Studies of Methane Fluxes Reveal That Desert Soils Can Mitigate Global Climate Change

Jean E. T. McLain and Dean A. Martens
Southwest Watershed Research Center, USDA-ARS, Tucson, AZ

Abstract—*Moisture limitations have led researchers to believe that semiarid soils are not significant consumers or producers of trace gases, and these regions are often overlooked in greenhouse gas inventories. We are studying environmental influences on soil fluxes of methane (CH_4) in southeastern Arizona. We found negligible CH_4 consumption in the very dry pre-monsoon period, but the first moisture pulses stimulated soil CH_4 flux. Thereafter, significant CH_4 consumption was found through the summer and winter months. The soil CH_4 consumption averaged 471 ± 278 μg CH_4 m^{-2} d^{-1} throughout the year, confirming the presence of a large, previously unreported CH_4 sink, and strongly suggesting that soils of semiarid ecosystems cannot be discounted in potential mitigation of climate change.*

Introduction

Atmospheric methane (CH_4) concentrations have risen from 0.7 to 1.8 ppm since the beginning of the Industrial Revolution. Methane is a greenhouse gas that has been implicated in global warming (Lelieveld et al. 1993; Rodhe 2001) and thus, its atmospheric concentration is a major focus of global change studies. Although researchers have estimated the contribution of world soils to the budgets of CH_4, flux data are extremely sparse for semiarid ecosystems. Moisture limitations in semiarid life zones have led to the belief that these soils are not significant consumers or producers of trace gases and as a result, semiarid soils are often largely overlooked in greenhouse gas inventories (Bowden 1986; Streigl et al. 1992).

Microbial production and consumption of CH_4 in soils are of crucial importance to the global CH_4 budget. Soil CH_4 production by methanogenic bacteria is a strictly anaerobic process, common in wetland soils with high carbon availability. Soil CH_4 consumption results from the activity of methanotrophic bacteria, organisms that thrive near the soil surface and intercept almost half of all CH_4 produced lower in the soil profile before it is released to the atmosphere. They also consume approximately 40-60 Tg per year of CH_4 directly from the atmosphere (Reeburgh et al. 1993; Watson et al. 1990). As a result, soils are the largest terrestrial CH_4 sink, in the absence of which atmospheric CH_4 concentrations would increase by at least 1.5 times the current rate (Duxbury 1994).

Only limited scientific information exists on soil CH_4 fluxes in semiarid ecosystems. A single study reported CH_4 consumption rates of 1.87 ± 1.45 mg CH_4 m^{-2} d^{-1} in Mojave Desert soils following rainfall (Striegl et al. 1992). The authors suggested that high rates of CH_4 consumption in semiarid soils may be concentrated in brief periods following wetting events but decreases following soil drying because methanotrophic bacteria are not particularly xerotolerant (King 1997; West and Schmidt 1998).

Clearly, additional structured monitoring of CH_4 fluxes across different dryland vegetation zones is needed to improve our understanding of the role that semiarid soils play in the global CH_4 budget. Because semiarid soils constitute more than 25% of the terrestrial land mass worldwide (Bailey 1996; Potter et al. 1996), research examining the environmental controls of CH_4 production and consumption in these regions is of particular importance. Here we report the results of a monitoring study conducted in two ecosystems in southeastern Arizona. Over 18 months, we monitored gas fluxes and soil environmental variables to quantify CH_4 production and consumption as well as identify the factors controlling CH_4 fluxes in these soils.

Study Sites

San Pedro Riparian National Conservation Area

Our first study area is in the San Pedro Riparian National Conservation Area (SPRNCA) in southeastern Arizona. This Federally managed preserve is the subject of considerable scientific study, as it is a rare remnant of what was once an extensive network of similar riparian systems throughout the Southwest. Here, plants and animals thrive locally because of an availability of water and thus, the SPRNCA represents a unique system to quantify the effects of ecosystem desertification and vegetation change on trace gas fluxes.

Precipitation along the San Pedro averages ~350 mm per year, 60% of which falls in the monsoon season of July to September. We measured CH_4 fluxes in soils of three distinct vegetation types: (1) mesquite (*Prosopis* spp.), an N-fixing desert legume, (2) sacaton (*Sporobolus* spp.), a coarse perennial bunchgrass, and (3) a mixture of annual grasses and forbs.

Santa Rita Experimental Range

Our second area includes three vegetation zones in the Santa Rita Experimental Range (SRER), a Sonoran Desert grassland with a history of grazing dating back to the late 19th century. This area receives approximately 325 mm of rainfall per year, 60% of which falls in the summer monsoon season. Overgrazing and fire suppression have induced major vegetation changes in this area since the early 1900s. Currently, mesquite is the dominant overstory species on the majority of the rangeland where shrub-free grassland dominated 80 years ago. The non-native Lehman's lovegrass (*Eragostis lehmanniana*) is the dominant grass. We monitored CH_4 fluxes under a mesquite canopy, in a grass-dominated area, and an area over a mesquite stump that was killed by herbicides about 40 years ago.

Methods

Trace gas monitoring in the SPRNCA began in June 2002. Monitoring was done once or twice weekly during the summer monsoon period, and monthly or bi-monthly in the fall and winter. Trace gas monitoring in the SRER began in June 2003 and was done bi-weekly through the end of the monsoon period. Methane fluxes were measured by the static chamber technique using 22-cm diameter PVC chambers permanently installed at the soil surface. On sampling dates, lids were firmly affixed to the chamber surface and sub-samples of the chamber atmosphere were removed using gas tight syringes every 15 min for 1 h. Gas samples were analyzed in the laboratory using a Shimadzu GC14-A Gas Chromatograph fitted with a Flame Ionization Detector. Certified CH_4 standards (Praxair Inc., San Ramon, CA) were used for calibration. Net fluxes were calculated from the exponential regression of the time series of CH_4 concentrations (Koschorreck and Conrad 1993).

Environmental variables thought to impact CH_4 fluxes were measured using data logging stations installed at each of the monitoring sites in the SPRNCA and SRER. Every 5 minutes, these stations measured air and dew point temperatures at 60 cm above the soil surface, soil temperature at 15 and 30 cm depths, soil moisture at 5-10, 15, and 30 cm depths, and CO_2 concentrations at 15 cm above the soil surface.

Laboratory incubations to quantify methanotroph activity (CH_4 consumption) were performed once during the monitoring period using SPRNCA soils. Soils collected in 5 cm increments down to 50 cm were incubated under optimum conditions for CH_4 consumption (temperature of 20 °C; moisture of 80% of field capacity). Gas samples were collected from the incubation flasks every 24 h. Flasks were then flushed with ambient air and re-sealed. Methane consumption was calculated from the decrease in headspace CH_4 over the 24 h incubation period. Incubations were performed over a period of five days. In order to localize maximum CH_4 consumption *in situ*, and to quantify the effects of soil moisture on that activity, soil gas probes were installed in September 2003 at the Santa Rita sites. These probes allowed us to collect soil porespace gases at nine depths from 5 to 100 cm.

Results and Discussion

San Pedro Riparian National Conservation Area

SPRNCA surface soils were extremely dry in early July 2002, as the sites had received only 15 mm of precipitation in the previous 9 months. The first flux measurements on July 16, 2002, showed CH_4 consumption rates close to zero (figure 1). The arrival of monsoon precipitation on July 18 induced the development of a sizeable CH_4 sink, which continued through the winter and spring of 2003. Methane consumption averaged 25.7 ± 6.8, 32.6 ± 8.8, and 20.1 ± 6.8 µg CH_4 m^{-2} h^{-1} in the mesquite, open, and sacaton sites from July 2002 through April 2003 (figure 1), representing a net CH_4 sink similar in magnitude to that of temperate forest soils, reported to average 33.4 ± 28.3 µg CH_4 m^{-2} h^{-1}(Koschorreck and Conrad 1993). Lack of rain in May and June 2003 reduced the soil CH_4 sink strength by 25 to 55% in all three sites, but maximum CH_4 consumption rates were restored with the onset of monsoon rainfall in July 2003 and thereafter averaged 26.4 ± 6.8, 30.1 ± 10.8, and 7.5 ± 6.2 µg CH_4 m^{-2} h^{-1} in the mesquite, open, and sacaton sites through the end of the monsoon season in September 2003. This finding of sizeable CH_4 consumption nearly year-round was somewhat surprising, given that semi-arid soils had previously not been thought to contribute strongly to the terrestrial CH_4 sink.

Results of the laboratory incubations of SPRNCA soils collected in July 2002 showed that under optimum environmental conditions (moist soils, moderate temperatures), the largest CH_4 consumption rates occurred at a depth of 10-15 cm below the soil surface (figure 2), slightly deeper than that reported for temperate forest soils (Koschorreck and Conrad 1993). It should be noted, however, that the conditions imposed on these soils in the laboratory were rare *in situ*, as optimum moisture

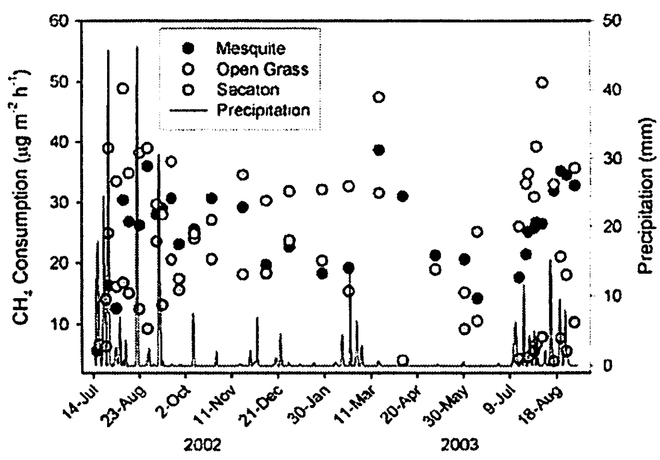

Figure 1—Soil methane consumption in three vegetation zones of the San Pedro Riparian Area from July 2002 through September 2003.

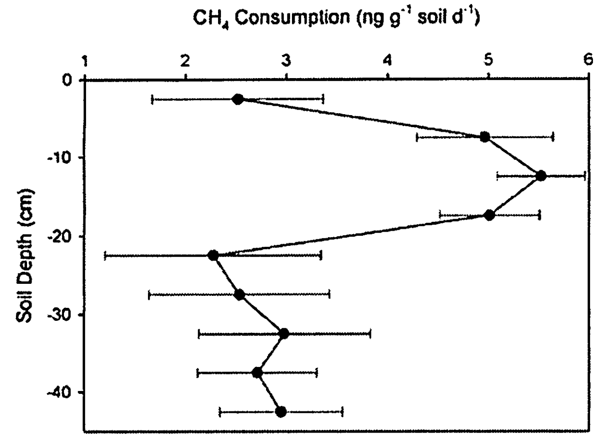

Figure 2—Methane oxidation in laboratory incubations of soils (0-50 cm depth) collected from the San Pedro Riparian Area.

levels (80% field capacity) were measured only three times during the summer of 2002 following rainfalls of 30 mm or greater, and were never measured during the summer of 2003.

Santa Rita Experimental Range

Monitoring of CH_4 flux in SRER soils began before monsoon rains in mid-June 2003. From that time until late fall, mesquite soils showed steady CH_4 consumption, averaging12.2 ± 7.5 µg CH_4 m^{-2} h^{-1} (figure 3), while monsoon CH_4 consumption averaged 8.8 ± 5.2 µg CH_4 m^{-2} h^{-1} in the grassland soil and 8.7 ± 3.6 µg CH_4 m^{-2} h^{-1} in the mesquite stump soil (figure 3).

A very surprising finding was that soils of the grassland and mesquite stump sites were net producers of CH_4 in the extremely dry pre-monsoon season, averaging CH_4 production of 10.3 ± 5.0 and 38.0 ± 18.0 µg CH_4 m^{-2} h^{-1}, respectively (figure 3). During this time, soil moisture potentials were below the permanent wilting point (-1500 kPa) to a depth of at least 30 cm. These conditions would preclude widespread formation of anoxic microsites necessary for soil methanogenic activity. We hypothesize that these differences may be attributable to termite activity in decaying roots. Poth et al. (1995) speculated that networks of underground termite nests could be sources of CH_4 in arid soils, and if so, this soil termite source could reduce the net soil sink for this ecosystem. Additional work is currently ongoing to explore the possibility that methanogenic bacteria are seasonally active in these semiarid soils.

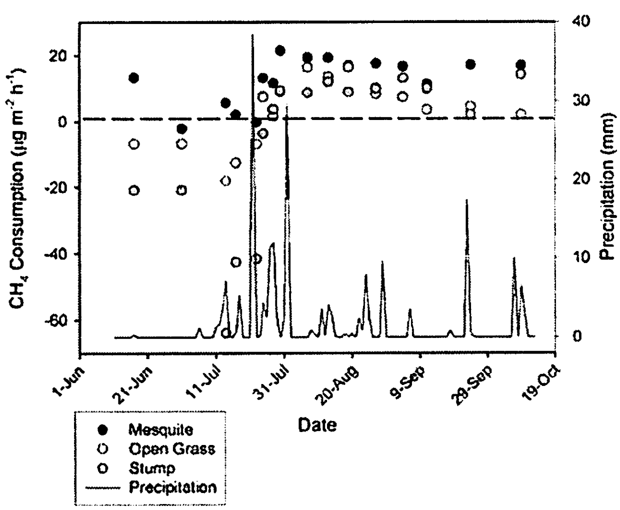

Figure 3—Soil methane flux in three vegetation zones of the Santa Rita Experimental Range from June through September 2003. Positive flux represents methane consumption, while negative flux represents methane production.

Analyses of gases collected from soil probes confirmed that monsoon-moist soils represent a strong sink, reducing porespace CH_4 to < 0.2 ppm (figure 4). In agreement with our laboratory incubation data (figure 2), strong CH_4 consumption activity was found at 5-30 cm depth in soils when moisture was retained in the profile. As soils dried at the end of monsoon rains, CH_4 flux decreased in the surface soils while CH_4 consumption increased at 30+ cm depths in the soil profile. Eleven weeks after the monsoon rains ended, the Santa Rita Range experienced a 20 mm rainfall, and probe measurements taken following this moisture input showed that the belowground CH_4 profile had shifted once again as maximum CH_4 consumption moved upward in the soil in response to the moisture input (figure 4). This data confirms that depth zones of maximum CH_4 consumption change seasonally in semiarid soils and explains, in part, how methanotrophs remain active in semiarid soils during periods of extreme surface soil dryness. Research is ongoing to further elucidate seasonal variations in depth of maximum CH_4 consumption.

Environmental Controls on CH_4 Consumption in Semiarid Soils

Environmental data collected during the summer of 2003 from the SPRNCA weather stations were used to perform some

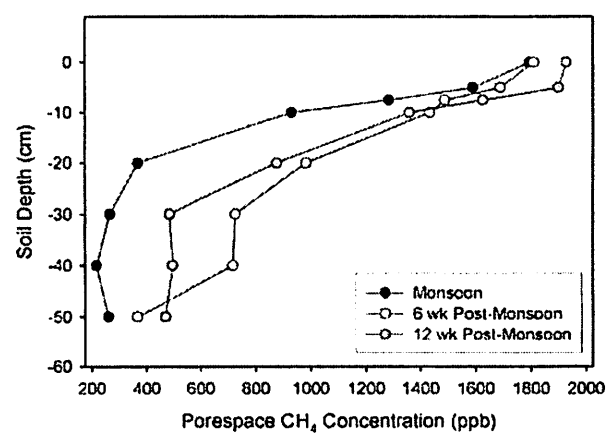

Figure 4—Porespace methane data from Santa Rita Experimental Range, showing alterations in methanotroph activity in response to soil moisture input.

Table 1—Estimated annual CH_4 consumption by San Pedro Riparian Area soils. Monsoon CH_4 consumption is estimated for monsoon period of July through September, non-monsoon consumption reflects fall, winter, and spring (~300 days).

		Consumption		
Area	**Model variables**	**Monsoon CH_4 (mg m^{-2})**	**Non-monsoon (mg m^{-2})**	**Annual total (mg m^{-2})**
Open	Soil moisture, dew point	56.6 ± 5.7	143.0 ± 14.4	199.6 ± 20.1
Mesquite	Moisture, dew point, air temperature	42.6 ± 3.5	120.8 ± 10.0	163.4 ± 13.5
Sacaton	Rainfall, dew point	12.7 ± 1.7	130.1 ± 17.6	142.8 ± 19.3
Average				168.6 ± 18.0

preliminary statistical calculations of the CH_4-consumption capacity of these soils. First, stepwise regression identified the environmental variables that best predicted CH_4 flux over all measurement dates during the summer monsoon period. The three vegetation areas differed slightly in variables predicting net CH_4 consumption (table 1), but in each case the driving environmental variables accounted for nearly 90% of the variability in CH_4 consumption. Using the stepwise regression models, we calculated daily CH_4 consumption for each vegetation zone for the summer of 2003. The monsoon CH_4 consumption data were then extrapolated to non-monsoon seasons using CH_4 flux data collected in 2002. For example, if CH_4 flux in the mesquite site was 20% lower than monsoon rates during December of 2002, then daily December CH_4 consumption for the mesquite was calculated by multiplying the monsoon rates by 0.8. These preliminary calculations indicate average annual CH_4 consumption rates of 168.6 ± 18.0 mg CH_4 m^{-2} in SPRNCA soils (table 1), a significantly larger sink than that estimated for temperate grassland (115.9 mg CH_4 m^{-2}), cool temperate forest (130.8 mg CH_4 m^{-2}), or warm temperate forest (128.4 mg CH_4 m^{-2}) soils throughout the world (Potter et al. 1996). If we assume that our three vegetation measurement areas are representative of the 22,660 ha of the SPRNCA, then the San Pedro soils consume more than 38,000 kg of CH_4 from the atmosphere annually.

Environmental data and CH_4 flux collection from the SRER is ongoing to allow future calculations of a similar nature of annual CH_4 consumption in those soils.

Conclusions

At the San Pedro and Santa Rita sites, we found net CH_4 consumption during periods when surface soils were extremely dry, even though CH_4 consumption has been shown to be intolerant of soil drying in numerous field and laboratory studies. This ongoing study demonstrates an ability of methanotrophic bacteria to adjust their activities upward and downward in soils in response to seasonal drying, allowing semiarid soils to act as a previously underestimated terrestrial sink for CH_4. Although the CH_4 sink strengths measured in the Santa Rita soils were smaller than that measured in temperate soils, the contribution of arid soils to the global CH_4 balance cannot be discounted because semiarid systems represent ~25% of the Earth's land mass. The importance of soil moisture in determining the magnitude and direction of CH_4 flux demonstrates the sensitivity of CH_4 consumption and production to future changes in climate.

The presence of CH_4-producing bacteria in desert soils has been previously confirmed using molecular techniques. Our work is the first, however, to suggest that methanogens in semiarid systems are active when surface soils are extremely dry. Our continued work will utilize isotope pool dilution to elucidate factors controlling the balance of methanotroph and methanogen activity in the SRER soils.

References

Bailey, R. G. 1996. Ecosystem geography. New York: Springer-Verlag, Inc. 204 p.

Bowden, W. B. 1986. Gaseous nitrogen emissions from undisturbed terrestrial ecosystems—an assessment of their impacts on local and global nitrogen budgets. Biogeochemistry. 2(3): 249-279.

Duxbury, J. M. 1994. The significance of agricultural sources of greenhouse gases. Fertilizer Research. 38: 151-163.

King, G. M. 1997. Responses of atmospheric methane consumption by soils to global climate change. Global Change Biology. 3: 351-362.

Koschorreck, M.; Conrad, R. 1993. Oxidation of atmospheric methane in soil: measurements in the field, in soil cores, and in soil samples. Global Biogeochemical Cycles. 7(1): 109-121.

Lelieveld, J.; Crutzen, P. J.; Bruhl, C. 1993. Climate effects of atmospheric methane. Chemosphere. 26(1-4): 739-768.

Poth, M.; Anderson, I. D.; Miranda, H .S.; Miranda, A. C.; Riggan, P. J. 1995. The magnitude and persistence of soil NO, N_2O, CH_4 and CO_2 fluxes from burned tropical savanna in Brazil. Global Biogeochemical Cycles. 9: 503-514.

Potter, C. S.; Davidson, E. A.; Verchot, L. V. 1996. Estimation of global biogeochemical controls and seasonality in soil methane consumption. Chemosphere. 32(11): 2219-2246.

Reeburgh, W. S.; Whalen, S. C.; Alperin, M. J. 1993. The role of methylotrophy in the global methane budget. In: Murrell, J. C.; Kelly, D .P., eds. Microbial growth on C_1 compounds. Andover, UK: Intercept Press: 1-14.

Rodhe, H. 2001. A comparison of the contribution of various gases to the greenhouse effect. Science. 248(4960): 1217-1219.

Striegl, R. G.; Mc Connaughey, T. A.; Thorstenson, D. C.; Weeks, E. P.; Woodward, J. C. 1992. Consumption of atmospheric methane by desert soils. Nature. 357: 145-147.

Watson, R. T.; Rodhe, H.; Oeschger, H.; Siegenthaler, U. 1990. Greenhouse gases and aerosols. In: Houghton, J. T.; Jenkins, G. J.; Ephraums, J. J., eds. Climate change: The IPCC scientific assessment. Cambridge, UK: Cambridge University Press: 1-40.

West, A. E.; Schmidt, S. K. 1998. Wetting stimulates atmospheric CH_4 oxidation by alpine soil. FEMS Microbiology Ecology. 25(4): 349-353.