Climate Mitigation Potential of the San Pedro River Riparian Zone

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

Abstract—*Carbon (C) and nitrogen (N) cycling within an open brush site, a sacaton (*Sporobolus wrightii*) grass and a mesquite (*Prosopis velutina*) grove, in the riparian zone was closely linked to the yearly litter N inputs. Yearly mesquite litter fall for 2 yr was remarkably similar and averaged 4.0 g N m^{-2} and 65 g C m^{-2} soil and resulted in higher soil C content compared to other riparian vegetation. The riparian soils held 7,000 metric tons more C than an adjacent nonriparian area suggesting the riparian zone processes result in a sink for atmospheric C. Water is essential for ecosystem function, and loss of water from the San Pedro River will severely impact the C sink in the riparian area.*

Introduction

Due to the semi-arid climate, few researchers have speculated on the role of the Madrean Archipelago for forcing or mitigating climate change. Since the mid-1800s, global average temperatures have increased by 0.6 °C, but during the 1990s, North American average temperatures were 0.9 °C warmer than during the centuries prior to Industrial Revolution, and comparison with ice cores, tree rings, and other proxy measures suggests that the warming of the 20th century is unprecedented (National Synthesis Report 2001). Predictions for the 21st century include further temperature increases for the continental United States of 3 to 5 °C, suggesting that current climate change parameters are inducing a positive feed-back mechanism on climate change. Thus it is vital to identify and research known zones of C sequestration as a means for limiting climate change.

Research into semi-arid terrestrial sinks for atmospheric C has been nonexistent due to the perceived notion that due to seasonal moisture deficits, semi-arid regions are not a source or sink for atmospheric C. Semi-arid lands are very sensitive to climate change because if regional temperatures increase or precipitation patterns change, then the rates of soil C mineralization from the existing soil organic C pools will increase, thus limiting the potential of semi-arid soils to sequester C as a mechanism for offsetting increasing levels of atmospheric CO_2.

Water is the most limiting resource to biological activity in semi-arid lands (Noy-Meir 1973). The increased demands for water due to the growing human presence in the San Pedro River valley has resulted in a need for understanding the water needs of both the growing human presence and the water needs of a healthy riparian zone. Here we report on the riparian C and N budget in the different vegetation communities that comprise the riparian area and also the surrounding nonriparian area.

Study Site

San Pedro Riparian National Conservation Area

The climate of the San Pedro valley is semi-arid with temperatures ranging from a mean maximum of 24.8 °C to a mean minimum temperature of 9.9 °C (30 year record in Tombstone) with a bimodal distribution of precipitation (total 343 mm) with 60% of the rainfall coming during the summer monsoon months of July–September. The study site is a mesquite grove located just south of Fairbank, Arizona, along the San Pedro River on river terraces that were historically composed of grazed grasses and forbs. The study site encompassed three vegetation types, the first dominated by velvet mesquite, a leguminous tree (mesquite site). Within the mesquite grove were open sites with only annual vegetation and sites with sacaton grass, each with significant impact from the mesquite canopies. The second site was dominated by sacaton, 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 site), both removed from mesquite impacts.

Soil Analyses

Triplicate soil and litter (O-horizon) samples were collected at 24 sites within the vegetation sites over a two year period. Each vegetation site was sampled at each of three collection times to establish a replication in time analysis. From each site, samples composed of the litter layer from 27.3 cm^2, the 0–5 cm depth, and the 5–10 cm depth from a 109.86 cm^3 volume were collected, with additional soil samples from the study sites taken by soil cores to a depth of 60 cm. The soils were stored at 4 °C until processing, weighed for bulk density determination, processed to remove rocks and passed through a 1 mm sieve for further analysis. Samples were analyzed for pH (2.5 g soil:10 mL 0.05 M CaCl) and C and N by dry combustion with isotope ($^{13}C/^{12}C$ ratio, $\delta^{13}C$; $^{15}N/^{14}N$ ratio, $\delta^{15}N$) analysis (Europa Hydra 20/20 mass spectrometer, Northwich UK). Carbohydrate content (Martens and Loeffelmann 2002) and amino acid content (Martens and Loeffelmann 2003) were extracted by separate acid digestion and determined by ion chromatograph coupled with pulsed amperometry detection.

Trace Gas Measurement

Nitrous oxide (N_2O) and methane (CH_4) fluxes were measured by the static chamber method (Hutchinson and Mosier 1981) using 22-cm diameter PVC chambers permanently installed at the soil surface. Lids were firmly affixed to the chamber surface 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 and electron capture detection), and an 80/100 HayeSep-Q column (Supelco, Inc., Bellefonte, PA). Net gas fluxes were then calculated from exponential regression of the time series of gas concentrations within the chamber headspace (Koschorreck and Conrad 1993). Carbon dioxide (CO_2) fluxes were measured using the same static chamber with sealed lid as describe above. After 1 hour, the headspace air was pumped from the chamber into an infra-red gas analyzer (Qubit Systems, Inc., Kingston, Ontario, Canada). The CO_2 concentration in the chamber headspace was used to quantify net efflux from the soil surface.

Mesquite litter inputs were measured in the fall of 2001 through spring 2002 and again in the fall of 2002 through spring 2003. Litter traps (24.5 cm by 39 cm) were placed in triplicate under seven trees of various canopy diameters. The litter traps were emptied on a regular basis and the litter returned to the laboratory, dried, and weighed for total amount. Subsamples of litter fall (seven) were ground and analyzed for C and N content and isotope composition by the same method used for soils described above. In addition during 2002, sacaton bunches were harvested to determine the biomass produced within the mesquite grove and in isolated sacaton patches not influenced by litter fall and shading from the mesquite trees. The C and N content and isotopes of the different vegetation are reported in table 1.

Results and Discussion

The upper San Pedro River Basin in southeastern Arizona and northern Sonora, Mexico has a lengthy reach of perennial flow, which sustains relatively lush riparian vegetation (Grantham 1996), unlike many former semi-arid riparian areas that have been destroyed due to heavy use of ground water like the Santa Cruz River near Tucson. Vegetation along this stretch of the San Pedro River is mainly mesquite with areas of whitethorn acacia (*Acacia constricta*), sacaton, and open brushy areas outside of the mesquite growth. The vegetation sampled differed little in C content, although the isotopic composition ($\delta^{13}C$) directly reflected the differences noted between C_3 (mesquite and acacia) and C_4 (sacaton) plants (table 1). The plants also had distinctly different N contents due to N fixation by the mesquite and acacia trees and shrubs, but the $\delta^{15}N$ ratios were not different (table 1). The biochemistry of the shrubs versus the grasses was even more pronounced with the mesquite and acacia material lower in carbohydrates and higher in amino acid concentration compared to the sacaton grass. The sacaton grass bunches (n = 6) sampled under the mesquite growth that receives mesquite litter input was intermediate between the mesquite and the isolated sacaton grass (n = 6), suggesting that the mesquite N inputs were changing the biochemistry of the sacaton growing under the mesquite trees.

An extensive soil sampling under the different vegetation exhibited few differences between the C content of the litter layer (O-horizon) or the 0–5 and 5–10 cm depths in the mesquite community regardless of whether the samplings were in the open areas between the trees or directly under the trees (table 2). The isotopic composition of the organic C content within the mesquite community is a direct reflection of the mesquite C input even inside the sacaton grass growth ring. Only outside of the mesquite community in the sacaton and

Table 1—Properties of selected plant species (average ± standard deviation) present in the San Pedro Riparian Area (n = 3).[a]

Species	Organic Carbon	$\delta^{13}C$	Total Carbohydrates	Nitrogen	$\delta^{15}N$	Amino Acids
	-- g kg-1 --		----------- g kg-1	--------------		-- g kg-1 --
Acacia	531+14.1	-25.9	266+49.8	30.6+5.12	5.32	145+20.0
Mesquite	561+19.6	-27.1	246+30.9	35.9+3.33	3.38	187+6.10
Sacaton-Mesquite	492+9.17	-14.7	467+31.5	15.4+2.44	3.32	78.6+7.80
Sacaton	492±2.35	-13.5	528±28.2	13.0±1.37	2.16	66.9±5.20

[a] Sacaton-mesquite represents sacaton grass bunches growing within the mesquite groves, while the sacaton grass sampled was not impacted by mesquite litter fall.

Table 2—Properties of soils (averages ± standard deviation) developed under different vegetation in the San Pedro Riparian area (n = 4).[a]

Vegetation	pH	Organic Carbon	$\delta^{13}C$	Carbohydrates	Total Nitrogen	$\delta^{15}N$	Amino Acids
		-- g kg^{-1} --		----------- g kg^{-1}	--------------		-- g kg^{-1} --
Acacia							
O-Horizon	ND	169+29.7	-25.9	54.3±13.9	14.9±5.83	7.52	53.5±22.7
0–5 cm	5.59	43.7±27.0	-24.9	13.8±3.40	4.29±2.33	8.38	12.9±8.54
5–10 cm	6.38	19.8±4.57	-23.1	6.13±1.71	1.98±0.38	8.85	5.70±3.04
Mesquite							
O-Horizon	ND	172+60.5	-24.1	43.6±21.8	15.5±5.34	6.62	37.4±8.24
0–5 cm	6.38	48.7±14.2	-24.2	15.0±2.59	5.22±1.58	7.69	17.3±5.44
5–10 cm	6.99	21.9±12.0	-22.2	6.43±2.52	2.25±1.12	7.80	7.80±4.41
Mes–Open							
O-Horizon	ND	174+56.1	-25.8	46.4±6.59	16.2±4.96	6.96	53.9±14.6
0–5 cm	6.13	48.9±16.9	-23.8	20.2±13.7	5.40±1.87	8.06	23.6±12.6
5–10 cm	6.87	17.7±2.58	-21.7	5.00±1.69	1.89±0.19	8.37	6.21±0.89
Sac–Mes							
O-Horizon	ND	191+70.0	-23.3	52.9±21.7	18.4±9.36	6.60	54.0±19.3
0–5 cm	6.22	40.9±6.78	-22.2	21.4±13.1	4.23±0.68	8.41	15.8±3.79
5–10 cm	6.79	27.9±11.1	-21.1	10.5±6.33	2.81±1.11	7.98	11.3±4.64
Sacaton							
O-Horizon	ND	315+106	-13.4	22.2±3.22	13.9±0.43	4.31	26.2±1.86
0–5 cm	6.68	29.2±17.3	-16.3	12.0±2.33	2.85±1.53	7.92	12.8±1.54
5–10 cm	6.26	20.7±11.3	-15.8	5.92±1.32	1.98±0.95	7.83	7.99±0.89
Open							
O-Horizon	ND	94.4+8.3	-19.8	54.7±6.58	6.59±1.09	7.78	30.2±1.28
0–5 cm	7.14	13.8±6.61	-20.3	3.80±2.04	1.31±0.85	7.44	5.76±4.52
5–10 cm	7.20	10.2±3.29	-20.0	2.53±0.23	0.87±0.18	6.68	3.87±2.50

[a] Sacaton-mesquite represents sacaton grass bunches growing within the mesquite groves, while the sacaton grass sampled was not impacted by mesquite litter fall, and open area is outside of the riparian zone with annual grass and forb vegetation.

open areas did the soil C and N values not reflect the impact of the mesquite litter on the soil C and N content. The soil carbohydrate and amino acid concentrations also reflected the respective vegetation and the total C and N of the soil. The carbohydrates and amino acids are very important constituents of the soil organic matter as the fractions are generally very labile due to the ease of mineralization by soil microorganisms. The accumulation of large pools of C and N as carbohydrates and amino acids in these semi-arid soils is only possible due to the disconnect in time between production by the plants and mineralization by soil microorganisms. When litter is returned to the soil in the fall, cool soil temperatures limit decomposition that could occur with winter or early spring rains. The litter layer then is dry when the warm spring and summer temperatures occur. The brief summer monsoon period is very important for providing moisture while soil temperatures are warm enough for rapid microbial activity to mineralize the organic matter and return nutrients to the soil.

While the C and N content are indicators of amounts of C and N present in the different vegetation communities, determining the amount of C and N on a volume basis (m^2) provides a means for a more accurate comparison of total soil C and N. To determine the amount of soil C and N in a defined depth of soil, samples were taken to 60 cm, and by utilizing the bulk density of the depths (g cm^{-3}), the C and N content (mg C g^{-1} soil) of the soil depth sampled can be multiplied by the bulk density to obtain a total C and N content on the volume basis. Table 3 shows that although the C content of the sacaton O-horizon (table 2) had a higher C content [315 g (sacaton) versus 172 g (mesquite) kg^{-1} litter] when the amount (g) of litter on a m^2 basis was multiplied by the C content, the mesquite vegetation contained a much greater amount of C and N. The lack of O-horizon C in the open areas outside of the riparian mesquite community confirm the importance of the O-horizon C in the riparian zone as the O-horizon under the mesquite community accounts for 71% of the average profile C difference between the mesquite and open brush communities (table 3).

The San Pedro riparian zone covers approximately 22,660 ha in area and by assuming that mesquite impact 80% of the riparian zone as open areas within the mesquite, mesquite-sacaton and under mesquite trees, with an additional 10% impacted by acacia shrubs. By converting the g m^{-2} C values based on C and bulk density values taken from tables 2 and 3 to kg ha^{-1}, the riparian zone contains 21,660 metric tons of soil C compared to the 14,620 metric tons in a comparably sized area of shrub and brush that lie outside the riparian zone. The riparian zone is responsible for sequestration of an additional

Table 3—Minimum, maximum, and average total C and N contents for soils developed under different vegetation in the San Pedro Riparian area.[a]

Soil	Bulk Density	Organic Carbon Minimum	Organic Carbon Maximum	Organic Carbon Average	Total Nitrogen Minimum	Total Nitrogen Maximum	Total Nitrogen Average
		g m^{-2}			g m^{-2}		
Mesquite Vegetation							
O-horizon	ND	91.0	377	234	9.64	26.7	10.9
0–10	0.88	122	313	217	14.0	31.2	22.6
10-20	1.07	100	123	112	10.5	12.3	11.4
20-30	1.21	61.3	124	92.5	6.14	12.9	9.51
30-40	1.31	69.6	133	101	6.70	13.1	9.89
40-50	1.35	55.7	113	84.1	5.40	10.5	7.96
50-60	1.39	119	149	134	10.2	12.8	11.5
Total	ND	619	1330	974	62.5	119	83.7
Sacaton Vegetation							
O-horizon	ND	26.3	55.9	41.1	1.75	1.87	1.81
0–10	1.02	141	250	196	13.8	25.4	19.6
10-20	1.22	140	202	171	12.7	15.9	14.5
20-30	1.33	112	130	121	10.0	14.4	9.07
30-40	1.35	94.0	119	106	7.52	8.88	7.99
40-50	1.37	88.0	92.1	90.5	4.95	6.31	5.60
50-60	1.42	64.1	68.3	66.3	3.92	5.33	4.40
Total	ND	670	913	792	53.3	72.7	63.0
Outside Brush Vegetation							
O-horizon	ND	0.00	0.00	0.00	0.00	0.00	0.00
0–10	1.26	141	194	167	10.8	15.2	13.0
10-20	1.32	163	189	176	13.8	15.2	14.5
20-30	1.37	97.1	169	133	8.07	13.5	10.8
30-40	1.39	77.1	81.2	79.1	7.01	11.3	9.06
40-50	1.44	60.3	68.5	64.4	6.92	7.83	7.52
50-60	1.48	22.3	27.8	24.4	1.75	3.25	2.80
Total	ND	569	720	645	52.0	63.3	57.7

[a] Outside area is outside of the riparian zone with annual grass and forb vegetation.

7,040 metric tons of soil C, and the value does not include C stored in the woody plant tissue.

The litter accumulating in the soil O-horizon under the mesquite vegetation was measured during two seasons of litter collection to accumulate at the rate of between 170 g litter m^2 during 2002-2003 (249 mm monsoon moisture) and 127 g litter m^2 in 2001-2002 with 177 mm monsoon moisture (figure 1). The mesquite litter contained 469 $\pm$ 29.1 g C and 28.5 $\pm$ 2.7 g N kg^{-1} litter with a δ^{15}N of 4.25 and a δ^{13}C of -27.1. The results suggest that the moisture input during the monsoon season is very important for production of mesquite inputs to the riparian zone. The size of the mesquite tree was important for the amount of litter returning to the riparian community (r^2 = 0.91 and 0.92, respectively, for 2002 and 2003) for the seven trees monitored. The large amount of litter remaining under the mesquite trees (table 3) was greater than the amount of litter returning yearly to the understory by a factor of 1.5 (minimum O-horizon value) to 6.4, suggesting that less litter decomposes each year than is returned by leaf litter.

Cycling of C in ecosystems involves cycling of atmospheric C into plants and then through the soil environment via leaf litter and woody plant parts. Only part of the atmospheric C sequestered in plant growth is returned to the soil each year, and the plant material returned would be utilized by soil microorganisms for energy and growth. The C cycle also includes by-products of the microbial utilization of plant C as C is returned to the atmosphere as CO_2. Additional trace gases such as CH_4 and N_2O are also implicated in the C cycle and potential greenhouse warming. These trace gases were monitored in the San Pedro Riparian area during 2002 and 2003 to provide a yearly C budget for the system. Results showed little difference in CO_2 emissions from the open (208 g C m^{-2} yr^{-1}), sacaton (221 g C m^{-2} yr^{-1}), or mesquite (257 g C m^{-2} yr^{-1}) vegetation communities even though the soil C and N content were 2 to 3 times higher under mesquite than in the open areas (tables 2 and 3). The monitoring found higher levels of N_2O flux from under the mesquite (82 mg N_2O m^{-2} yr^{-1}) compared with the open area (35 mg N_2O m^{-2} yr^{-1}) and the sacaton vegetation (24 mg N_2O m^{-2} yr^{-1}). But the N_2O emissions are very small next to the C fluxes even if the greenhouse gas potential of N_2O (310 x CO_2) is applied. A surprising aspect of the study was the finding of a perennial sink in the riparian zone for CH_4. The CH_4 sink consumed 206 mg CH_4 m^{-2} yr^{-1} for the mesquite sites and 207 mg CH_4 m^{-2} yr^{-1} in the open and 149 mg CH_4 m^{-2} yr^{-1} in the sacaton grass site. By estimating the amount of mesquite litter fall (figure 1) and estimates of grass and shrub litter in the riparian zone, the amount of C accounted for, not including woody plant biomass is approximately 52% of the C equivalents exiting the riparian area as CO_2 and N_2O. By accounting for the C returned to the sacaton grass community,

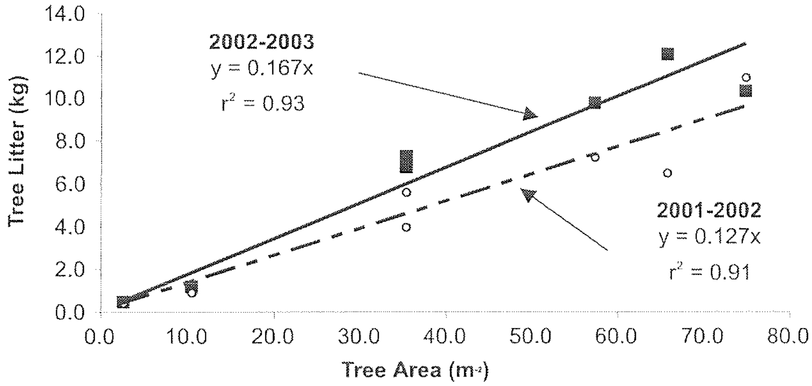

Figure 1—Mesquite litter collected during the fall of 2001 through spring 2002 and fall of 2002 through spring 2003 from seven mesquite trees of various sizes.

only 20% of the C emissions are recaptured by vegetation inputs to the system.

The San Pedro River supports a great array of animal and plant life and is a rare remaining example of a semi-arid riparian ecosystem. In addition to the great habitat, the riparian zone is also a major sink for atmospheric C. It is extremely difficult to place a value on a semi-arid ecosystem that is possibly a major player in the ecoregions ability to reduce the impact of increasing atmospheric C content.

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