Vegetation Community Impacts on Soil Carbon, Nitrogen and Trace Gas Fluxes

Dean A. Martens, Jean E. T. McLain

Abstract

Changes in C and N cycling were pronounced with mesquite (*Prosopis* spp.) N inputs into a previously N limited grassland or riparian area. Expansion of mesquite into semi-arid grasslands (*Sporobolus* spp.) increased soil C content and decreased C isotope values compared with soils of non-mesquite grasslands. Cool season litter (2.9% N) collection (October 2001 to March 2002) recovered 66 g mesquite C and 4.5 g mesquite N m^{-2}. Measurement of surface litter present in the different riparian plant communities ranged from 750 g litter m^{-2} (mesquite-sacaton), 598 g litter m^{-2} (mesquite) to160 g litter m^{-2} (annuals and forbs). An estimated 3 to 8 years of high quality plant litter remained on the soil surface under mesquite due to yearly inputs. Soil cores removed from the mesquite understory and incubated at constant moisture potentials determined CO_2–C was linearly respired for up to 80 d indicating the litter remaining on the mesquite soil was highly labile, but the disconnect between high litter fall and low moisture conditions present in the ecosystem allowed the mesquite litter to accumulate. Changes in the chemistry of the mesquite soil, especially the N content, resulted in greater fluxes of the greenhouse gas nitrous oxide compared to grass or sacaton soils, but no differences were found in carbon dioxide evolved from the three sites. Of interest was the finding that the semi-arid soils were a strong sink for atmospheric methane during the majority of the year.

Keywords: riparian, nitrous oxide, carbon dioxide, methane

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Introduction

The abundance of woody plant species in semi-arid environments has increased substantially during the last 50 to 300 yrs with a concomitant observed loss of grassland productivity (Humphrey 1958). Such changes in plant species over a large area have potential regional and global impacts, including increased desertification and changes in watershed hydrology, nutrient cycling, soil erosion and energy fluxes. Shifting dominance among herbaceous and woody vegetation also alters primary production, plant allocation, rooting depth and soil faunal communities that in turn affect nutrient cycling and carbon storage (Jackson et al. 2000).

The quantity and composition of the plant litter falling to the soil surface has a tremendous impact on the composition of the soil carbon (C) and nitrogen (N) pools (Barth and Klemmedson 1978). When water is available during summer rainy periods, semi-arid ecosystem productivity is tightly linked to soil nitrogen availability (Ettershank et al. 1978). Mesquite is a N-fixing legume that produces high quality litter compared with the low N, high fiber litter from native grass vegetation, and thus, the quality and quantity of soil C and N under and in between woody species increases with mesquite abundance (Klemmedson and Barth 1975). Tiedemann and Klemmedson (1973) reported that N availability was up to 15 times higher under mesquite than in adjacent open sites. The increased availability of N under mesquite coupled with the lack of leaching from semi-arid environment can result in very high spatial variability of N and a strong localized impact on N cycling.

In this study, we investigated the distribution of soil C and N content between a mesquite, a mesquite-sacaton, a sacaton (without mesquite), and a brush with forb and annual grass community. The C and N content of the vegetation and the litter fall were also monitored. The greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) were also measured to determine the impact of soil C and N distribution with different vegetation on trace gas fluxes.

Methods

Site and soil sampling

The study site is located along the San Pedro River just south of Fairbank, Arizona on river terraces that were historically composed of grasses and forbs. The study site encompassed three distinct vegetation types, the first dominated by velvet mesquite (*Prosopis velutina*), a leguminous tree (mesquite site). The second soil was dominated by sacaton (*Sporobolus wrightii*), a perennial bunchgrass (sacaton site), and the third was populated by annual herbaceous dicots, including peppergrass (*Lepidium thurberi*), Fremont's goosefoot (*Chenopodium fremontii*), and toothleaf goldeneye (*Viguiera dentata*) (open/outside site). Additional soil samples were taken from a mesquite site with a sacaton under story (mesquite-sacaton). Triplicate soil and litter (O-horizon) samples were collected to a depth of 60 cm from the different vegetation zones, weighed for bulk density determination, processed to remove rocks and passed through a 1 mm sieve.

Litter and soil analyses

Samples were analyzed for pH (2.5 g soil:10 mL 0.05 M CaCl) and C and N by dry combustion with isotope analysis (Europa mass spectrometer). Carbohydrate content (Martens and Loeffelmann 2002) and amino acid content (Martens and Loeffelmann 2003) were extracted by acid digestion and determined by ion chromatograph and pulsed amperometry detection. Mineralization experiments were conducted with cores removed from the site (0-5 cm with litter and 5-10 cm) and incubated at 20°C in 1 liter sealed jars fitted with gas sampling valves. The amount of CO_2-C evolved from the incubations was determined with an infrared gas analyzer (Qubit Systems, Inc., Kingston, Ontario) for up to 78 d.

Trace gas measurement

Nitrous oxide and methane fluxes were measured by the static chamber method (Hutchinson and Mosier 1981) using 22-cm diameter PVC collars permanently installed at the soil surface. Lids were firmly affixed to the collar and 10 ml sub-samples of the chamber atmosphere were removed through a sampling port every 15 min for 1 hour. Gas sub-samples were transported to the laboratory and analyzed within 24 hours using a Shimadzu GC14-A Gas Chromatograph (Shimadzu Corp., Columbia, MD), fitted with dual detectors (Flame Ionization Detector and Electron Capture Detector), and an 80/100 HayeSep-Q column (Supelco, Inc., Bellefonte, PA). Net gas fluxes were then calculated from the exponential regression of the time series of gas concentrations within the chamber headspace (Koschorreck and Conrad 1993).

CO_2 fluxes were also measured using the static chamber with sealed lid. After 1 hour, the headspace air was pumped from the chamber into an infra-red gas analyzer (Qubit Systems, Inc.), and the CO_2 concentration in the chamber headspace was used to quantify net efflux from the soil surface.

Soil moisture potentials were measured at the 0-5 and 5-10 cm depths using permanently installed gypsum blocks and the Delmhorst KS-D1 Soil Moisture Tester system (Delmhorst Instrument Company, Towaco, NJ). Soil temperatures were also monitored on sampling days using a long stem handheld thermometer (Fisher Scientific, Pittsburgh, PA).

Results

Detailed chemical analysis of litter at the soil surface shows vast differences between the plant communities included in this study, indicating that the mesquite has the potential to alter the C and N cycling in this semi-arid riparian area (Table 1). The high N content (up to 3.5% N) of the mesquite litter enhances the under story sacaton grass productivity compared to sacaton sites without the input of mesquite-N. The yearly pulse of mesquite N increased sacaton productivity in the mesquite grove to 550 g (n = 3 plants) of above ground biomass compared with 148 g (n = 3) in the sacaton grassland without mesquite. The increased productivity of the mesquite-sacaton community has resulted in accumulation of large amounts of C and N in the litter and soil horizons (Table 1). The incorporation of mesquite C into the soil C pool can be determined by investigating the soil □$^{13}C/^{12}C$ composition (Table 1). The mesquite tree is a C_3 plant that produces litter with a reduced □$^{13}C/^{12}C$ enrichment of –27‰ compared with the –14 to –15‰ found for the C_4 sacaton grass. The lower ^{13}C content of soils sampled from the mesquite community is an indication of the importance of mesquite inputs to the soil C. Leaf litter fall results from the fall 2001 through spring 2002 found an average yearly input of 66 g litter C and 4.5 g litter N per m^{-2} from the mesquite-dominated communities. This large litter input from the mesquite and mesquite-sacaton sites results in pronounced litter layers not found in the non-mesquite "outside" sites (Figure 1). In mesquite sites, an organic matter build-up representing 3 to 8 yrs of litter fall is present under the trees, due to two possible reasons. First, the litter may increase yearly because of an existing disconnect between litter input and the seasonality of rainfall. The time of maximum litter input (fall and early winter) does not historically coincide with sufficient rainfall necessary to support maximum decomposition. Second, the chemistry of the mesquite litter may render it resistant to decomposition. In addition, seasonal cold winter temperatures may influence the accumulation of litter fall C and N as winter moisture has little impact on litter mineralization due to very cool temperatures that limit microbial activity. Thus the lack of residue mineralization may be due to temperature, moisture, residue biochemistry, or interactions among all three.

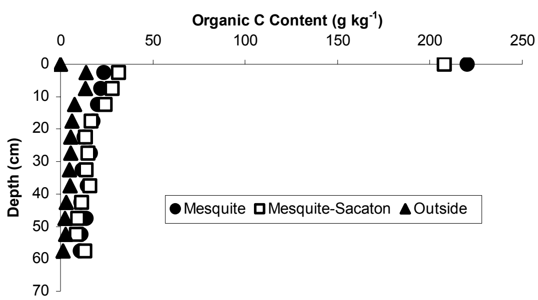

Figure 1. Organic C content of the litter and soil under different vegetation communities to 60 cm.

Laboratory studies found that a substantial portion of the mesquite litter is composed of carbohydrates and amino acids, substrates which do not accumulate in the litter layer or soil in more temperate areas, where plants and microbes favor them as highly labile forms of C and N. When soil and litter samples from the mesquite-sacaton site were incubated at optimum moisture conditions, the mineralization of plant litter and soil C was linear for the 78 d incubation (Figure 2). The results confirm that the mesquite litter will mineralize at a very fast rate if optimum moisture and temperature conditions are present and confirms that litter accumulates in the mesquite sites due to the interaction of the seasonality of precipitation events and soil temperatures.

The high soil N content (Table 1) and the rapid rate of mineralization (Figure 2) result in enhanced sacaton growth as sacaton growing under the mesquite canopy is larger and has a higher leaf N content than sacaton growing in open areas with no mesquite N additions. Enhanced plant productivity resulting from the mesquite-N also translate into increased soil C and N in the mesquite grove. Soil C to a 60 cm depth is twice as high under the mesquite and the mesquite-sacaton communities than in sacaton outside of the mesquite grove (Figure 3).

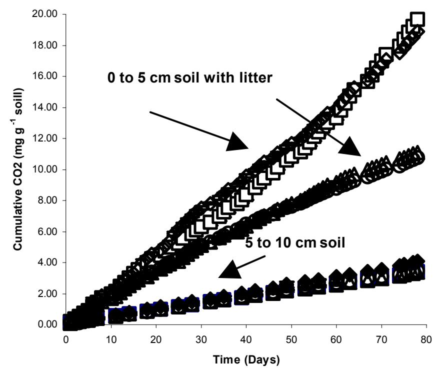

Figure 2. Cumulative carbon dioxide-C evolved from mesquite soil cores incubated at 23 °C for up to 78 d.

The importance of N additions for the increase in soil C has just begun to be understood (Martens and Loeffelmann 2003). It has been shown that N addition from atmospheric or plant fixation is important for stabilization of the N-organic matter mineral complexes (Neff et al. 2002). The close correlation found between N content and C content of the soils in this San Pedro riparian zone is shown in Figure 4.

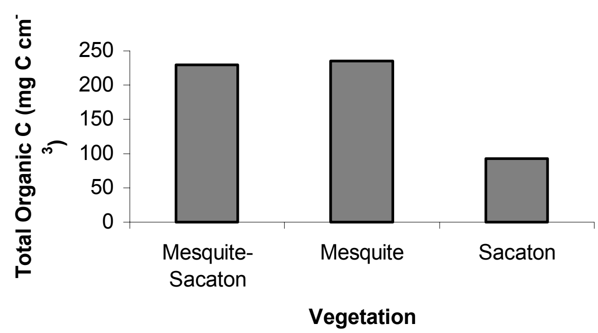

Figure 3. Organic C content to a 60 cm depth accumulating under different vegetation communities.

Because of the wide range in soil C and N under the different vegetation communities (Table 1) and the importance of C and N cycling to the production of greenhouse gases, the fluxes of CO_2, N_2O and CH_4 were monitored to confirm the climate forcing or mitigation potential of this semi-arid riparian zone.

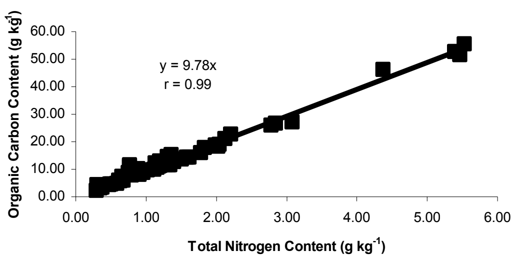

Figure 4. Relationship between C and N in the San Pedro riparian soils.

Nitrous oxide

Field monitoring prior to the 2002 monsoon rains showed that N_2O fluxes were nearly zero in the mesquite, sacaton, and grass/forb "open" vegetation systems (Figure 5), but emissions were evident soon after monsoon moisture inputs began in July. From July through the end of the monsoon in mid-September, N_2O emissions from the mesquite soils averaged 21.02 ± 13.42 µg N_2O m^{-2} h^{-1}, a number ~6 times higher than the sacaton site (3.66 ± 4.70 µg N_2O m^{-2} h^{-1}) and more than 10 times higher than the open site (1.91 ± 3.99 µg N_2O m^{-2} h^{-1}). As soils dried and seasonal temperatures fell after monsoon rainfalls ended in the fall 2002, N_2O emissions in all 3 vegetation sites fell to nearly zero (Figure 5), but increased temporarily in response to sporadic rainfall and warmer temperatures in March and April 2003. Nitrous oxide production was highest following heavy rainfall, leading to a weak, but significant relationship between soil moisture potential

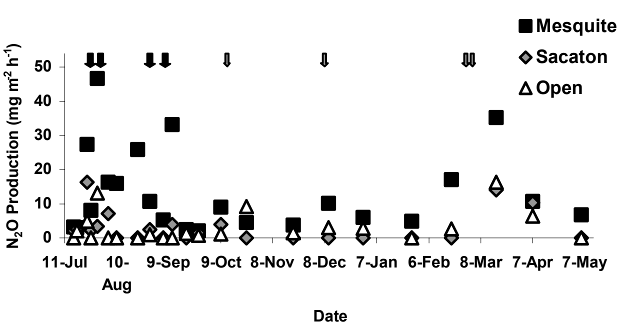

Figure 5. Flux of N_2O from the San Pedro soils in 2002 and 2003. The large arrows indicate moisture events >20 cm and small arrows indicate non-monsoon moisture events >6 cm.

and N_2O efflux across all three sites ($r^2 = 0.33$, $p = 0.01$). When data from each vegetation type was considered separately, however, the correlation between N_2O efflux and soil moisture was only significant in the mesquite ($r^2 = 0.47$, $p = 0.03$) and not in the sacaton ($r^2 = 0.26$, $p = 0.24$) or the open ($r^2 = 0.02$, $p = 0.93$) areas.

Methane

Methane consumption at the soil surface was minimal prior to the start of the monsoon rains in July (Figure 6). Precipitation induced the development of a sizeable CH_4 sink, which was highest during the monsoon season in the open area (-36.35 ± 6.54 µg CH_4 m^{-2} h^{-1}), closely followed by the mesquite (-25.63 ± 7.61 µg CH_4 m^{-2} h^{-1}) and the sacaton (-16.39 ± 5.37 µg CH_4 m^{-2} h^{-1}) sites. Because methanotrophs (methane-consuming microbes) are not particularly xerotolerant (Schnell and King 1996), it was hypothesized that the CH_4 sink would weaken as soils dried in the fall and winter, but surprisingly, the CH_4 sink strength did not disappear with the autumn drying of surface soils (Figure 6). Only when extremely warm and dry conditions prevailed in late spring of 2003 did the CH_4 sink diminish to pre-monsoon levels (Figure 6).

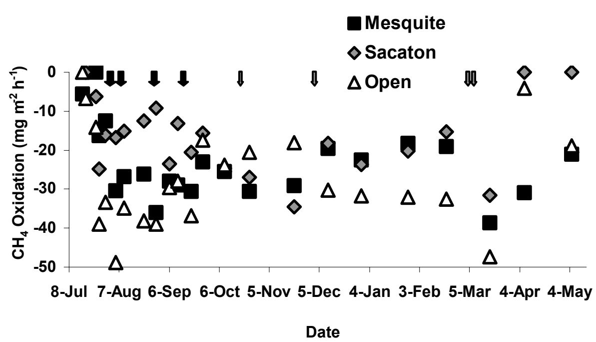

Figure 6. Flux of CH_4 from the San Pedro soils in 2002 and 2003. The large arrows indicate moisture events >20 cm and small arrows indicate non-monsoon moisture events >6 cm.

Statistical analyses showed that neither moisture ($r = 0.0$, $p = 0.99$) nor temperature ($r = 0.02$, $p = 0.32$) was significantly correlated with CH_4 consumption in this semi-arid ecosystem. This result was surprising, given the strong moisture and temperature controls of CH_4 consumption in other ecosystems (Torn and Harte 1996). Laboratory incubations of soils collected in July 2002 from the open system indicate that methanotrophs were most active at the 10-15 cm soil depth (data not shown), agreeing with the close-to-surface maximum in

CH_4 consumption in temperate soils (Koschorreck and Conrad 1993). It is possible, however, that the depth of maximum CH_4 oxidation moves downward in the soil profile as the soil dries after the monsoon season.

Carbon dioxide

CO_2 efflux from the soils under the 3 vegetation types was also low prior to the onset of monsoon rains (27.00 ± 16.93 mg CO_2 m^{-2} h^{-1}). Monsoon moisture input stimulated CO_2 efflux in all 3 vegetation zones, which averaged 241.99 ± 64.30 mg CO_2 m^{-2} h^{-1} in the mesquite site, 240.62 ± 60.74 mg CO_2 m^{-2} h^{-1} in the open site, and 224.90 ± 62.94 mg CO_2 m^{-2} h^{-1} in the sacaton site from July through September. As rainfall decreased and temperatures cooled in the winter and spring, CO_2 production diminished in all three sites, and averaged 49.90 ± 31.87 mg CO_2 m^{-2} h^{-1} in the mesquite site, 37.02 ± 27.83 mg CO_2 m^{-2} h^{-1} in the open site, and 43.63 ± 29.78 mg CO_2 m^{-2} h^{-1} in the sacaton site.

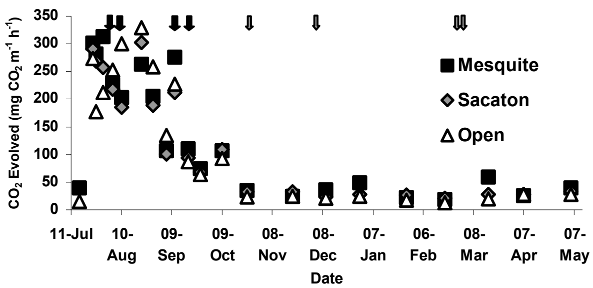

Figure 7. Flux of CO_2 from the San Pedro soils in 2002 and 2003. The large arrows indicate moisture events >20 cm and small arrows indicate non-monsoon moisture events >6 cm.

Monitoring of CO_2, N_2O, and CH_4 fluxes is continuing in the 3 vegetation sites to quantify annual source and sink strengths and to calculate the global mitigation potential of the San Pedro Riparian ecosystem. Preliminary data from the first year of C and N balancing in the San Pedro suggests the existence of a sink of atmospheric C and N in the riparian ecosystem.

Conclusions

The San Pedro riparian zone is a unique oasis in a semi-arid environment. Availability of water in the riparian zone is the driving force that creates this diverse environment. The C and N accumulation in the mesquite under story is mainly due to seasonal moisture limitations that occur in the semi-arid site. Mesquite encroachment in semi-arid systems could significantly impact climate change by creating a sizeable sink for atmospheric C and N. Changes in water availability in the riparian zone, resulting either from climate change or from increased water use in neighboring communities could have tremendously dire impacts on the C and N resources in these plant communities and could thus spell the end of the vibrant San Pedro riparian zone, as has happened in other semi-arid riparian areas in the southwestern United States.

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Table 1. Carbon and nitrogen content and isotope composition of a mesquite, a mesquite-sacaton, a sacaton and a open forb/annual grass communities.

Sample Site (cm)	$\delta^{15}N/^{14}N$	$\delta^{13}C/^{12}C$	Total N	Organic C	C/N Ratio
		-- ‰ --	------- $g\ kg^{-1}$	-------	
Mesquite 0-5	7.09	-25.42	4.79	46.53	9.67
Mesquite 5-10	8.25	-22.50	1.63	15.19	9.32
Mesquite >10	9.17	-19.14	0.92	10.55	10.23
Mesquite-sacaton 0-5	8.07	-21.27	3.08	29.90	9.58
Mesquite-sacaton 5-10	8.95	-18.08	1.27	11.34	8.94
Mesquite-sacaton >10	7.26	-16.74	0.77	8.18	9.02
Sacaton 0-5	7.07	-15.96	1.81	17.61	9.68
Sacaton 5-10	6.95	-15.27	1.21	11.61	9.61
Sacaton >10	6.65	-14.49	1.23	13.48	10.93
Open 0-5	9.38	-18.90	0.63	5.83	9.19
Open 5-10	9.34	-20.01	0.58	6.04	10.16
Open >10	8.86	-17.97	0.37	3.65	9.03

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