

# Comparing Ecosystem Water and Carbon Exchange Across a Riparian Mesquite Invasion Gradient

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**Abstract**—Ecosystem water and carbon fluxes were monitored over a riparian grassland, mesquite-invaded grassland, and mesquite woodland to understand the consequences of woody plant encroachment. Water use and carbon gain were largest at the woodland site. Results suggest that the deep roots of mesquite will lead to a decoupling of ecosystem water sources as the invading mesquites mature in former grasslands. The ability of mesquite to rely on stable groundwater sources rather than precipitation enhanced net carbon uptake in the dry periods and net carbon loss in rainy periods. These results highlight the important role that water sources and ecosystem morphology play on controlling water and carbon balances in semiarid areas.

## Introduction

How vegetation and climate interact to affect terrestrial carbon, water, and soil nutrient cycles is not well understood. Between 50 and 90% of North America's biomes may see significant shifts in vegetation composition and land cover in the near future (Neilson 1993), which may become the most ubiquitous form of global change. Additionally, the timing and magnitude of precipitation inputs into North American ecosystems have been forecasted to change (Houghton et al. 1996). With these shifts in climate and land cover, understanding potential linkages between ecosystem structure, function, and climate variability is warranted.

In the Southwest, precipitation is often the dominant control on biological activity (Noy-Meir 1973). Altered depth-duration frequency distributions of precipitation events, combined with shifts in vegetation (through woody-plant encroachment of grasslands, non-native species invasions, riparian encroachment by phreatophytes, etc.) may alter biological activity across a landscape in quite unpredictable ways. The historic increase of woody plants within the grasslands and savannas worldwide is an aspect of land cover change with large-scale ramifications (Archer 1994; McPherson 1997). Woody plant encroachment can decouple primary productivity from summer rains in the Southwest; deeply rooted woody plants access water sources unavailable to grassland species (Scott et al. 2004). However, increases in primary productivity may be offset by larger respiratory fluxes from soil microbial communities that are still highly responsive to summer precipitation and fueled by high quality litter inputs from the woody vegetation.

In this paper, we briefly investigate the consequences of mesquite encroachment on water and carbon exchange in a Southwestern riparian area. Encroachment by mesquite (*Prosopis* spp.) is arguably the most pervasive and temporally dynamic land-cover change in the Southwestern United States.

Our goal is to predict how on-going woody plant encroachment affects ecosystem water and carbon cycling by understanding the abiotic and biotic controls on these fluxes. Fulfillment of this goal will provide important information about the role of riparian vegetation in basin water balances and how woody plant encroachment changes the carbon cycling and carbon sequestration potential of semiarid lands. Our approach is to make multiyear observations of carbon and water fluxes from a grassland, a grassland that has been encroached by mesquite (a shrubland), and a mesquite woodland, assuming that the space for time substitution adequately represents the ecosystem dynamics throughout the encroachment process.

## Methods

Three study sites representing a grassland, a grassland that has been encroached by mesquite (a shrubland), and a mesquite woodland were established along the San Pedro River in southeastern Arizona. The Charleston Mesquite (CM) study site is located on the east side of the San Pedro River at an elevation of 1,200 m, approximately 16 km northeast of Sierra Vista, Arizona. The site is a woodland dominated by velvet mesquite (*Prosopis velutina*). The understory is primarily sacaton grass (*Sporobolus wrightii*) with scattered greythorn shrubs (*Zizyphus obtusifolia*) and various summer active annual herbaceous species. The average canopy cover is ~70%. The measured Leaf Area Index (LAI) ranges from an average ( $n = 40$ ) of ~1.0 prior to leaf-out to ~1.6 during most of the growing season. The mean canopy height is approximately 7 m and the maximum canopy height ~10 m. Depth to groundwater is ~10 m.

The Lewis Springs Sacaton (LSS) and Lewis Springs Mesquite (LSM) study sites are located in close proximity to each other on the east side of the San Pedro River at an elevation of 1,230 m, approximately 12 km east of Sierra Vista,

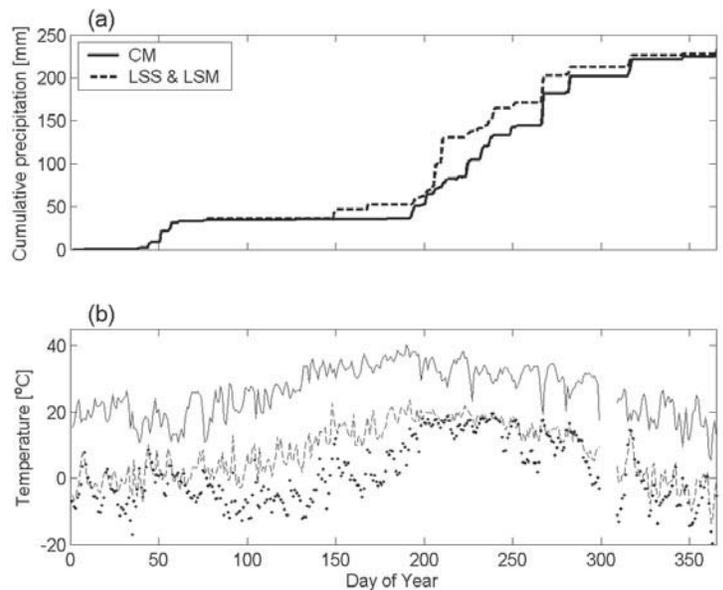
Arizona. The micrometeorological tower at the Lewis Springs Sacaton Site (LSS) lies in the center of a low alluvial terrace bordering the river. The tower is surrounded by a lush growth of sacaton grass roughly 200 m east/west and 800-1,000 m north/south. The canopy height is about 1 m, and average canopy density is ~ 70%. The mean depth to groundwater in a co-located piezometer is ~2.8 m. LAI ranges from an average ( $n = 40$ ) of ~1.0, prior to the initiation of the growing season, ~1.5 during the pre-monsoon season, and ~2.5 during and after the monsoon season. The flux tower at LSM lies immediately to the northeast of LSS in a moderately dense shrubland of velvet mesquite, roughly 500 m east/west by 500 m north/south. The mesquite canopy density is estimated to be 60% with an average tree height of 3-4 m. The depth to groundwater is ~7 m, and the LAI ranges from about 0.3 (prior to leaf production by the mesquite shrubs) to a peak of 0.6 during the height of the summer monsoon.

Evapotranspiration (ET) and carbon dioxide ( $\text{CO}_2$ ) fluxes were measured using the eddy covariance technique throughout most of the active growing season from 2001 till present at CM and from mid-2002 till present at LSS and LSM. Basic meteorological, soil moisture, and groundwater height data were also collected. A three-dimensional sonic anemometer and an open path infrared gas analyzer mounted at approximately 2 to 3 m above the height of the canopy measured the three components of the wind velocity vector, sonic temperature, and the densities of water vapor and  $\text{CO}_2$ . These were sampled at 10 Hz by a datalogger, which also calculated their 30-minute covariances using block Reynolds averaging. Surface fluxes were later calculated off-line, after performing a two-dimensional coordinate rotation and accounting for density fluctuations (Webb et al. 1980). The sonic temperature was used to calculate sensible heat flux using the method suggested by Paw U et al. (2000). Fluxes measured when the wind was coming from a direction that was within  $20^\circ$  of behind the anemometer were ignored due to possible interference from the anemometer support and the IRGA mounted behind the anemometer.

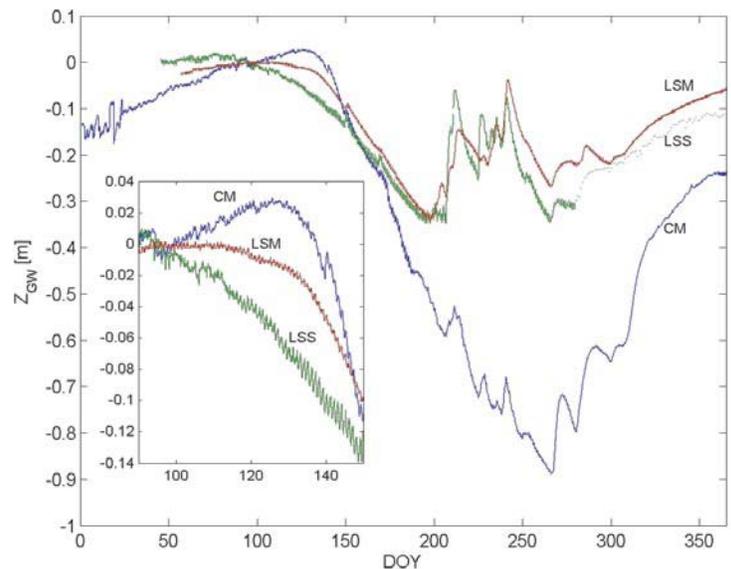
## Results and Discussion

We discuss the measurements made in 2003, as this was the first year in which comparable measurements were available across all sites. Detailed results from the water and carbon exchange studies conducted during 2001 and 2002 at the CM woodland site have been published by Scott et al. 2003, Yopez et al. 2003, and Scott et al. 2004.

Surprisingly, total annual precipitation was nearly identical at all three sites (figure 1). The annual total precipitation was 232 mm at CM and 234 mm at LSS and LSM, much less than the 30-year average of 343 mm at nearby Tombstone, AZ. Air and dew point temperatures at LSS and LSM (not shown) were very similar to those found at CM (figure 1). The difference between the daily maximum and minimum temperatures often exceeded  $20^\circ\text{C}$  for most of the year and was around  $15^\circ\text{C}$  during the monsoon. In the San Pedro Valley, the 2003 monsoon began on DOY 194 and ended on DOY 255 (using the standard of greater than/less than  $12.8^\circ\text{C}$  dew point temperature for three consecutive days), though there were several large rain events between the end of the monsoon and the end of



**Figure 1**—(a) 2003 cumulative precipitation at the Charleston Mesquite Site (CM) and the Lewis Springs Sites (LSS and LSM). Since LSS and LSM are adjacent to each other, their precipitation is nearly identical. (b) Daily maximum (solid line), minimum (dashed line), mean dew point (dots) air temperatures at CM. Temperatures at LSS and LSM were very similar.



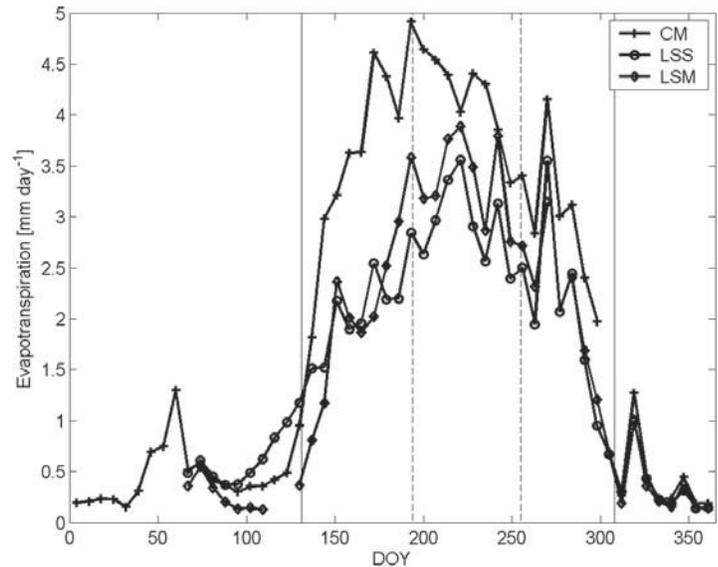
**Figure 2**—2003 relative ground water depths,  $Z_{\text{GW}}$  for all three sites.  $Z_{\text{GW}}$  was computed by adding the water table depths from DOY 90 (CM = 9.51 m, LSS = 2.44 m, LSM = 5.28 m) to all values. Inset expanded figure shows the water table changes during the spring green up that initiated water table drawdowns and regular diurnal fluctuations due to ground water extraction by the plants.

growing season. Spring nighttime freezing ended on DOY 131 and several nights of hard freezes began on DOY 308 in the fall. Scott et al. (2004) reported that the minimum temperatures inside the riparian corridor are as much as  $10^\circ\text{C}$  cooler than on the valley floor due to nocturnal cold air drainage.

Mean depths to groundwater for piezometers at all three sites were 2.6 m, 5.4 m, and 9.8 m at LSS, LSM, and CM, respectively. The annual changes in water levels were about 0.9 m at CM and 0.4 m at both LSM and LSS (figure 2). Groundwater levels generally declined from the time of new leaf production until the beginning of the monsoon. During the monsoon, the water levels record the complex effects of passing floods in the river channel that recharge the alluvial aquifer. The effects of these propagating flood waves in the aquifer were more dampened going from LSS to LSM to CM, corresponding to the increasing distance of each site's piezometers to the nearest stream channel. The presence of regular diurnal fluctuations at all sites following leaf flush indicates that all ecosystems used groundwater. These regular diurnal fluctuations (with a minimum depth to groundwater in the early morning and a maximum around sundown) began around DOY 120 at LSS, about 10 days earlier than LSM and 20 days earlier than CM. This agrees well with visual observations that indicated an earlier green up for the grass at LSS and the mesquite at LSM. Before these fluctuations began at LSS, water levels had already begun to decline. Since the sacaton piezometer was closer to the stream and cottonwood gallery, this general decline was likely due to the activity of nearby cottonwood trees, which greened up around DOY 90. CM is located along a losing reach and has a greater density of trees, which possibly is the reason why once the mesquites at CM began using groundwater, the rates of water level decline were much greater than the other two sites. While water table heights began to recover around DOY 270, regular fluctuations at both LSM and CM did not cease until DOY 307 when a hard freeze forced mesquite senescence (diurnal measurements were unavailable at LSS after DOY 275).

The seasonal water uses of the adjacent shrubland (LSM) and grassland (LSS) sites followed a very similar pattern to that seen at the woodland (CM) site (figure 3). The grassland initiated photosynthetic activity and began to transpire earlier in the year, whereas the frost sensitive mesquite were more conservative. However, after mesquite leaf flush, ET rates at LSM rapidly caught up to, and then began to exceed, those of the grassland, perhaps due to an enhanced ability of the deeper rooted trees to acquire groundwater more effectively. During the growing season, ET at CM always exceeded the other two sites. ET increased at LSM and LSS during the monsoon period, whereas it stayed the same at CM perhaps indicating that the grassland and shrubland are not as coupled to the groundwater source, ephemerally utilizing summer precipitation events. From the end of the monsoon until the end of the growing season, LSM and LSS had similar rates of ecosystem water loss to the atmosphere.

The water use pattern of the LSS site differed considerably from a similar site across the river that was monitored in 1997-1998 using the Bowen ratio technique (Scott et al. 2000). The earlier sacaton site was shown to have a tight coupling between precipitation and ET from which Scott et al. (2000) concluded that it used little groundwater. The cumulative water use at LSS indicates that ET was significantly in excess of precipitation—implying groundwater use by the grassland. Regular diurnal fluctuations during the growing season in a

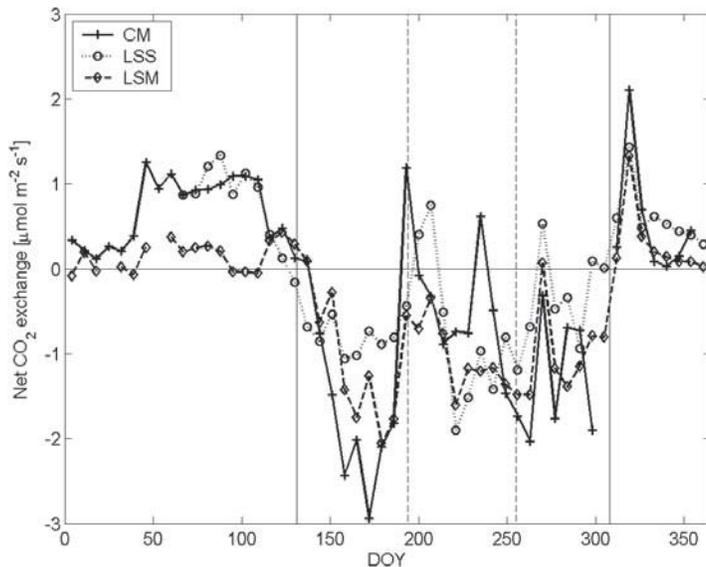


**Figure 3**—2003 weekly average ET. The days of the last freeze of spring and first freeze of fall (solid line) and monsoon period (between the dashed lines) are also indicated.

piezometer at the site confirmed this (figure 2). The likely explanation for this disparity between the two grassland sites is that the earlier sacaton grassland site had a depth to groundwater of >3.5 m, whereas at LSS it was often less than 3 m. Thus, sacaton appears to not acquire groundwater from sites where the groundwater depths are greater than ~3 m. This conclusion is supported by a study using stable isotopes that identified a water table depth threshold of ~3 m for sacaton groundwater use (J. Stromberg, Arizona State University, personal communication).

Net ecosystem exchange of CO<sub>2</sub> (NEE) reflected the competing influences of plant carbon acquisition and both autotrophic and heterotrophic respiratory processes (figure 4). In general, most plants at all the sites were dormant during the winter, and respiration losses were evident. Groundwater, available to deeply-rooted plants but not to shallow soil heterotrophs, fueled net carbon gain during the pre-monsoon summer period. High temperatures and shallow soil wetting associated with monsoon rains correlated with strong respiration responses, offsetting net uptake of carbon. Strong respiration responses to precipitation inputs were seen in all seasons (compare figure 1a and figure 4). The greater respiratory efflux following precipitation events at LSS and CM was probably a result of the greater availability of labile carbon in the surface soils at these sites as evident by the copious amounts of plant litter and debris found at them. Also, respiration at LSS was likely more responsive than LSM because of the finer textured soils and greater amount of ground cover that sustained higher levels of soil moisture for longer time periods (data not shown).

To better quantify the differences in carbon exchange between the three sites we computed seasonal average NEE for three separate periods in 2003: (1) Dormant—the wintertime period when most plants were dormant, (2) Dry Growing—the pre-monsoon growing season with typically very little rainfall, and (3) Rainy Growing—the monsoon and post-monsoon



**Figure 4**—2003 weekly average net ecosystem exchange (NEE) of carbon dioxide. Negative NEE indicates net atmospheric loss and a net uptake of carbon by the ecosystem. The days of the last freeze of spring and first freeze of fall (solid line) and monsoon period (between the dashed lines) are also indicated.

growing season when the majority of the rain fell (table 1). During the dormant period, the seasonal averages of NEE indicate that both CM and LSS were sources of atmospheric CO<sub>2</sub>. During the pre-monsoon growing season, carbon sequestration increased with woody plant density. NEE at all sites actually decreased during the rainy season indicating that soil respiration losses outweighed the increase in plant carbon uptake. The reduction in ecosystem carbon gain from the dry to the rainy season increased with mesquite encroachment, possibly indicating that the grassland productivity was more closely tied and responsive to the increases in near-surface moisture.

## Summary

These initial 2003 results are summarized as follows:

- All ecosystems used groundwater. The grassland groundwater use was due to the shallow groundwater availability at the site, which is not the case for many grasslands within the riparian area of the San Pedro. Groundwater use was highest at the woodland site.
- Decoupling of ET from precipitation was most evident at the woodland site, though all sites showed some degree of

decoupling due to the ability of the dominant vegetation to access groundwater.

- All sites had high respiration losses of carbon following precipitation events. The response was stronger and longer lasting at the grassland and woodland sites. The decreased response at the shrubland site relative to the grassland site was likely due to the coarser soil texture and lower amount of plant debris found there.
- All ecosystems had a lower net gain in carbon during the rainy growing season, relative to the dry part of the growing season. This decreased gain in carbon was magnified by woody plant density.

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**Table 1**—2003 average net ecosystem exchange of carbon dioxide [ $\mu\text{mol m}^{-2} \text{s}^{-1}$ ] for the pre-monsoon growing season and the monsoon through post-monsoon growing season.

Period	(Day of Year)	LSS	LSM	CM
Dormant	65-105 & 309-365	0.79	0.23	0.75
Growing, dry	148-196	-0.78	-1.30	-1.66
Growing, rainy	197-301	-0.60	-1.05	-0.88