near or below 0°C, and the soil was mostly snow covered thus the prairie was assumed to be a source of CO<sub>2</sub> during the period due to losses to the atmosphere from soil respiration (Fig. 7). Accurate estimates of CO<sub>2</sub> flux during this dormant season are necessary for estimating annual CO<sub>2</sub> fluxes for these grasslands. Our BREB estimate for dormant season fluxes was from a very similar adjoining mixed-grass prairie. Mielnick and Dugas (2000) showed that soil respiration was strongly related to soil temperature and that soil respiration was near zero when soil temperature approached 0°C. Because the soils at Mandan are frozen to about 1.3 m depth from about mid November through March (Willis and Haas, 1969), one could expect respiratory CO<sub>2</sub> losses to be greater (more negative) than the -0.5 g CO<sub>2</sub> m<sup>-2</sup> per day estimated by Frank et al. (2000) from late autumn and early spring measurements. The dormant season fluxes measured by BREB were -349 g CO<sub>2</sub> m<sup>-2</sup> and by soil flux were -265 g CO<sub>2</sub> m<sup>-2</sup> for an average daily flux over 156 days of -1.7 g CO<sub>2</sub> m<sup>-2</sup> (Table 1). Adding these two dormant season fluxes to the growing season fluxes during 1999 resulted in annual fluxes for both measurement methods of 209 and 125 g CO<sub>2</sub> m<sup>-2</sup> or an average annual flux of 167 g CO<sub>2</sub> m<sup>-2</sup> per year or 45 g C m<sup>-2</sup> per year. The transfer of plant C to 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 about 5 g C m<sup>-2</sup> per year would be stored in the soils at this prairie site. These results suggest that this Northern Great Plains mixed-grass prairie site is a small sink or near equilibrium for C sequestration, as was the Texas tallgrass prairie (Dugas et al., 1999).

### 3.7. Variability in flux data

The measured net CO<sub>2</sub> flux was highly variable within and across years (Fig. 4 and Table 1). Such variability is related to changes in above-ground

biomass and LAI (Fig. 2) that occurred in response to precipitation (Fig. 1), especially short-term drought periods, and to temperature stress and the resulting effects on CO<sub>2</sub> uptake. The large variation in green biomass across years is typical in the Northern Great Plains where precipitation and temperature often vary widely. Rogler and Haas (1947) showed that antecedent soil water along with precipitation amount and distribution were important factors controlling grassland biomass production. This was especially evident in 1997 and 1998 when below-average precipitation from March through July resulted in less above-ground biomass and lower growing season fluxes compared to the higher precipitation years of 1996 and 1999. Also, Sims and Singh (1978b) showed above-ground net primary production and below-ground net primary production across 10 western North American grasslands were most highly correlated with long-term mean annual temperature, growing season precipitation, and actual evapotranspiration.

There was considerable day-to-day variability in daily CO<sub>2</sub> fluxes during the summer when flux was greatest (Fig. 4). This was due to varying radiation levels and precipitation events. For example, short-term droughts reduced CO<sub>2</sub> fluxes to near zero during April–May and August–October 1996, April–May 1997, August 1998, and September 1999. Also, timing and magnitude of precipitation events influenced total growing season flux. For example, growing season fluxes were 2.6 times greater in 1999 (474 g CO<sub>2</sub> m<sup>-2</sup>) than in 1998 (181 g CO<sub>2</sub> m<sup>-2</sup>) (Table 1) even though annual precipitation exceeded the long-term average during both years. However, in 1998 precipitation was 517 mm, exceeding the long-term average of 404 mm, but 245 mm of the annual total were received after August 15, which is after the period of greatest biomass production and CO<sub>2</sub> uptake. The inter- and intra-annual flux and precipitation variability in this study underscores the need for extended measurements over several years to accurately assess ecosystem CO<sub>2</sub> fluxes.

Another source of variability in measuring net CO<sub>2</sub> fluxes can be attributed to the BREB method being less valid for measuring nighttime CO<sub>2</sub> fluxes, especially during instances of stable atmospheric conditions when diffusivities for heat and water vapor may not be equal or when gradient and energy fluxes

become very small and difficult to measure. Frank et al. (2000) showed that CO<sub>2</sub> fluxes measured at night by the BREB method only slightly underestimated the sum of estimated nighttime plant and soil respiratory losses. Also, Angell et al. (2001) showed fluxes from the BREB method were very similar to those for closed chamber measurements for both daytime and nighttime CO<sub>2</sub> flux measurements on a sagebrush steppe site.

The uncertainty of the magnitude of the dormant season respiratory losses on the annual flux is difficult to resolve because we did not operate the instrumentation each year during the cold dormant season common to the Northern Great Plains. However, the dormant season fluxes measured in the 1999–2000 dormant season by both the BREB and soil flux methods provides some indication of the magnitude of dormant season fluxes.

#### 4. Conclusions

The grassland ecosystem represented in this study is typical of the Northern Great Plains mixed-grass prairie region. Since grasslands generally occupy the less productive part of the landscape, as compared to cultivated agriculture, it has been suggested that grassland soils normally have little capacity to store additional C, mainly because of the inherently low soil fertility and low precipitation to support greater biomass production (Cole, 1996). However, the soil organic C and N contents for this mixed-grass prairie site dominated by cool-season grasses were relatively high, averaging 6.6 and 0.6 kg m<sup>-2</sup> to 30 cm depth, respectively. The soil productivity at this site and the extensive root biomass, which is characteristic of a cool-season dominated mixed-grass prairie, supports the premise that this prairie system has served in the past as a net sink for atmospheric CO<sub>2</sub>. The average growing season CO<sub>2</sub> flux of 345 g CO<sub>2</sub> m<sup>-2</sup> suggests that this prairie has potential to capture C. However, the dormant season data, although limited, indicated that a significant portion of that C may be lost. Also, these grasslands are generally grazed by livestock that would reduce LAI and above-ground biomass and potentially affect CO<sub>2</sub> fluxes.

Carbon storage in these systems may be increasing as a result of increasing atmospheric CO<sub>2</sub> that



produces a CO<sub>2</sub> fertilization effect that generally increases photosynthesis and improves plant water-use efficiency, both of which could increase biomass C and possibly soil C (Batjes, 1998; Gifford, 1994; Schimel, 1995). Both C<sub>3</sub> and C<sub>4</sub> native prairie grasses have exhibited increased photosynthetic capacity with increasing CO<sub>2</sub> concentration, which along with the extensive fibrous root system characteristic of the grasses at this prairie site, provides further evidence for carbon storage potential in grassland ecosystems (Morgan et al., 1994).

The CO<sub>2</sub> fluxes measured in this study suggest that Northern Great Plains mixed-grass prairie probably serves as a small sink for atmospheric CO<sub>2</sub>. 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<sub>2</sub>. They estimated 70–100% of the terrestrial sink in North America was located in the broadleaf plant (forests) regions south of 51°N latitude. These result suggest the vast Northern Great Plains grasslands also may be contributing to this North American sink. The functionality of these grasslands as a sink for atmospheric CO<sub>2</sub> depends on the future land use management and climate, especially precipitation.

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