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► **To cite this version:**

A. R. Mosier, E. G. Pendall, J. A. Morgan. Effect of water addition and nitrogen fertilization on the fluxes of CH₄, CO₂, NO_x, and N₂O following five years of elevated CO₂ in the Colorado Shortgrass Steppe. *Atmospheric Chemistry and Physics*, 2003, 3 (5), pp.1703-1708. hal-00295343

HAL Id: hal-00295343

<https://hal.science/hal-00295343>

Submitted on 18 Jun 2008

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Effect of water addition and nitrogen fertilization on the fluxes of CH₄, CO₂, NO_x, and N₂O following five years of elevated CO₂ in the Colorado Shortgrass Steppe

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Received: 28 January 2003 – Published in Atmos. Chem. Phys. Discuss.: 20 May 2003

Revised: 12 August 2003 – Accepted: 28 August 2003 – Published: 13 October 2003

Abstract. An open-top-chamber (OTC) CO₂ enrichment ($\sim 720 \mu\text{mol mol}^{-1}$) study was conducted in the Colorado shortgrass steppe from April 1997 through October 2001. Aboveground plant biomass increased under elevated CO₂ and soil moisture content was typically higher than under ambient CO₂ conditions. Fluxes of CH₄, CO₂, NO_x and N₂O, measured weekly year round were not significantly altered by CO₂ enrichment over the 55 month period of observation. During early summer of 2002, following the removal of the open-top-chambers from the CO₂ enrichment sites in October 2001, we conducted a short term study to determine if soil microbial processes were altered in soils that had been exposed to double ambient CO₂ concentrations during the growing season for the past five years. Microplots were established within each experimental site and 10 mm of water or 10 mm of water containing the equivalent of 10 g m⁻² of ammonium nitrate-N was applied to the soil surface. Fluxes of CO₂, CH₄, NO_x and N₂O fluxes within control (unchambered), ambient CO₂ and elevated CO₂ OTC soils were measured at one to three day intervals for the next month. With water addition alone, CO₂ and NO emission did not differ between ambient and elevated CO₂ soils, while CH₄ uptake rates were higher and N₂O fluxes lower in elevated CO₂ soils. Adding water and mineral N resulted in increased CO₂ emissions, increased CH₄ uptake and decreased NO emissions in elevated CO₂ soils. The N addition study confirmed previous observations that soil respiration is enhanced under elevated CO₂ and N immobilization is increased, thereby decreasing NO emission.

1 Introduction

During the past few decades the atmospheric concentration of CO₂ has increased at historically unprecedented rates, as have N₂O and CH₄ concentrations (IPCC, 2001). Increasing CO₂ concentrations will have a direct effect on plant production and plant communities and indirectly feed back into a number of soil biotic systems that influence long term ecosystem viability (Hungate et al., 1997a, b, c; Owensby et al., 1993a). The impact of elevated CO₂ on the shortgrass steppe, which is used extensively for grazing and is similar to regions which occupy about 8% of the U.S. and about 11% of global land area (Bailey, 1979) has not been previously addressed. These interactive feedbacks on the soil C and N cycles and their influence on trace gas fluxes have potentially important impacts on the global atmospheric budgets of the gases and the long term sustainability of the grassland. Earlier studies within the shortgrass steppe have demonstrated that such grasslands play an important role as consumers of atmospheric CH₄, and producers of N₂O (Mosier et al., 1991; 1996; 1997). Doubling CO₂ had little impact on trace gas fluxes in the shortgrass steppe (Morgan et al., 2001; Mosier et al., 2002a). The few measurements of NO_x, N₂O, CH₄ and CO₂ fluxes in CO₂ enrichment studies in other ecosystems have given contradictory results.

Growth chamber studies suggest that plant C/N ratios, nitrogen use efficiency and water use efficiency all increase under elevated CO₂ (Drake et al., 1996; Morgan et al., 1994; Rogers et al., 1994). In the short term, increases in soil moisture content resulting from higher water use efficiency (Hungate et al., 1997a, b, c) may accelerate rates of C and N mineralization, increasing N availability for plant uptake. Over the long term, however, decreased litter quality is expected to increase N immobilization rates and reduce N availability for plant uptake. From these observations we hypothesized that initially elevated CO₂ would induce increased soil

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Table 1. Selected soil properties* of the soil at the Open-Top-Chamber study site

Soil Depth (cm)	Sand	Silt %	Clay	pH	Total N %	Total C %	Bulk Density g cm ⁻³
0–10	76	14	10	7.3	0.101	0.891	1.28
10–20	74	15	11	8.1	0.077	0.606	1.42
20–30	74	13	13	8.0	0.076	0.584	1.48

*Gravimetric soil water content for the 0–15 cm depth at water filled pore space of 0.2, 0.4 and 0.6 is 7.2, 14.4 and 21.6 kg kg⁻¹, respectively (Mosier et al., 1998).

moisture and increased N mineralization rates (Hunt et al., 1988). As a result, CO₂, NO and N₂O emissions should increase on the short term under elevated CO₂, while CH₄ uptake should decrease. Over the longer term, however, increased C/N ratios in plant litter and roots would result in longer term decreases in N mineralization rates, and decreased NO and N₂O fluxes would be observed. To test these responses, Mosier et al., (2002a) monitored the soil-atmosphere exchange of CO₂, NO_x, N₂O and CH₄ weekly, year-round, April 1997 to November 2001 on unchambered control, ambient CO₂ and ~720 μmol mol⁻¹ CO₂ experimental plots in the Colorado shortgrass steppe. Mosier et al., (2002a, b) observed no statistically significant CO₂ enrichment effect on ecosystem respiration, oxidation of atmospheric CH₄, or emissions of NO_x or N₂O. Methane oxidation tended to be higher under elevated CO₂ while NO_x and N₂O tended to be lower, but not significantly in either case. Above ground biomass production was higher under elevated CO₂ (Morgan et al., 2001), which utilized more soil N (King et al., 2003). However, soil N mineralization was probably enhanced under elevated CO₂ because of more moist soils (Hungate et al., 1997a, b, c). The two opposing processes apparently offset each other because NO_x and N₂O emissions, which reflect system N mineralization and nitrification, did not differ. Ecosystem respiration, which included soil and aboveground plant respiration, was not generally higher under elevated CO₂ (Mosier et al., 2002a). During the 5 years of the study trace gas exchange measurements suggested that soil microbial processes were not greatly altered under double CO₂ concentrations, at least in the short term. Plant production during a year of above average rainfall did, however, appear to be limited by N availability (King et al., 2003). By analyzing the concentration of soil CO₂ at different depths in the OTCs and calculating soil respiration, Pendall et al., (2003) found that elevated CO₂ increased soil respiration by about 25% in a moist growing season and by about 85% in a dry season. Significant increases in soil respiration rates occurred only during dry periods. δ¹³C analyses of soil CO₂ revealed that soil organic matter decomposition rates were more than doubled under elevated CO₂ whereas rhizosphere respiration rates were not changed. Estimates of net ecosystem production, which account for both inputs and losses of

carbon, suggest that soil carbon sequestration is not increased under elevated CO₂ during dry years, but may be in wet years (Pendall et al., accepted).

We were interested to determine if residual effects on microbial processes persisted following CO₂ enrichment. During early summer of the year following the removal of the open-top chambers from the CO₂ enrichment sites we conducted a short term study to determine if soil microbial processes were altered in soils that had been exposed to double ambient CO₂ concentrations during the growing season for the past five years. The response of emissions of CO₂, NO_x and N₂O and the uptake of atmospheric CH₄ to water addition and water and mineral nitrogen fertilization to soils that had or had not been exposed to elevated CO₂ are reported in this paper.

2 Materials and Methods

The CO₂ enrichment studies were conducted at the USDA/ARS Central Plains Experimental Range (CPER) on which is located the Shortgrass Steppe long-term-ecological-research (LTER) project, about 60 km NE of Fort Collins, CO, USA (40°50' N, 104°42' W). The semiarid grassland site is at 1650 m elevation and has a long term average annual precipitation of ~320 mm with mean summer air temperatures of 15.6°C and 0.6°C mean winter air temperatures (Morgan et al., 2001). Annual mineral nitrogen input is an estimated 0.5 g N m⁻² mainly through wet and dry atmospheric deposition (Mosier et al., 1996).

Experimental Site

In the fall of 1995, vegetation and soil surveys were conducted in native shortgrass steppe at the experimental site. The survey results enabled a selection of relatively similar experimental plots on the basis of soil and plant community information and documented plot differences before the treatments were implemented. The grassland community is comprised of over 25 species of forbs and grasses, but dominated by three grass species, *Bouteloua gracilis* (C₄, accounts for approximately 42% of total

aboveground biomass), *Pascopyrum smithii* (C₃, 21% of total aboveground biomass) and *Stipa comata* (C₃, 26% of total aboveground biomass). After 5-years of exposure to double ambient CO₂ concentrations the plant species composition had changed to approximately 50% *Stipa comata* (Morgan et al., 2003). Nine experimental plots of similar plant species composition were selected on the basis of this initial survey. The soil within the study site is a Remmit fine sandy loam (Ustollic camborthids) which holds 18% (gravimetric) water at field capacity, and 4% at the permanent wilting point (Table 1).

On six of the nine plots, open-top chambers (4.5 m diameter by 3 m height) of similar design to Owensby et al., (1993a, b) were installed in March 1997 (Morgan et al., 2001a). All chambers were equipped with blowers to exchange ~1.5 air volumes per minute. Three of the chambers had precision valve outlets located in-line between the blowers and the chambers and attached to a compressed CO₂ source for elevating CO₂ to approximately 720 mol mol⁻¹. Carbon dioxide in the chambers was controlled only during the growing season, from early April to late October. Chambers were removed in the winter. Daily precipitation was measured at a meteorological station located about 50 m from the OTCs. The CO₂ enrichment was terminated in late October of 2001.

Establishment of Microplots and Trace Gas Flux Measurements

In late April, 2002 two microplots and gas flux sampling locations were established by driving flux chamber anchors (20 cm diameter, 10 cm high PVC cylinder) 8 cm into the soil within each OTC and control (unchambered) plot. In the morning of 11 June 2002, water (1-cm) or water plus N-fertilizer (1-cm of water containing the equivalent of 10 g N m⁻² of ammonium nitrate) was added to each microplot. Soil moisture was the same in all treatments at the beginning of this study and emissions of all trace gases were small at this time. We measured fluxes of NO_x, N₂O, CH₄ and CO₂, two hours after water addition and then at one to three day intervals until 12 July 2002. Measurements were typically made midmorning of each sampling day using vented closed chambers (Hutchinson and Mosier, 1981; Mosier et al., 1991) where the changes in concentration of N₂O, CO₂ and CH₄ within the chamber were measured by withdrawing samples from the chamber by syringe at three time periods and analyzing the gas concentrations by gas chromatography (Mosier et al., 1996; 1997; 1998). Nitric oxide flux was monitored from the same chamber anchors on the same day using a flow-through chamber system (Martin et al., 1998) and a Thermo Environmental Instruments model 42C chemiluminescence NO-NO₂-NO_x analyzer that is housed in the instrument trailer (Mosier et al., 1998). NO_x emissions from the soil are typically >90% NO, so fluxes will generally be discussed in terms of NO only (Martin et

al., 1998; Mosier et al., 1998). Air and soil temperatures were monitored at each flux measurement using a hand held digital thermometer.

Statistical Analyses

Gas flux measurements, soil moisture and soil temperatures within each treatment replicate (OTC or unchambered location) were averaged (n=3) for each observation time. Over the month long analysis period the eleven flux measurements were averaged and single factor analysis of variance was performed (Microsoft Excel). Individual CO₂ treatments were compared for a designated time interval using a paired t-test. Significance levels of 0.05 were used unless specifically noted.

3 Results and Discussion

Trace Gas Fluxes

During the five year study prior to the N-addition experiment NO_x flux averaged 4.3 in ambient and 4.1 μg N m⁻² hr⁻¹ in elevated chambers. NO_x flux was negatively correlated to plant biomass production. Nitrous oxide emission rates averaged 1.8 and 1.7 μg N m⁻² hr⁻¹, CH₄ flux rates averaged -31 and -34 μg C m⁻² hr⁻¹ and ecosystem respiration averaged 43 and 44 mg C m⁻² hr⁻¹ under ambient and elevated CO₂, respectively, over the same time period (Mosier et al., 2002a, b). We conducted the short-term N-addition to see if any residual effects of elevated CO₂ remained during the growing season following the five years of CO₂ fumigation and found that some important changes in soil microbial responses resulting from CO₂ enrichment.

NO and N₂O Emissions

Under the hot and very dry conditions at the study site when this study was initiated NO and N₂O emissions are typically very low (Mosier et al., 1998). NO emissions from the control soils were higher than from soils that had been under ambient or CO₂ enriched chambers when the soils were irrigated (Table 2). This response was similar to the long term NO fluxes observed where control soil NO emissions averaged 11 μg m⁻² hr⁻¹ compared to 4.3 and 4.1 in ambient and CO₂ enriched chambers (Mosier et al., 2002a). Plant production and uptake of nitrogen was opposite this trend with plant biomass being greater under elevated CO₂>ambient CO₂>unchambered control (Morgan et al., 2001). This suggests that N availability for NO production by nitrifiers is partly regulated by plant uptake (Mosier et al., 2002a). Nitrous oxide emissions were significantly lower (P<0.05) from soils that had been exposed to elevated CO₂ (Table 2). This may also reflect the lower N availability to soil microbes under elevated CO₂ due

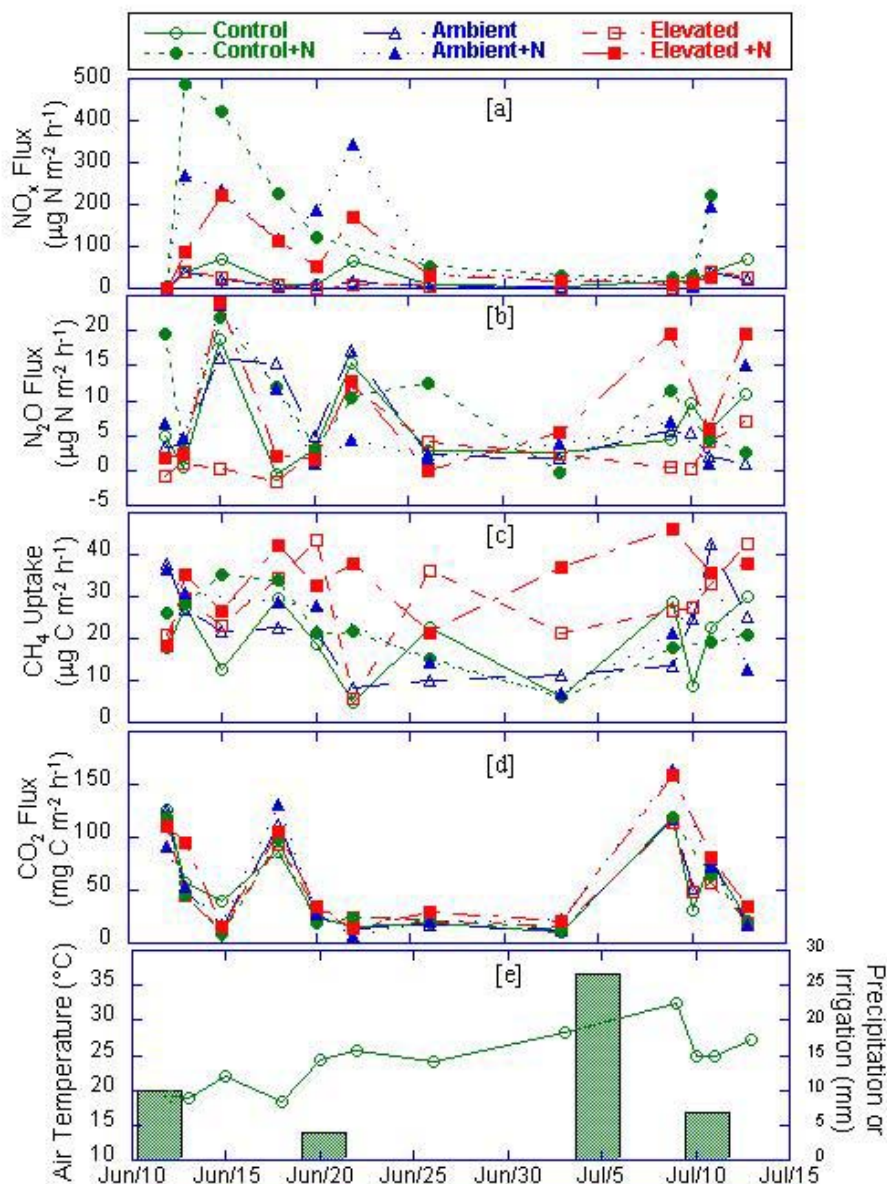


Fig. 1. Trace gas flux, air temperature and soil water content in ambient and elevated CO₂ chambers: (a) NO_x flux; (b) N₂O flux; (c) uptake of atmospheric CH₄ by soil micro-organisms; (d) dark chamber CO₂ flux which includes above ground plant respiration, plant root respiration and soil microbial respiration; (e) air temperature at time of flux measurements and water addition and precipitation.

to enhanced plant production (King et al., 2003). Soil mineral N concentrations were typically very low (<1 mg/kg) in all treatments (Mosier, unpublished data). Both N₂O and to a lesser extent NO emissions increased following water application (Figs. 1a and b). Over the measurement period when water alone was added, NO/N₂O ratios ranged between 2 and 5 with the highest in the elevated CO₂ soils.

When NH₄NO₃ was added N₂O flux tripled in elevated CO₂ soils ($P < 0.05$), and increased slightly in control and ambient chamber soils ($P > 0.05$). NO emissions and N₂O emissions in N-fertilized soils increased markedly following

each irrigation and precipitation event (Figs. 1a, b, and e). Nitric oxide fluxes increased almost 10 fold with N addition in control and ambient CO₂ soils but only about 5-fold in elevated CO₂ soils. NO emissions were significantly lower from elevated CO₂ soils than from control or ambient CO₂ soils, again indicating the lower availability of N in the elevated CO₂ soils. Hungate et al., (1997b, c) found that, during wet up, NO emissions were depressed by 55% in high nutrient conditions under elevated CO₂ (ambient+360 µmol mol⁻¹) while there was no difference among treatments in N₂O emissions. They attributed the

Table 2. Mean mean trace gas flux rates within the shortgrass steppe open-top-chamber CO₂ enrichment study area the summer following 5-years of CO₂ enrichment, 11 June–12 July 2002

CO ₂ Treatment	CO ₂ mg C m ⁻² hr ⁻¹	CH ₄ μg C m ⁻² hr ⁻¹	NO _x μg N m ⁻² hr ⁻¹	N ₂ O
Water Only				
Control	52a	−19b	25a	6.5a
Ambient	53a	−22b	13b	6.6a
High	49a	−28a	13b	2.6b
Water + N				
Control	50b	−22b	160a	9.1a
Ambient	57b	−24ab	121a	7.4a
High	64a	−34a	63b	8.6a

*Numbers in each column followed by the same letter are not significantly different ($P > 0.05$).

decreased NO emissions under elevated CO₂ to increased N immobilization. Increased utilization of added N by soil microbes, thus a decrease in NO emissions, appears to be the case in this study as well (Table 2).

CO₂ and CH₄ Fluxes

Plant growth during the time of the study was virtually nonexistent because of the very low amount of precipitation that had fallen in the preceding year. Ecosystem CO₂ flux (dark chamber respiration which includes plant, root and soil microbial respiration) increases following water addition were similar in all soils (Fig. 1d; Table 2). Only with water+N addition did CO₂ fluxes from elevated CO₂ soils exceed those from control and ambient soils ($P < 0.05$). Microbial respiration appears to be enhanced under elevated CO₂ (Pendall et al., 2003), especially when microbes are not limited by water or N availability. N addition appeared to stimulate soil microbial respiration while decreasing NO emissions because of increased microbial immobilization of added N. Hu et al., (2001) suggest that over the long term, soil microbial decomposition is slowed under elevated CO₂ because of N limitation. The rate of uptake of atmospheric CH₄ was significantly greater ($P < 0.05$) in elevated CO₂ soils than either control or ambient CO₂ soils (Fig. 1c; Table 2). CH₄ uptake rates were not measurably enhanced with N addition in control or ambient CO₂ soils but tended to be greater in elevated CO₂ soils ($P > 0.05$). During the 5-years of CO₂ enrichment CH₄ uptake rates tended to be higher under elevated CO₂. This short term study suggests that a microbial population developed under elevated CO₂ which tended to increase utilization of atmospheric CH₄. Ineson et al., (1998) observed lower CH₄ uptake rates under elevated CO₂ within a free-atmosphere CO₂-enrichment (FACE) study in Switzerland. They also observed lower CO₂ respiration rates and increased N₂O emissions under elevated CO₂. McLain et al., (2002) also observed lower

CH₄ consumption rates under elevated CO₂ in a pine plantation. The decrease in CH₄ consumption was attributed, in part to wetter soils under elevated CO₂. Soil conditions in the pine forest were likely much more comparable to the grassland soils in Switzerland (Ineson et al., 1998) than to the much drier conditions in the Colorado shortgrass steppe. The wetter soil conditions under elevated CO₂ in the Colorado grassland (Ferretti et al., 2003) likely produced more favorable conditions for methanotrophic activity, rather than limiting CH₄ diffusion into the soil in the Swiss grassland (Ineson et al., 1998) and the pine forest (McLain et al., 2002).

Summary

In a semi-arid shortgrass steppe, addition of water and ammonium nitrate to soils that had been exposed to double-ambient CO₂ concentrations during the growing season of the previous five years increased ecosystem respiration and atmospheric CH₄ oxidation and decreased NO emissions. These observations suggest that methanotroph populations were enhanced under elevated CO₂ while soil N supply was depleted by increased plant growth (King et al., 2003; Morgan et al., 2001). Soil respiration was higher in elevated CO₂ soils following irrigation and N addition, suggesting that microbes were becoming N limited. Although decomposition rates were twice as high under elevated as ambient CO₂ mid-way through the 5-year experiment (Pendall et al., 2003), the N fertilization response observed here suggests that eventually microbial decomposition rates will slow, as predicted by Hu et al., (2001), leading to increased C sequestration potential.

Acknowledgements. We thank David Jensen who collected the trace gas data. We also thank the Terrestrial Ecology and Climate Change Initiative grants (NSF-IBN-9524068 and USDA/NRICGP-98-134), NSF DEB-9708596 for funding support, for SGS-LTER that provided partial salary support for David Jensen and USDA-ARS which provided the remaining support for this project.

References

- Bailey, H. P.: Semiarid climates: Their definition and distribution, in: *Agriculture in Semiarid Environments*, edited by Hall, A. E., Cannell, G. H., and Lawton, H. W., Springer-Verlag NY, NY, 73–97, 1979.
- Drake, B. G., Gonzalez-Meler, M. A., and Long, S. P.: More efficient plants: A consequence of rising atmospheric CO₂?, *Annual Review of Plant Physiology and Molecular Biology*, 48, 607–637, 1996
- Ferretti, D. F., Pendall, E., Morgan, J. A., Nelson, J. A., LeCain, D., and Mosier, A. R.: Partitioning evapotranspiration fluxes from a Colorado grassland using stable isotopes: Seasonal variations and implications for elevated atmospheric CO₂, *Plant and Soil*, in press, 2003.
- Hu, S., Chapin III, F. S., Firestone, M. K., Field, C. B., and Chiariello, N. R.: Nitrogen limitation of microbial decomposition in a grassland under elevated CO₂, *Nature*, 409, 188–191, 2001.
- Hunt, H. W., Ingham, E. R., Coleman, D. C., Elliott, E. T. and Reid, C. P. P.: Nitrogen limitation of production and decomposition in prairie, mountain meadow, and pine forest, *Ecology*, 69, 1009–1016, 1988.
- Hungate, B. A., Canadell, J., and Chapin, E. S.: Plant species mediate changes in soil microbial N in response to elevated CO₂, *Ecology*, 77, 2505–2515, 1996.
- Hungate, B. A., Holland, E. A., Jackson R. B., Chapin, F. S., Mooney, H. A., and Fields, C. B.: The fate of carbon in grasslands under carbon dioxide enrichment, *Nature*, 388, 576–579, 1997a.
- Hungate, B. A., Lund, C. P., Pearson, H. L., and Chapin, F. S.: Elevated CO₂ and nutrient addition alter soil N cycling and N trace gas fluxes with early season wet-up in a California annual grassland, *Biogeochemistry*, 37, 89–109, 1997b.
- Hungate, B. A., Chapin, F. S., Zhong, H., Holland, E. A., and Field, C. B.: Stimulation of grassland nitrogen cycling under carbon dioxide enrichment, *Oecologia*, 109, 149–153 1997c.
- Hutchinson, G. L. and Mosier, A. R.: Improved soil cover method for field measurement of nitrous oxide fluxes, *Soil Sci. Soc. Am. J.*, 45, 311–316, 1981.
- Ineson, P., Coward, P. A., and Hartwig, U. A.: Soil gas fluxes of N₂O, CH₄ and CO₂ beneath *Lolium perenne* under elevated CO₂: The Swiss free air carbon dioxide enrichment experiment, *Plant and Soil*, 198, 89–95, 1998.
- IPCC (Intergovernmental Panel on Climate Change): Technical Summary of the 3rd Assessment Report of Working Group 1, Albritton, D. L. and Meira Filho, L. G. (Co-ordinating lead authors), 63 p. 2001.
- King, J. Y., Mosier, A. R., Morgan, J. A., LeCain, D. R., and Milchunas, D. G.: Plant nitrogen dynamics in a shortgrass steppe under elevated atmospheric CO₂, *Ecosystems*, in press, 2003.
- Martin, R. E., Scholes, M. C., Mosier, A. R., Ojima, D. S., Holland, E. S. and Parton, W. J.: Controls on annual emissions of nitric oxide from soils of the Colorado shortgrass steppe, *Global Biogeochem. Cycles*, 12, 81–91, 1998.
- McLain, J. E. T., Kepler, T. B., and Ahmann, D. M.: Below-ground factors mediating changes in methane consumption in a forest soil under elevated CO₂, *Global Biogeochemical Cycles* 16: (23)1–14, 2002.
- Morgan, J. A., Knight, W. G., Dudley, L. W. and Hunt, H. W.: Enhanced root system C-sink activity, water relations and aspects of nutrient acquisition in mycotrophic *Bouteloua gracilis* subjected to CO₂ enrichment. *Plant and Soil*. 165, 139–146, 1994.
- Morgan, J. A., LeCain, D. R., Mosier, A. R., and Milchunas, D. G.: Elevated CO₂ enhances water relations and productivity and affects gas exchange in C₃ and C₄ grasses of the Colorado shortgrass steppe, *Global Change Biology*, 7, 451–466, 2001.
- Morgan, J. A., Mosier, A. R., Milchunas, D. G., LeCain, D. R., Nelson, J. A., and Parton, W. J.: CO₂ enhances productivity but alters species composition and reduces forage quality in the Colorado shortgrass steppe, *Ecological Applications*, accepted April 4, 2003.
- Mosier, A. R., Schimel, D. S., Valentine, D. W., Bronson, K. F., and Parton, W. J.: Methane and nitrous oxide fluxes in native, fertilized, and cultivated grasslands, *Nature*, 350, 330–332, 1991.
- Mosier, A. R., Valentine, D. W., Parton, W. J., Ojima, D. S., Schimel, D. S., and Delgado, J. A.: CH₄ and N₂O fluxes in the Colorado shortgrass steppe: I. Impact of landscape and nitrogen addition, *Global Biogeochemical Cycles*, 10, 387–399, 1996
- Mosier, A. R., Parton, W. J., Valentine, D. W., Ojima, D. S., Schimel, D. S. and Heinemeyer, O.: CH₄ and N₂O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change, *Global Biogeochemical Cycles*, 11, 29–42, 1997.
- Mosier, A. R., Parton, W. J., and Phongpan, S.: Long-term large N and immediate small N addition effects on trace gas fluxes in the Colorado shortgrass steppe, *Biol. Fertil. Soils*, 28, 44–50, 1998.
- Mosier, A. R., Morgan, J. A., King, J. Y., LeCain, D., and Milchunas, D. G.: Soil-atmosphere exchange of CH₄, CO₂, NO_x and N₂O in the Colorado shortgrass steppe under elevated CO₂, *Plant and Soil*, 240:200–211, 2002a.
- Mosier, A. R., Morgan, J. A., King, J. Y., LeCain, D., and Milchunas, D. G.: Soil-atmosphere exchange of CH₄, CO₂, NO_x, and N₂O in the Colorado Shortgrass Steppe under Elevated CO₂, 7th Scientific Conference of the International Global Atmospheric Chemistry, Heraklion, Crete Greece, 18–25 September 2002, 2002b.
- Owensby, C. E., Coyne, P. I., and Auen, L. M.: Nitrogen and phosphorus dynamics of a tall grass prairie ecosystem exposed to elevated carbon dioxide, *Plant Cell Environ.*, 16, 843–850, 1993a.
- Owensby, C. E., Coyne, P. I., Ham, J. M., Auen, L. M. and Knapp, A. K.: Biomass production in a tallgrass prairie ecosystem exposed to ambient and elevated CO₂, *Ecol. App.*, 3, 644–653, 1993b.
- Pendall, E., Del Grosso, S., King, J. Y., LeCain, D. R., Milchunas, D. G., Morgan, J. A., Mosier, A. R., Ojima, D. S., Parton, W. A., Tans, P. P., and White, J. W. C.: Elevated atmospheric CO₂ effects and soil water feedbacks on soil respiration components in a Colorado grassland, *Global Biogeochemical Cycles*, 17, 1046, 2003.
- Pendall, E., King, J. Y., Mosier, A. R., Morgan, J. A., and Milchunas, D. S.: Stable isotope constraints on net ecosystem production in elevated CO₂ experiments, in: *Stable isotopes and biosphere atmosphere interactions*, edited by Flanagan, L., Ehleringer, J., and Pataki, D., accepted, 2003.
- Rogers, H. H., Runion, G. B., and Krupa, S. V.: Plant responses to atmospheric CO₂ enrichment with emphasis on roots and the rhizosphere, *Environ. Pollu.*, 83, 155–189, 1994.