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Six Years of CO_2 Flux Measurements for a Moderately Grazed Mixed-Grass Prairie

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ABSTRACT / The large area occupied by temperate grassland ecosystems makes it important to determine their strength as a carbon sink. The Bowen ratio/energy balance (BREB) technique was used to determine CO_2 fluxes over a moderately grazed mixed-grass prairie at Mandan, North Dakota, USA, over a 6-year period from 1996 to 2001. Above-ground biomass and leaf area index (LAI) were measured about every 21 days throughout the growing period. Root biomass was determined to 1.1 m depth in mid-July each year. Peak above-ground biomass typically occurred between mid-July to early August and ranged from 782 kg/ha in 1998 to 2173 kg/ha in 1999. Maximum LAI ranged from 0.4 in 1998 to 0.9 in 1999. Root biomass ranged from 11.8 Mg/ha in 1997 to 17.4 Mg/ha in 1996. Maximum daily CO_2 fluxes generally coincided with periods of maximum LAI and above-ground green biomass. The average time period for CO_2 uptake was 5 May to 3 October. Annual CO_2 fluxes ranged from a low of 13 g CO_2/m^2 in 1998 to a high of 247 g CO_2/m^2 in 2001, nearly a 20-fold difference, and averaged 108 g CO_2/m^2. The cumulative annual flux over all 6 years was 646 g CO_2/m^2 or 176 g CO_2-C/m^2. These results indicate that the strength of the carbon sink for this moderately grazed prairie site is about 30 g CO_2-C/m^2/yr, which is quite small, but considering that the site was grazed and still remains a sink for carbon, it is significant.

Carbon dioxide flux measurements have shown grasslands to be a net sink for atmospheric CO_2 (Kim and others 1992, Dugas and others 1999, Frank and others 2000, Frank and Dugas 2001, Sims and Bradford 2001, Suyker and Verma 2001). Tropical forests are the largest terrestrial biomass sink for C, containing about 40% of the total C stored in terrestrial ecosystems (Dixon and others 1994). Grassland ecosystems comprise about one fifth of the earth's land surface and contain more than 10% of the global C stocks (Eswaran and others 1993). Temperate-region grassland ecosystems are well suited for storing soil organic carbon because of their extensive fibrous root systems, which makes these ecosystems important C sinks that must be considered for balancing the global C budget (Rastetter and others 1992, Sundquist 1993, Gifford 1994, Schimel 1995, Keeling and others 1996, Batjes 1998, Fan and others 1998). Native grasslands are highly resilient due to the highly diverse mixture of species that are adapted to the harsh conditions common to temperate grasslands. These factors make grasslands effective sequesters of atmospheric CO_2 even though they generally occupy landscape sites that have less productive soils than cropland and are found in regions that receive limited precipitation.

KEY WORDS: Carbon sequestration; Global carbon cycle; Carbon budget; Bowen ratio; Grasslands

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Seasonal flux measurements have shown that grasslands are a sink for atmospheric CO_2, especially during periods of peak biomass accumulation. Kim and others (1992) reported average daily CO_2 fluxes for a prairie site dominated by warm-season tallgrasses of 4.1 g CO_2/m^2/day from May through October. During the grassland senescence phase, the CO_2 budget was in balance with the atmosphere, but during droughts and after senescence, the grassland was a source of CO_2 with a flux of nearly -3 g CO_2/m^2/day. Dugas and others (1999) reported an annual CO_2 flux for a tallgrass prairie site of 0.7 g CO_2/m^2/day. Frank and Dugas (2001) estimated an annual CO_2 flux for a nongrazed mixed-grass prairie of 167 g CO_2/m^2. The generally low productivity of grassland soils and the low precipitation amounts and nitrogen availability limit the potential of grassland ecosystems to capture and store C (Cole 1996, Houghton and others 1999). Others claim that the carbon budgets of grasslands are near equilibrium (Sims and Singh 1978, Bruce and others 1999). Estimating carbon storage potential of grasslands is difficult and requires long-term measurements because of the extensive vegetation diversity and climate variability in which they occur. Assuming the CO_2 budget for this moderately grazed prairie site is near equilibrium, the objective of this research was to determine the annual CO_2 flux for a moderately grazed mixed-grass prairie site typical of the Northern Great Plains mixed-grass prairie region.

Materials and Methods

The site is a 12-ha mixed-grass prairie located at the Northern Great Plains Research Laboratory, Mandan, North Dakota, USA (latitude 46°46'N, longitude 100°55'W, elevation 518 m) on slopes of 2%–10%. The soil is a Werner-Sen-Chama complex (loam, silt loam, and silty clay loam Entic and Typic Haploborolls). This site has been grazed for 86 years at a moderate stocking rate of 2.6 ha/steer from mid-May to early October each year. The site has never had fertilizer or herbicides applied and has never been burned. Vegetation, determined by point frame procedures (Levy and Madden 1933) (25 frames, 50 hits/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.

Green plant biomass, standing-dead plant biomass, and leaf area were measured by clipping at the soil surface four representative 0.25 m^2 quadrats about every 21 days beginning in mid-April through mid-October each year from 1996 to 2001. Quadrats were randomly located within 40 m of the Bowen ratio/energy balance tower. Leaves were manually separated from stems and leaf area was measured using a belt-driven photoelectric area meter. Green leaves, green stems, and standing-dead material were oven dried and weighed to obtain total above-ground live and dead biomass.

Root biomass was measured each year near the above-ground biomass sampling areas during the period of peak above-ground biomass production. Samples were collected on 15 July 1996, 18 July 1997, 21 July 1998, 12 July 1999, 27 July 2000, and 16 July 2001 by taking three 66-mm-diameter soil cores to 1.1-m depth. Cores were divided 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 removed from the soil cores by washing, oven dried, and weighed. All live and dead roots were included in the sample.

Carbon dioxide flux was measured using BREB instrumentation (model 023/CO_2 Bowen ratio system, Campbell Scientific, Inc., Logan, Utah, USA) mounted on a tower located centrally in a minimum fenced area within the mixed-grass prairie site to provide 200 m of fetch in all directions from the tower. Fluxes were measured using the BREB system from 24 April through 17 October in 1996, 1997, and 1998, and continually from 24 April 1999 to 31 December 2001. Fluxes were calculated using methods described by Dugas (1993) and Dugas and others (1999). Bowen ratios were calculated from temperature and humidity gradients measured every 2 sec 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, Washington, 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_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 and others 1980), were calculated as a product of turbulent diffusivity and the 20-min average CO_2 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 and others 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, Nebraska, USA). The airstream 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_2 concentration. Fluxes were not corrected for temperature differences in the two airstreams, because in tests described by Angell and others (2001), fine wire thermocouple measurements indicated air temperatures from the two arms were 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 the need for equipment repair caused periods of missing data. Fluxes were not calculated during periods when precipitation exceeded 6.35 mm/day, when the system was shut down due to adverse weather, or during periods of equipment failure that exceeded several hours. Average daily CO_2 fluxes were calculated for 10-day increments.

Growing period CO_2 fluxes were calculated from flux measurements made during the 24 April–17 October period each year. Dormant period fluxes for 1996, 1997, and 1998 were estimated from the relationship between soil temperature and soil CO_2 flux as reported by Frank and others (2002). They used soil temperature at 3.8 cm depth to estimate soil CO_2 flux from the following: soil flux = $(A_1\, A_2^{A3})^z \cdot$ maximum flux, where $A_1 = (T_{max} - T)/(T_{max} - T_{opt})$, $A_2 = (T - T_{min})/(T_{opt} - T_{min})$, $A_3 = (T_{opt} - T_{min})/(T_{max} - T_{opt})$, T is the measured soil temperature, T_{max} is the maximum soil temperature, T_{min} is the minimum soil temperature, and T_{opt} is the optimum soil temperature for soil CO_2 flux rates. Dormant season fluxes for 1999, 2000, and 2001 were measured with the BREB system. Estimates of annual fluxes for all years were calculated from growing period and dormant period fluxes. Net radiation data were used to determine the time period for day time (net radiation > 25 W/m^2) and nighttime (net radiation < 25 W/m^2) flux calculations. All dormant period flux calculations are for 24-hour time periods, whereas daytime and nighttime flux calculations are for variable time periods due to changes in length of time when radiation exceeds 25 W/m^2 over the growing period.

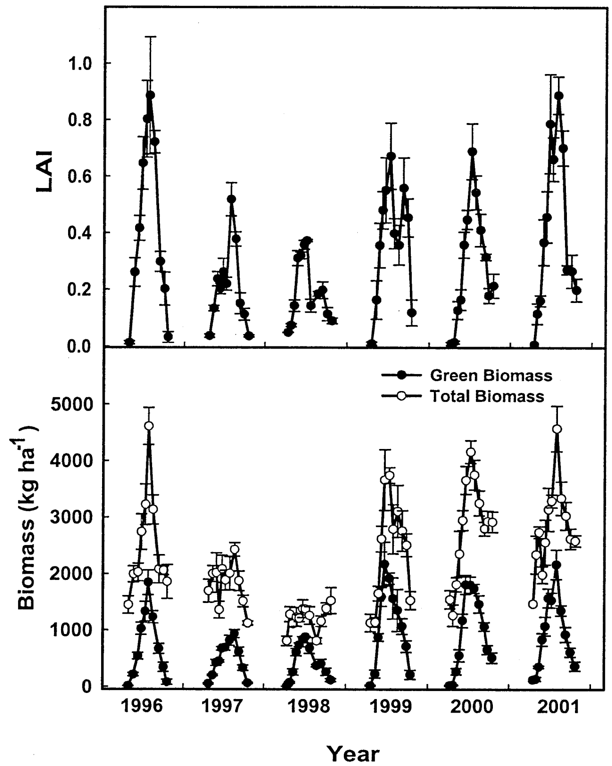

Figure 1. Leaf area index (LAI) and above-ground-green and dead biomass during-6 years for a moderately grazed mixed grass prairie at Mandan, North Dakota, USA. Vertical bars are standard error of the mean.

Results and Discussion

Significant growing period precipitation events on the Northern Great Plains generally orginate as thunderstorms, which can cause a wide difference in seasonal distribution and amount of precipitation received each year. Annual precipitation totals varied from 345 mm in 1997 to 565 mm in 1999. The long-term (85-year) annual precipitation total at Mandan is 404 mm. The greatest monthly precipitation generally occurs in June, when an average 21% of the annual precipitation is received. Unusually high amounts of precipitation were received in single-day, high-intensity, high-runoff events in August (120 mm) and October 1998 (65 mm) and May (128 mm) and August (116 mm) 1999. Precipitation during the growing period (24 April–17 October) was 381, 230, 405, 508, 323 and 383 mm in 1996, 1997, 1998, 1999, 2000, and 2001 respectively, compared to the long-term average for this period of 320 mm.

Period of peak green biomass typically occurred during the July to early August sampling period (Figure 1) and ranged from 782 kg/ha in 1998 to 2173 kg/ha in 1999 and averaged 1634 kg/ha over all 6 years. Maximum LAI occurred on similar dates as green biomass and ranged from 0.4 in 1998 to 0.9 in 1999 and averaged 0.7 over the 6 years. Peak above-ground standing dead biomass ranged from 1377 kg/ha in 1998 to 4612 kg/ha in 1996 and over years averaged 3483 kg/ha (Figure 1). Above-ground biomass production from Northern Great Plains prairie grasslands is primarily a function of timing and quantity of precipitation, with early spring precipitation being most important (Rogler and Haas 1947). Generally, precipitation received after peak biomass production does not significantly increase biomass in a Northern Great Plains mixed grass prairie. Net CO_2 uptake is generally correlated to the amount of green biomass present (Dugas and others 1999, Frank and Dugas 2001, Suyker and Verma 2001).

Root biomass in the upper 30 cm of soil depth accounted for 80% of the total root biomass over all increment sampled to 1.1 m depth (Figure 2). Total root biomass varied across years ranging from 11.8 Mg/ha in 1997 to 17.4 Mg/ha in 1996. Sims and Singh (1978) reported root biomass amounts of 30 Mg/ha for an ungrazed North Dakota mixed-grass prairie, which is significantly more than for the moderately grazed prai-

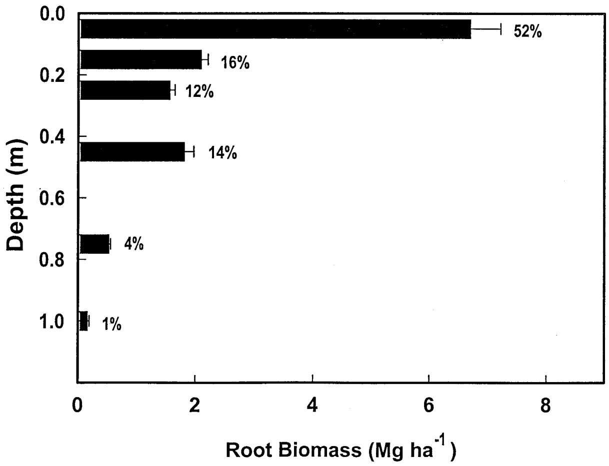

Figure 2. Mid-season mean root biomass at increments to 1.1 m depths over-6 years for a moderately grazed mixed grass prairie at Mandan, North Dakota. Data are plotted in the midrange of the depth increment sampled. The percent of total root mass is given for each increment. Horizontal bars are standard error of the mean.

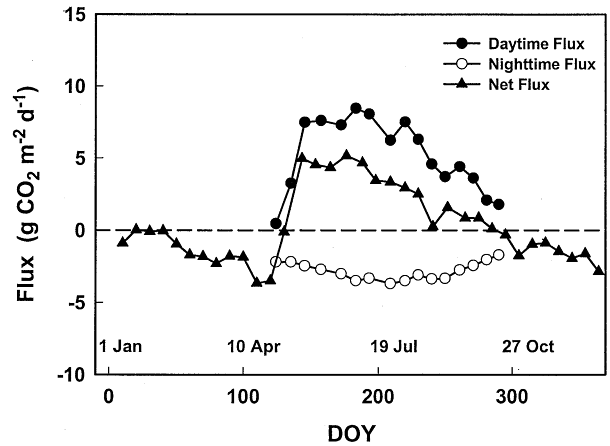

Figure 3. Carbon dioxide flux components over a moderately grazed mixed grass prairie at Mandan, North Dakota. Data are 10-day averages over 6 years. Daytime and nighttime flux data are for the growing period when green vegetation was present.

rie site reported here, but their data included both plant crown and root material. Below ground biomass constituted 75% of the total biomass over years in the mixed-grass prairie. Total peak above-ground green and dead biomass plus total root biomass was 23.8, 15.1, 18.0, 21.2, 21.0, and 23.9 Mg/ha for 1996, 1997, 1998, 1999, 2000, and 2001, respectively.

The duration of positive CO_2 flux (CO_2 uptake) varied considerably over years mainly from delayed vegetation green-up in the spring due to cold air temperatures and the lack of precipitation during the late summer and early autumn, which caused early plant senescence and reduced CO_2 uptake. For the beginning of the growth period, the earliest 10 day average positive flux for any year occurred on 25 April 1998 and the latest on 13 May 2001. First positive flux dates for other years were similar: 5 May in 1996, 6 May in 1997, 8 May in 1999, and 5 May in 2000. The 6-year average date for positive net fluxes to occur in the spring period was 5 May (Figure 3). The last date for positive fluxes to occur was more variable because precipitation is typically reduced in the autumn resulting in periods of drought stress which increases plant senescence and reduces green biomass and photosynthesis. The earliest negative flux (CO_2 loss) date was on 18 July 1999 and the latest on 17 October 2001. Drought induced negative fluxes also occurred in 1998 during the 31 July to 16 September period, but precipitation received in early September was sufficient to return positive fluxes until 17 October. The early date for negative fluxes in 1999 was caused by drought during late summer and autumn periods. The 6-year average date for the first negative fluxes in the autumn was 3 October (Figure 3).

Nighttime fluxes during the growing period were relatively uniform averaging -2.8 gCO_2 /m^2/d and ranging from -3.7 on 28 July to -1.7 on 17 October (Figure 3). Carbon dioxide loss during the dormant period was greater during the November through December and the February to 26 April periods than during January. The smaller CO_2 loss in January can be attributed to colder soil temperatures reducing soil CO_2 flux (Bremer and others 1998, Frank and others 2002, Mielnick and Dugas 2000). Direct comparisons of net flux during the dormant period flux and growing period nighttime fluxes were not valid as the time periods for each determination differed. The net flux during the dormant period was measured over the entire day whereas the growing period nighttime flux was measured only during the night period. Adjusting for time period differences would increase (more negative nighttime flux) the growing period nighttime fluxes on average by about 1.6 times. Overall the trend between dormant period flux and growing period nighttime fluxes during the transition from the dormant period to the growing period appeared reasonable (Figure 3).

Annual CO_2 fluxes ranged from a low of 13 g CO_2/m^2 in 1998 to a high of 247 g CO_2/m^2 in 2001, nearly a 20-fold difference (Table 1). The average annual flux was 108 g CO_2/m^2 and the cumulative flux over all 6 years was 646 g CO_2/m^2 or 176 g CO_2-C/m^2. The range in growing period fluxes was about twofold, as the low flux was 268 g CO_2/m^2 in 1996 and the high

Table 1. Annual, growing period, and dormant period CO_2 fluxes for moderately grazed mixed-grass prairie over 6-year period

	CO_2 flux (g CO_2/m^2)						
Period	1996	1997	1998	1999	2000	2001	Avg.
Annual flux	94	193	13	57	42	247	108
Growing period	268	383	322	299	436	554	377
Dormant period	−174	−190	−309	−242	−394	−307	−269

was 554 g CO_2/m^2 in 2001. The cumulative growing period flux over the 6-year period was 2262 g CO_2/m^2, which gives an annual flux of 377 g CO_2/m^2 or 103 g CO_2-C/m^2. Dormant period fluxes ranged from −174 g CO_2/m^2 in 1996 to −394 g CO_2/m^2 in 2000 and averaged −269 g CO_2/m^2 for the 6 years. The cumulative dormant period flux over the six year period was −1616 g CO_2/m^2 or about 71% of the net growing period flux. Suyker and Verma (2001) reported that nighttime carbon losses from a tallgrass prairie site was about 67% of the annual daytime carbon uptake. The results from these two studies are not directly comparable because of the difference in partitioning of the dormant period and night-time fluxes, but they indicate the importance of measuring year-long respiratory carbon losses in determining net annual CO_2 fluxes.

Dormant period fluxes were related to the dormant season soil temperatures at 3.8 cm soil depth. The mean hourly soil temperature for the dormant period months of January, February, March, November, and December was coldest in 1996 (−3.14°C) and 1997 (−2.43°C), the two years when dormant period fluxes were lowest. Soil temperatures for years 1998 to 2001 ranged from a high of −0.59 in 1999 when flux was −242 g CO_2/m^2 to a low of −1.97°C in 2001 when flux was −307 g CO_2/m^2. The relationship between soil CO_2 flux and soil temperature has been reported previously by Bremer and others (1998), Frank and others (2002), and Mielnick and Dugas (2000).

The cumulative growing and dormant period CO_2 flux showed an increasing trend over the entire 6 years, with the largest increase occurring in 2001. Total flux for the 5-year period from 1 January 1996 to 31 December 2000 was 399 g CO_2/m^2 (Figure 4). Total flux for the entire 6-year period increased to 646 g CO_2/m^2 because of the large annual flux in 2001. This is much lower than in a seven year study on a tall-grass prairie site that had cumulative CO_2 fluxes of 7700 g CO_2/m^2 with an LAI that exceeded 3.5 and biomass that exceeded 5000 kg/ha at peak values (W. A. Dugas, personal communications). The large dormant season fluxes measured during the November 1999 to March 2000 period contributed greatly to the decreasing trend

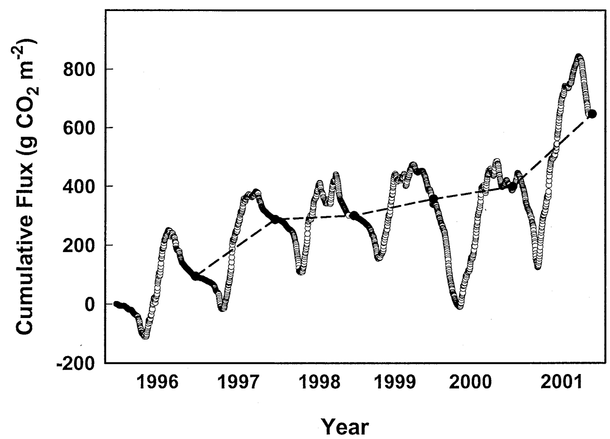

Figure 4. Cumulative CO_2 flux over a moderately grazed mixed-grass prairie from 1 January 1996 to 31 December 2001 at Mandan, North Dakota. The dashed line depicts the cumulative CO_2 flux on 31 December of each year.

in cumulative fluxes during the 1996 to 2000 period. The large increase in cumulative flux in 2001 was due to the high growing period flux as the dormant period flux in 2001 did not differ greatly form that in 1998, 1999, and 2000.

Conclusions

A 6-year study was completed to determine the net annual CO_2 fluxes for a moderately grazed mixed-grass prairie in the Northern Great Plains. There was considerable yearly variation in the growing period, dormant period, and annual net fluxes, which could be attributed to yearly difference in precipitation and temperature effects on LAI and biomass. Annual CO_2 fluxes ranged from 13 to 247 g CO_2/m^2 with an cumulative six year total of 646 g CO_2/m^2 or about 30 g CO_2-C/m^2/yr. Dormant period CO_2 losses were 71% of the net growing period CO_2 flux. These results suggest the strength of the carbon sink for this moderately grazed prairie site is quite small, but considering the site was moderately grazed and still remains a sink for carbon, it is significant.

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