Highlight FLUXNET site
Santa Rita Creosotebush

Highlighting Site: Santa Rita Creosotebush
by Shirley A. (Kurc) Papuga

Compared to other areas which receive greater annual precipitation, dryland carbon uptake is highly sensitive to precipitation inputs (Huxman et al., 2004). The amount of precipitation in drylands is small; therefore, dryland ecosystems depend on pulses of moisture, i.e. small pulses that primarily trigger microbial activity and evaporation or large pulses that provide moisture to support photosynthesis and transpiration. Most global climate models predict changes in the intra-annual variability of precipitation (Knapp et al., 2008). Given the average annual precipitation in drylands globally is expected to decline (e.g. Seager et al., 2007), changes in the timing, frequency and magnitude of precipitation events will have important eco-hydrological consequences. Critical to predicting and understanding the implications of these climatic changes is a better understanding how dryland vegetation responds to and uses water resources.

Introduction to Larrea tridentata.

In the arid to semiarid areas of North America, a drought tolerant plant Larrea tridentata dominates the landscape, extending from Nevada, United States ("creosotebush") to Hidalgo, Mexico ("gobernadora" or "hediondilla") (Figure 1). *Larrea tridentata* (hereafter referred to as *Larrea*) already inhabited the southwestern United States by the Last Glacial Maximum (Duran et al., 2005). Now, *Larrea* is pervasive in three North American deserts: the Mojave, the Sonoran, and the Chihuahuan, even though they differ in topography, climate, and historical background. While *Larrea* typically forms extensive monotypic stands, they are greatest in density in the Chihuahuan Desert with decreasing density to the west (Barbour, 1969). A ploidy gradient also occurs in this species from east to west: generally speaking, the Chihuahuan populations are diploid, the Sonoran populations are tetraploid, and Mojave populations are hexaploid; higher ploidy races are believed to be an adaptation to increased aridity and/or higher temperature (Hunter et al., 2001). This unusual polyploidy is likely to have been a major factor in expansion in range of *Larrea* throughout the 20th century (Duran et al., 2005).

Larrea is a repeat-blooming, evergreen shrub, with a C3 photosynthetic pathway. With no defined trunk, it typically reaches heights of 1 to 1.5 m, but has been found to stretch as high as 4 m.   Both inverted-cone and
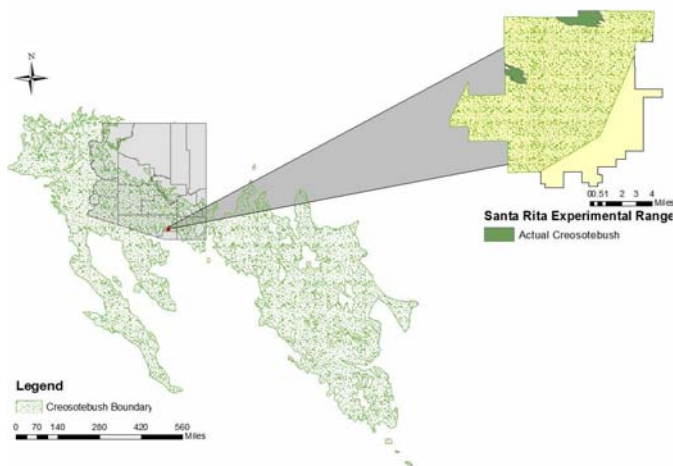

Figure 1: Distribution of creosotebush in North America and the location of the Santa Rita Creosotebush tower site at the northern boundary of the Santa Rita Experimental Range in southeastern Arizona. *Image by Michelle Cavanaugh.*

In This Issue:

Santa Rita Creosotebush

Figure 2: Close up view of *Larrea* leaves and flowers. *Photo by Shirley Papuga.*

hemispherical canopies have been identified, the architecture suggested to facilitate functional water and nutrient accumulation below the shrub (DeSoyza et al., 1997; Whitford et al., 1997). The bifoliolate leaves of *Larrea* are opposite, with two asymmetrical oblong leaflets joined at the base, measuring about 1 cm long and 3 to 4 mm wide (Figure 2). The odorous resin that coats these leaves has been shown to promote water use efficiency, deter herbivores, and screen ultra-violet radiation (Meinzer et al., 1990). This resin, secreted by a glandular epidermis of the stipules, is a complex mixture of phenolics, saponins, terpenoids, wax esters, partially o-methylated flavones and fla-vonols (Gonzalez-Coloma et al., 1994), which can be extracted for medicinal and industrial uses (Arteaga et al., 2005). Flowers of *Larrea* are solitary, axillary, and perfect, about 2 cm wide (Figure 2). More than 120 bee species have been found on the flowers of creosotebush, 21 of which are *Larrea* specialists;

illustrating the drought tolerant shrub provides a dependable resource in an unpredictable environment (Minckley et al., 2000). The spherical fruit, pea-sized and densely covered with fuzzy white hairs, eventually splits into 5 pieces, each containing a single seed. Moisture, temperature, and soil conditions are all thought to play a role in the ability of *Larrea* seeds to germinate.

Over the last century, the area dominated by *Larrea* in North America has increased, and is associated with coincident land degradation during that time (Grover and Musick, 1990). Therefore, the management of cattle grazing and fire has been modified to minimize shrub encroachment. Yet, widespread *Larrea* offers a predictable resource in an otherwise unpredictable and harsh environment. For better or for worse, climatic changes that will temperature and precipitation patterns are likely affect the distribution of *Larrea* in the region. How resilient is *Larrea*? If the distribution

of *Larrea* were to change, would a reduction in cover and subsequent exposure of soil strengthen feedback to local and regional climate?

Site Description.
As of February 2010, a full two years of flux observations will have been made at the Santa Rita Creosotebush (SRC) tower site (Figure 3) located about 30 miles south of Tucson within the boundaries of the Santa Rita Experimental Range (SRER) in southeastern Arizona, United States (Figure 1). The SRER is bounded at its southern and eastern borders by the Santa Rita Mountains. Since at least 1904 (Figure 4), *Larrea* has been the dominant species near the very northern boundary of the SRER where the SRC tower site is located (UTM: 0515177, 3530284) at an elevation of about 950 m.

Total canopy cover at the SRC tower site is 24% (14% *Larrea* and the other 10% a combination of annual grasses, annual herbaceous species, and cacti). Soil crusts are also prevalent throughout the site. The height of the average *Larrea* is 1.7 m, with an average of 24 stems about 10 mm in diameter. Thus, *Larrea* at the SRC tower site are larger than many encountered in the southwestern United States. Additionally, insect galls – potentially an indication of plants with minimal water stress (Waring and Price, 1990) – are common on the *Larrea* at this site.

Soil at the SRC tower site is sandy loam (~ 65% sand, ~ 24% silt, ~ 11% clay, averaged over

all depths) with no caliche layer, to at least 1 m. Long term records from the SRER archives (http://ag.arizona.edu/SRER/data.html) suggest that the SRC flux station area receives average annual precipitation of 330 mm, half occurring in July through September with monsoon rains and the other half occurring from December through February with winter and spring rains.

Unique long-term measurements at the SRC tower site include continuous measurements of soil moisture at multiple depths in multiple profiles all down to 1 m. Additionally, three digital "game" cameras, on a time-lapse setting, are monitoring the daily phenological activity of the *Larrea*, such as green up and flowering, within footprint of the flux tower.

Some Research Highlights.
We have seen that the depth of moisture reservoirs is largely associated with the nature of precipitation events in dryland ecosystems (Kurc and Small, 2004; Kurc and Small, 2007). Soil moisture pulses at the surface follow most storms while deep soil moisture pulses are less frequent. In fact, surface soil moisture decreases rapidly following rainfall events; the best fit exponential time constant is less than 3 days (Kurc and Small, 2004). Likely, this surface moisture is only available to shallow rooted plants, if they are able use the moisture before it is quickly lost to evaporation.

Because evaporation and respiration should be more influ-
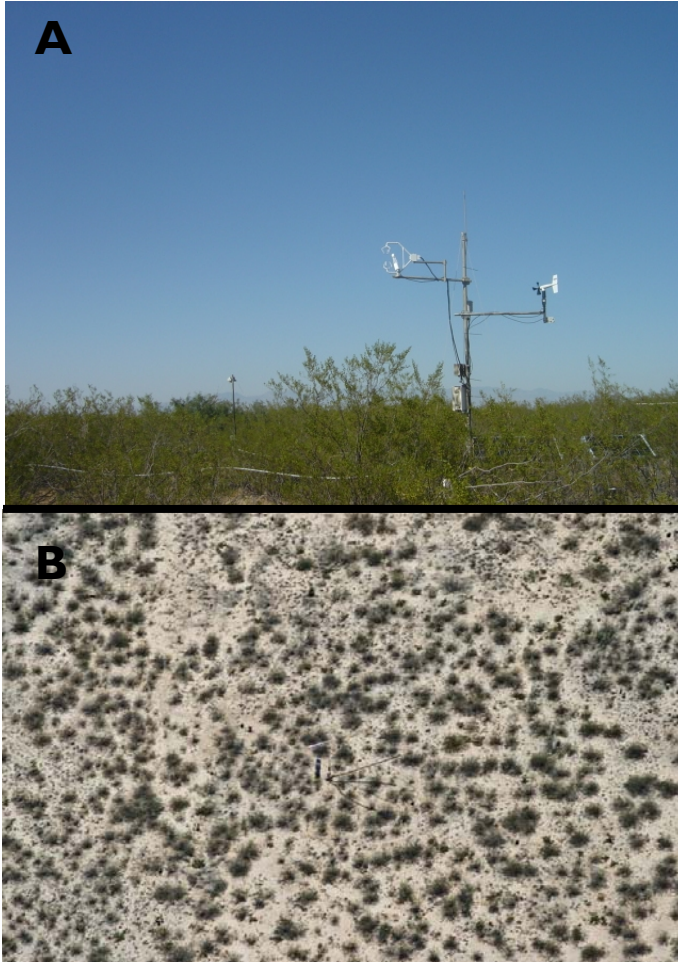
Santa Rita Creosotebush

Figure 3: Side view of the Santa Rita Creosotebush tower site (a) *Photo by Shirley Papuga.* An overhead view of the Santa Rita Creosotebush tower site (b) *Photo by Mark Heitlinger.*

tion (E) and soil moisture at several depths. *ET* was best correlated with soil moisture at 37.5 cm (deep soil moisture). At this depth, T and soil moisture were also most strongly correlated. On the other hand, E was best correlated with soil moisture at 2.5 cm (surface soil moisture). Given these statistics, undoubtedly large rainfall events or closely spaced small rainfall events are critical to the healthy structure and function of these *Larrea* ecosystems.

Finally, we recently processed a year of images from our time-lapse digital cameras to derive daily greenness at the SRC tower site (Kurc and Benton, in press). This digital image-derived greenness showed that the green-up of creosotebush is driven by deep soil moisture, just as for transpiration and net carbon uptake. We also show that carbon uptake in *Larrea* ecosystems is correlated with, and may be able to be predicted using, image-derived greenness, suggesting that this inexpensive tool has the potential to play a large role in developing a better spatial understanding of the carbon dynamics of shrub-dominated drylands.

The dependence of *Larrea* on deep soil moisture is evident from our research. Still, more work is necessary to under-

enced by soil moisture near the surface than by deep soil moisture, we break the soil profile into two regions: surface soil moisture (< 20 cm) and deep soil moisture (> 20 cm). A regression of net ecosystem exchange of CO_2 (*NEE*) versus evapotranspiration (*ET*) performed for four cases at a semiarid grassland and shrubland: (1) dry surface, wet deep; (2) wet surface, dry deep, (3) wet surface, wet deep, and (4) dry surface, wet deep revealed a strong negative correlation for case (1), corresponding to periods of net carbon uptake (Kurc and Small, 2007). Because carbon uptake and transpiration are inextricably linked, this suggests that semiarid grasses and shrubs are only able to use soil moisture to photosynthesize when the water has infiltrated deep enough into the profile to be uninfluenced by evaporative demand.

This is further supported in shrubs by a recent sap flow study (Figure 5) at the SRC tower site (Cavanaugh et al., in review). Linear regressions were performed between *ET*, transpiration (*T*), and evapora-
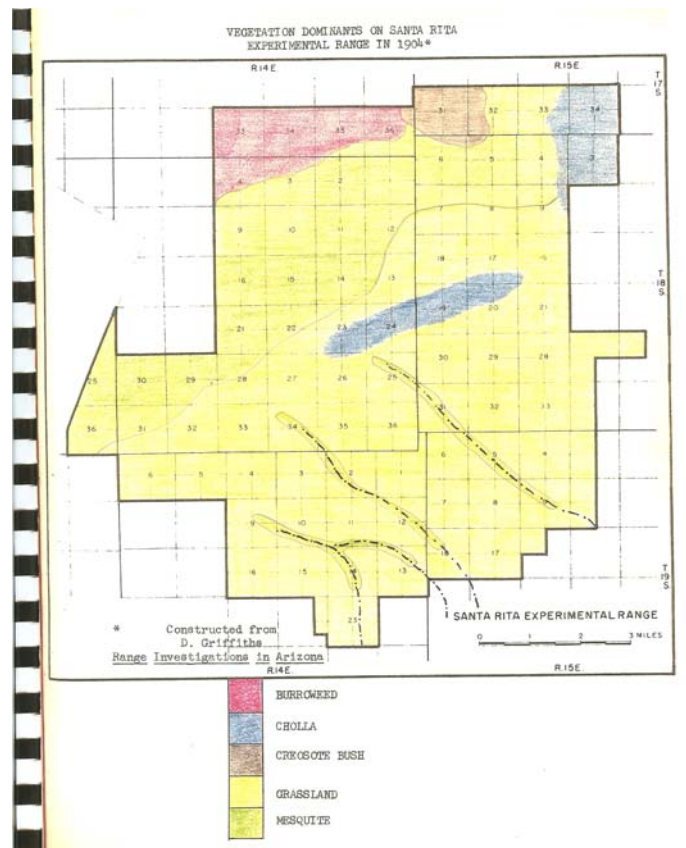
Figure 4: Map of vegetation distribution at the Santa Rita Experimental Range in 1904, *copy of original from the thesis of: L.A. Mehroff, University of Arizona, 1955.*

Santa Rita Creosotebush

Figure 5: An example of a heat balance sap flow sensor used at the Santa Rita Creosotebush tower site which was constructed in the laboratory. Insulation and weather protection would complete the installation of this instrument. *Image by Shirley Papuga.*

stand the implications of climate change for this important and pervasive dryland ecosystem and its interactions with ecosystems throughout southwestern North America. As such, this same *Larrea* ecosystem has also been selected as the core site for Domain 14 within National Ecological Observatory Network (NEON). Please contact me for further information or to participate in our research efforts.

contact:

Shirley A. (Kurc) Papuga
papuga@email.arizona.edu

School of Natural Resources and the Environment
University of Arizona
Tucson, AZ 85716

References

Arteaga, S., Andrade-Cetto, A. and Cardenas, R., 2005. Larrea tridentata (Creosote bush), an abundant plant of Mexican and US-American deserts and its metabolite nordihydroguaiaretic acid. Journal of Ethnopharmacology, 98(3): 231-239.

Barbour, M.G., 1969. Age and space distribution of desert shrub *Larrea-divaricata*. Ecology, 50(4): 679-&.

Cavanaugh, M., Kurc, S. and Scott, R., in review. Evapotranspiration partitioning in semiarid creosotebush dominated ecosystems: climate change implications of soil moisture control on shrubland transpiration. Ecohydrology.

DeSoyza, A.G., Whitford, W.G., MartinezMeza, E. and VanZee, J.W., 1997. Variation in creosotebush (Larrea tridentata) canopy morphology in relation to habitat, soil fertility and associated annual plant communities. American Midland Naturalist, 137(1): 13-26.

Duran, K.L., Lowrey, T.K., Parmenter, R.R. and Lewis, P.O., 2005. Genetic diversity in Chihuahuan Desert populations of creosotebush (Zygophyllaceae : Larrea tridentata). American Journal of Botany, 92(4): 722-729.

Gonzalez-Coloma, A., Wisdom, C.S., Sharifi, M.R. and Rundel, P.W., 1994. Water and nitrogen manipulations of the desert shrub larrea-divaricata subsp tridentata (Zygophyllaceae). Journal of Arid Environments, 28(2): 139-146.

Grover, H.D. and Musick, H.B., 1990. Shrubland encroachment in southern New Mexico, U.S.A.: an analysis of desertification processes in the American Southwest. Climatic Change, 17: 305-330.

Hunter, K.L. et al., 2001. Ploidy race distributions since the Last Glacial Maximum in the North American desert shrub, Larrea tridentata. Global Ecology and Biogeography, 10(5): 521-533.

Huxman, T.E. et al., 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia, 141 (2): 254-268.

Knapp, A.K. et al., 2008. Consequences of more extreme precipitation regimes for terrestrial ecosystems. Bioscience, 58(9): 811-821.

Kurc, S. and Small, E., 2004. Dynamics of evapotranspiration in semiarid grassland and shrubland during the summer monsoon season, central NM. Water Resources Research, 40 (W09305).

Kurc, S.A. and Benton, L.M., in press. Digital image-derived greenness links deep soil moisture to carbon uptake in a creosotebush-dominated shrubland. Journal of Arid Environments (Ecohydrology of NAM).

Kurc, S.A. and Small, E.E., 2007. Soil moisture variations and ecosystem-scale fluxes of water and carbon in semiarid grassland and shrubland. Water Resources Research, 43(6).

Meinzer, F.C., Wisdom, C.S., Gonzalezcoloma, A., Rundel, P.W. and Shultz, L.M., 1990. Effect of leaf resin on stomatal behavior and gas-exchange of *Larrea-tridentata (DC) Cov*. Functional Ecology, 4(4): 579-584.

Minckley, R.L., Cane, J.H. and Kervin, L., 2000. Origins and ecological consequences of pollen specialization among desert bees. Proceedings of the Royal Society of London Series B-Biological Sciences, 267(1440): 265-271.

Seager, R. et al., 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science, 316(5828): 1181-1184.

Waring, G.L. and Price, P.W., 1990. Plant water-stress and gall formation (cecidomyiidae, asphondylia spp) on creosote bush. Ecological Entomology, 15(1): 87-95.

Whitford, W.G., Anderson, J. and Rice, P.M., 1997. Stemflow contribution to the 'fertile island' effect in creosotebush, *Larrea tridentata*. Journal of Arid Environments, 33: 451-457.

Correspondence
New Investments in the Australian Flux Network
Derek Eamus

As many of you will know, Australia has a flux network (OZFLUX) that has been in existence for many years. Indeed, I think the first eddy covariance data for Australia were measured in 1997 in the Northern Territory of Australia, in the wet-dry tropics at a savanna site (Hutley et al. 2002, 2001; Eamus et al 2001). This site receives between 1500 mm and 2500 mm of rain each year in each 5 month long wet season. Despite the huge change in rainfall, VPD

Figure 1: The author inspects a fine example of Acacia aneura (mulga) growing at a site approximately 150 km north of Alice Springs in central Australia.

and soil moisture content (top 1 m) between wet and dry season, tree water use is highly conservative, showing minimal variation across season. Since those early days, more flux sites have been added, notably in Victoria, the Australian Capital Territory and tropical Queensland. All three of these sites are situated in tall (> 30 m) wet (>1000 mm annual rainfall) closed forest. However, most of Australia is arid or semi-arid, receiving less than 500 – 600 mm annual rainfall. Surpris-

ingly little ecophysiological or ecohydrological work, and no flux measurements have been undertaken in these regions.

As part of the Australian Federal Government's increase in funding for nationally important research, $542 million dollars was made available (over 2004 – 2011) through the National Collaborative Research Infrastructure Strategy to develop and fund national research infrastructure projects. One of the initiatives funded in this program was the Terrestrial Ecosystem Research Network (TERN).

Terrestrial Ecosystem Research Network (TERN)

The TERN initiative is designed to provide a nationally consistent approach to collecting and managing time-series datasets across Australian landscapes and investment from NCIRS to the TERN will assist in establishing a national, collaborative infrastructure that will facilitate enhanced ecosystem research. One part of the NCRIS investment in TERN is to provide funding for additional flux sites across Australia and to provide a centralised data management, data quality assurance and data storage/dissemination facility.

The new Alice Springs flux site

One of the new sites currently being established as part of the new TERN funding is located

one-hour drive from Alice Springs in Central Australia. Mean annual rainfall for this site is 277 mm but this statistic is too broad to be of much value. The annual minimum and maximum rainfall is 82 and 783 mm respectively. Over the past 60 years, all months have at some stage received zero rain but on average each month receives some rain, ranging on average from 4.2 to 73.1 mm per month (O'Grady et al 2009). However, maximum monthly rainfall recorded is 357 mm – yes, in March 2000, the rainfall exceeded the long-term annual rainfall for Alice. Mean daily potential evaporation rates range from 4 mm to 13 mm. Central Australia has been experiencing some of the most rapid rates of climate warming on the continent, especially since 1950 (Box et al 2008). The only prominent mesoscale meteorological feature that affects the region is the passage of subtropical cold fronts that develop in the late spring, before summer precipitation pulses initiate (Beringer and Tapper 2000). These cold fronts develop at night and generate profound effects on the partitioning of energy fluxes, often generating moisture pulses into the canopy from aloft.

Vegetation in this region tends to be dominated either by *Acacia* shrubland (to 4 m height) *Acacia* open woodland (taller) or extensive modified grasslands used in

Australian Flux Network

Figure 2: Acacia aneura (mulga) is a dominant woody species across much of the arid interior of Australia. To Aboriginal people of Australia, mulga is a much used food source with edible seeds.

the cattle industry. It is our intent to put the flux tower over *Acacia* shrubland, which contains a seasonal grass understory. The LAI at the site is low (*ca* 0.5), and situated in a landscape of sand swales. In addition to the gold standard eddy covariance system, we shall install our new small aperture scintillometer at the same site to compare the two methods in their estimation of surface energy budgets.

Key questions we wish address include the following:

* What is the daily, seasonal and annual carbon and water budget for the *Acacia* shrubland?

*What are the response-times and patterns of response to pulses of rain?

*Can we distinguish different ecohydrological types amongst species in the different patterns of response to pulses of rain?

*How does soil respiration and the understory pattern of water use and C uptake compare with the overstory?

*How do shaded and inter-canopy spaces vary in evaporation-induced enrichment of deuterium and ^{18}O?

*What attributes of *Acacia* makes it so resilient to this environment?

*What is the rate of deep drainage of water (groundwater recharge) and how is this related to the size of the rainfall event and antecedent soil moisture content?

*How will climate change, warming, and variability affect carbon, water, and energy fluxes, as well as the penetration of spring cold fronts?

A key activity that the ecohydrology research lab at UTS is undertaking is to take multiple-site EC data and to use these data to improve on the Australian standard land surface exchange model (CABLE). The Alice Springs site will be one of many sites we shall use in this CABLE model development project. CABLE, like all such

Australian Flux Network

Figure 3: Alongside dry river beds majestic River Red Gums (*Eucalyptus camaldulensis*) can be found, even in aird zone central Australia.

models, has representations of photosynthesis, transpiration and surface energy balances at landscape scales. However, it has major limitations in its accurate representation of landscape function for much of the continent. By combining data assimilation methods, remote sensing of land surface processes and attributes, and CABLE model development we intend to provide a more accurate assessment of land surface-atmosphere exchanges of CO_2, water and energy. One the first steps in this will be to improve the representation of the link between stomatal conductance and soil and atmospheric water content.

contact:
Derek Eamus
Derek.Eamus@uts.edu.au

University of Technology Sydney

Highlight Young Scientist   *Aline Jaimes*

My name is Aline Jaimes. I am from the city of Xalapa, Veracruz, located on the east coast of Mexico. After receiving my BSc. in Biology from Universidad Veracruzana, I pursued a MSc in Baja California - one of the most beautiful places in Mexico surrounded by Desert and Ocean. I studied physical and biological interactions focused on marine primary productivity and mesoscale structures (geophysical turbulence) at the entrance of the Gulf of California. This was program jointly managed between the Northwest Center of Biological Research (*CIBnor*) and the Center for Scientific Research and Higher Education of Ensenada, BC (*CICESE)*. While there, I had the opportunity to experience a range of different disciplines including biology, physics, oceanography, meteorology, remote sensing. These experiences broadened my vision and opened up a world of possibilities. Retrospectively, I believe that was the reason I became interested in micrometeorology. I think that interdisciplinary science allows a researcher to integrate and build on many amazing and well established areas of knowledge to address some of the most pressing environmental challenges we are facing - like climate change. My career goal is to be able to study, understand, and communicate findings related to complex environmental process to other researchers, the general public and decision makers. I hope that my research will someday be used to make more informed decisions regarding the management of our natural resources.

Currently, I am a 2nd year PhD student enrolled in the Environmental Science and Engineering program at the University of Texas at El Paso (UTEP). At UTEP I am working in the System Ecology Laboratory (SEL) under the direction of Dr. Craig Tweedie (www.sel.utep.edu). SEL is a fairly young lab and I have just finished building our first flux tower site, which is located on the Jornada Experimental Range (JER) in southern New Mexico (See figure 2). The JER is managed by the US Department of Agriculture Agricultural Research Service and is part of the Jornada Long Term Ecological Research Program, which has been active since 1982 (http://jornada-www.nmsu.edu/). Dr Kris Havstad, Dr Deb Peters (USDA-ARS, Jornada Experimental Range, Las Cruces, New Mexico) have been extremely helpful in accommodating our needs on the JER and Dr Al Rango's remote sensing team has been kind enough to fly their Unmanned Aerial Vehicle over our study site and take high resolution aerial photographs to help with site choice and description.

Building the tower site has been one of the most challenging tasks I have ever had, but I have been fortunate to have had a lot of help from other students in the SEL, access to experts in the field, in particular Dr. Marcy Litvak at the University of New Mexico who has helped me tremendously. I was also lucky enough to attend two training courses – the Open Path Eddy Covariance at CSI, Logan Utah, and the flux measurements and advanced modeling course convened by University of Colorado Mountain research station at Boulder, CO-. These colleagues and training courses have boosted my confidence and have allowed me to bring new skills to our young and growing research lab.

The primary aim of our research is to establish a flux tower site that will join the Ameriflux network and a common use field and cyber infrastructure that will advance capacities for examining land-atmosphere interactions and spatio-temporal scaling of ecosystem structure and function in desert shrublands. Our activities are funded through a National Science Foundation CREST (Centers for Research Excellence and Technology) award granted to UTEP to develop the Cyber-ShARE Center of Excellence (www.cybershare.utep.edu). The Cyber-ShARE Center gives me the opportunity to interact with research faculty and students from environmental, geo and computer science as well as mathematics and education. The aim of our collaboration is to address the challenge of minimizing random and systematic sources of error and improving trust in data collected from novel technologies such as Eddy covariance systems. Collaboration with CS has taught me how to build workflows, ontologies, a database and capacities to trace provenance in my flux data and also the optimization of a geospatial site-choice tools.

Our project focuses on the study of the changes in vegetation structure and ecosystem processes associated with change of ecosystem state interpreted as "desertification", the broad-scale conversion of perennial grasslands to dominance by xerophytic woody plants and the associated loss of soils and biological resources including biodiversity (Peters, D. et. al 2006).

Figure 1: Aline Jaimes

Highlight Young Scientist

Figure 2: Flux tower at the Jornada Basin Long Term Ecological Research, NMSU

about, CO_2, water and Energy balance, across spatial and temporal scales to improve the ability to understand current and historic patterns and dynamics. 2) To study processes interactions across a range of scales and under different conditions to drive desertification dynamics and regulate conservation of biological resources. 3) Describe interactions driving landscape dynamics such that we can predict spatial and temporal variation processes to strategically promote conservation of biological resources.

contact:
Aline Jaimes
ajaimes@miners.utep.edu

Systems Ecology Laboratory
http://www.sel.utep.edu/

If you want to know more about our research please visit our website or contact me. Our site is still growing and we would be delighted to have other students who have similar research interest to come and conduct research here at JER.

Further Reading
Havstad, K. M., Huenneke, Schlesinger, W., Eds. (2006). Structure and Function of a Chihuahuan Desert Ecosystem. The Jornada Basin Long-Term Ecological Research Site, Oxford University Press. Pp 447.

Peters, D., H. S. William, et al. (2006). Future direction in Jornada research: Applying an interactive landscape model to solve problems. Structure and Function of a Chihuahuan Desert Ecosystem. K. Havstad, L. Huenneke and W. Schlesinger, Oxford University Press: 447.

The hypothesis is that spatial and temporal variation in ecosystem dynamics is the result of patch structure interacting with transport vectors (i.e. wind, water) and environmental drivers (i.e. temperature, CO_2) to influence cross-scale resource redistribution. These interactions feedback to patch structure to cause cascading events with effects on ecosystem good and services.

The overall goals of my project are: 1) Provide an analysis to integrate diverse observations

Semiarid ECohydrological Array – SECA

Russell L. Scott, G. Darrel Jenerette, Travis E. Huxman

In this article we would like to highlight a little of the history of water vapor and carbon dioxide flux monitoring in our small part of the world (southern Arizona, USA) and highlight some of the research results and challenges. In comparison to more mesic regions, there is a general lack of data on net ecosystem exchange of carbon dioxide (NEE) in arid and semiarid regions. In these areas, water is the dominant control of NEE, and precipitation is much more variable in time and space. Someone remarked at an Ameriflux conference a few years ago that nothing goes on down here in terms of globally-relevant CO_2 exchange processes. Perhaps when looking at long-term and large-area means this might be true, but we have found that semiarid ecosystems can be both significant sinks and sources of CO_2, with much greater interannual variability than a "typical" forested site. Additionally, we argue that water limitation affects ecosystem carbon exchange for at least some part of the growing season in all but the wettest ecosystems around the world. By looking at the drier end of this water-limitation spectrum, we have ample opportunities to better understand these effects.

Our research using eddy covariance started in 2001 by establishing three sites over dominant riparian ecosystems of the San Pedro River in southeastern Arizona (Fig. 1). At the time, we

"The Southwestern ECohydrology Array (SECA)) is a multi-user network that serves to assess biosphere / atmospheric exchange processes, as well as surface hydrology in semiarid ecosystems. SECA is administered through the USDA-ARS Southwestern Watershed Research Center and the University of Arizona's B2 Earthscience. The components of the array were constructed with funds from the USDA-ARS, University of Arizona, and the NSF-Science & Technology Center SAHRA."

were driven by basic water balance questions like, "how much water do the plants use?" Riparian ecosystems are hotspots for ecosystem flora and fauna diversity. Since many riparian ecosystems share the same groundwater resource as the human population in these basins, quantifying their role in a basin's water balance is vital to sound water resource management. Accordingly, our results have highlighted the large evapotranspiration (ET) amounts with annual ET often exceeding precipitation by 2 -3 times (Scott et al., 2008; Scott et al., 2004; Scott et al., 2000) and this data has been instrumental in reducing the uncertainties in the water budget of the basin (Scott et al., 2006). These data have also been used to develop satellite-data-driven models which are used to scale up along river reaches in this and other basins (Nagler et al., 2005; Scott et al., 2008).

With the advent of low power and combined open-path water vapor and CO_2 IRGAs, our interest in the interaction between the water and carbon cycle was piqued. Riparian sites in arid lands experience high radiation loads, high vapor pressure defi-
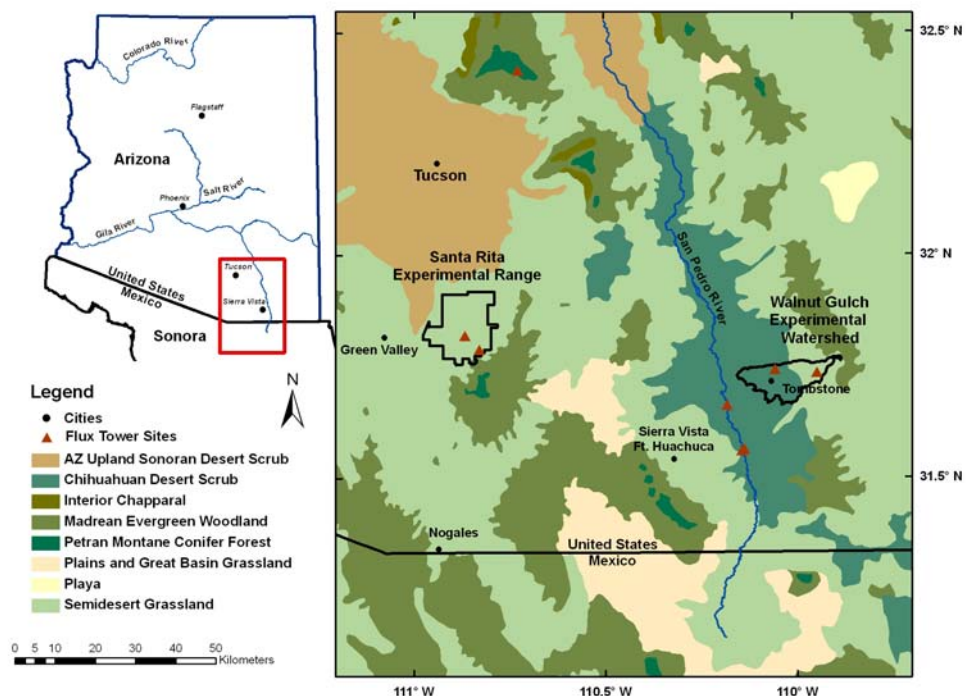

Figure 1: Figure 1 (low resolution): Location of the flux towers associated with SECA. Also, shown is the vegetation classification of Brown *et al.* [1979].

Page 11

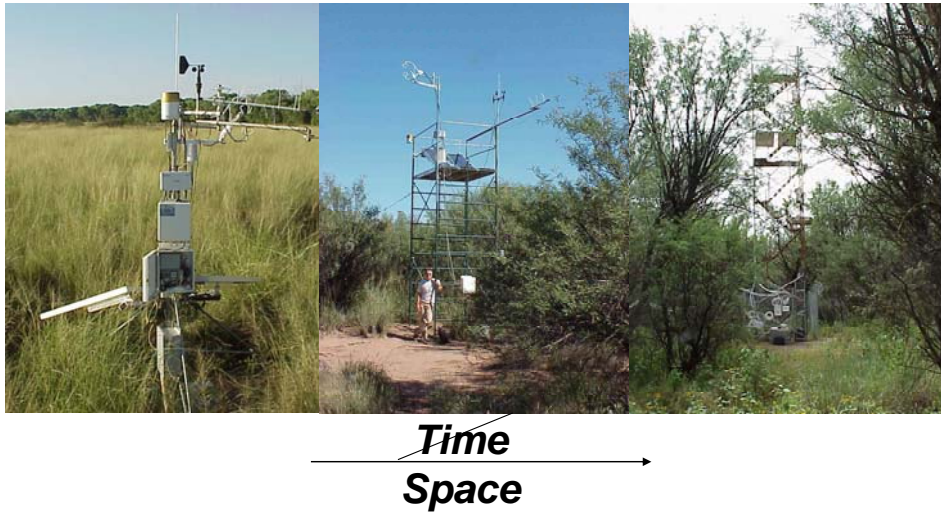# Semiarid ECohydrological Array – SECA

Time

Space

Figure 2. Using space for time substitution to study mesquite encroachment effects on riparian grasslands.

cits, and low rainfall amounts, but deep-rooted vegetation can access groundwater that can result in a decoupling of above-ground hydrometeorology and below-ground hydrology. Accordingly, we have observed large fluxes of CO_2 in these riparian systems that highlight the role of water limitation on ecosystem carbon fluxes. First, we have found that there are large amounts of net carbon uptake-- resulting from the consequences of the general lack of water limitation for the dominant phreatophytic plants (deep-rooted grasses and trees) that can access groundwater and strong water limitation for the microbial community that have only fleeting opportunities following rain events to break down carbon (Jenerette et al., 2008). The result of this interaction is that these ecosystems

accumulate more carbon in the driest parts of the growing season (Scott et al., 2004), a result that has been mirrored in the wettest parts of the world (Saleska et al., 2003). We are using these data to develop whole ecosystem carbon models to project likely changes associated with climate and land-cover change (Jenerette et al., 2009). We have also begun to understand the consequences, in terms of mass and material exchange, of woody plant encroachment, a phenomenon that is occurring here and in many dryland regions around the world (Goodale et al., 2002). Along the San Pedro and in the upland (non-riparian) regions of southern Arizona (Fig. 1), we have established sites that represent various levels of encroachment (Fig. 2). We are just starting to pull all of our results to-

gether to begin making mature conclusions. Early results for riparian systems suggest that as floodplain terrace grasslands are replaced by woody, mesquite-covered ecosystems the shallower-rooted grasses are less able to fully exploit stable groundwater sources, whereas the ecohydrological exchanges of encroached ecosystems become more decoupled from precipitation as the ecosystems become more woody (Scott et al., 2006; Jenerette et al., 2009). This results in a tradeoff between more carbon sequestration at the expense of greater water use in an region of over-exploited groundwater resources.

With the exception of our sole-remaining mesquite woodland tower that has been in operation since 2001, we are now moving beyond the riparian areas and into the surrounding "desert"

ecosystems, which we started monitoring around 2004 (Fig. 3). Because of the lack of groundwater access we are discovering that ecosystems with similar composition (e.g., a riparian mesquite shrubland and upland mesquite savanna) operate much differently, resulting in altered magnitudes and seasonality of the CO_2 flux response (Potts et al, 2006) We are also seeing that drought in these rainfall-dependent ecosystems results in net annual CO_2 loss and that this response varies depending on whether the drought occurs from lack of winter or summer rains (Scott et al., 2009). Finally, we have been able to combine our site ET data with surface hydrological measurements of small watershed water balances to show that the eddy covariance technique appears to provide a highly accurate estimate of ET with the two independent measures agreeing on an average within 3% of each other annually and differed

from -10 to +17% in any given year and site (Scott et al., 2009).

We have contributed some of our data to the global Fluxnet community (Santa Rita Mesquite and Kendall Grassland) with aims to eventually offer all of it for global use. As a prototype regional network our sites have initially been used to describe variation in whole ecosystem respiration pulses following rain events (Jenerette et al. 2008) and this work is leading into a global Fluxnet synthesis analysis. We also continue to expand our domain and scope with a nearby mixed conifer site in the moun-

Semiarid ECohydrological Array – SECA

Figure 3. Santa Rita mesquite savanna from the air. The site is representative of a fully encroached desert grassland.

tains surrounding our deserts to look at an elevation/precipitation transect and with *amigos* south of the U.S.-Mexico border in the state of Sonora (Instituto Tecnologico de Sonora, Universidad de Sonora) to look across gradients in the strength and importance of the summer rainfall from the North American Monsoon. Of course, we always welcome new collaborations.

contact:
Rusell L. Scott

Southwest Watershed Research Center, United States Department of Agriculture, Agricultural Research Service, Tucson, AZ

Russ.Scott@ars.usda.gov

References

Brown, D.E., Lowe, C.H., Pase, C.P., 1979. A digitized classification system for the biotic communities of North America, with community (series) and association examples for the Southwest. Journal of the Arizona-Nevada Academy of Science 14 1-16. Republished 1994 in Biotic Communities: Southwestern United States and Northwestern Mexico, edited by David E. Brown, pp. 302-315. University of Utah Press, Salt Lake City.

Goodale, C.L., Davidson, E.A., 2002. Uncertain sinks in the shrubs. Nature 418, 593-594, doi:10.1038/418593a. Jenerette, G.D., Scott, R.L., Barron-Gafford, G.A., Huxman, T.E., 2009. Gross primary production variability associated with meteorology, physiology, leaf area, water supply in contrasting woodland and grassland semiarid riparian ecosystems. J. Geophys. Res. [Biogeo.]G04010,

Jenerette, G.D., Scott, R.L., Huxman, T.E., 2008. Whole ecosystem metabolic pulses following precipitation events. Funct. Ecol. 22, 924-930,

Nagler, P.L., Cleverly, J., Glenn, E., Lampkin, D., Huete, A., Wan, Z., 2005. Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. Remote Sens. Environ. 94, 17-30,

Potts, D.L., Huxman, T.E., Scott, R.L., Williams, D.G., Goodrich, D.C., 2006. The sensitivity of ecosystem carbon exchange to seasonal precipitation and woody plant encroachment. Oecologia 150, 453-463,

Saleska, S.R., Miller, S.D., Matross, D.M., Goulden, M.L., Wofsy, S.C., Da Rocha, H.R., De Camargo, P.B., Crill, P., Daube, B.C., De Freitas, H.C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J.W., Pyle, E.H., Rice, A.H., Silva, H., 2003. Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses. Science 302, 1554-1557,

Scott, R.L., 2009. Using watershed water balance to evaluate the accuracy of eddy covariance evaporation measurements for three semiarid ecosystems. Agric. For. Meteorol. in press,

Scott, R.L., Cable, W.L., Huxman, T.E., Nagler, P.L., Hernandez, M., Goodrich, D.C., 2008. Multiyear riparian evapotranspiration and groundwater use for a semiarid watershed. J. Arid Environ. 72, 1232-1246,

Scott, R.L., Edwards, E.A., Shuttleworth, W.J., Huxman, T.E., Watts, C., Goodrich, D.C., 2004. Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. Agric. For. Meteorol. 122, 65-84,

Scott, R.L., Huxman, T.E., Williams, D.G., Goodrich, D.C., 2006a. Ecohydrological impacts of woody-plant encroachment: Seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. Global Change Biol. 12, 311-324,

Scott, R.L., James Shuttleworth, W., Goodrich, D.C., Maddock Iii, T., 2000. The water use of two dominant vegetation communities in a semiarid riparian ecosystem. Agric. For. Meteorol. 105, 241-256.

Scott, R.L., Jenerette, G.D., Potts, D.L., Huxman, T.E., 2009. Effects of seasonal drought on net carbon dioxide exchange from a woody-plant-encroached semiarid grassland. J. Geophys. Res. [Biogeo.] 114, G04004,

Scott, R.L., Williams, D.G., Goodrich, D.C., Cable, W.L., Levick, L.R., McGuire, R., Gazal, R.M., Yepez, E.A., Ellsworth, P., Huxman, T.E., 2006b. Chapter D: Determining the riparian groundwater use within the San Pedro Riparian National Conservation Area and the Sierra Vista Subwatershed, Arizona.

Lateral versus vertical carbon fluxes in Baja California, Mexico

Martín Escoto-Rodríguez, Stephen V. Smith and Stephen H. Bullock

Standard models and inventories of carbon balance place primary emphasis on vertical exchanges between the atmosphere and both the land and the ocean. "Flujos TERMAR" is a project funded by CONACYT (the Mexican equivalent to the U. S. National Science Foundation, NSF) and is designed to improve understanding of the role of lateral fluxes, along with vertical fluxes, in the carbon balance.

The project, as its name indicates ("TERMAR" stands for "Tierra y Mar", i.e. land and sea), was also designed to compare terrestrial and marine fluxes in immediately adjacent regions.

We study the area around Ensenada, Baja California, Mexico. On land, this area is characterized as a semi-arid Mediterranean-climate regime (cool, wet winters, warm-dry summers).

The region is topographically complex. Shrubland communities modified by human influence (introduced species) dominate the environment, with many of the low-elevation areas being sites of agricultural development. The marine environment is characterized by seasonally strong upwelling, characteristic of much of the Pacific coast of the Americas.

The underlying hypothesis is that a significant fraction of CO_2 fixed by autotrophic-dominated communities is transported as organic matter and oxidized outside the immediate uptake system. Moving organic matter from one site to another is likely to alter the oxidation rate. On land, the organic transport is by water or wind erosion, transport, and re-deposition. In the ocean the transport is by wind and tide

Figure 1. Flux tower at "El Mogor". The cultivated areas are outside the tower's footprint.

Lateral versus vertical carbon fluxes

Figure 2: Flux tower on Todos Santos Norte Island. The tower's height has been increased twofold after this picture was taken.

induced horizontal currents (including currents associated with coastal upwelling). The importance of the hypothesis is that local vertical fluxes of CO_2 may over-represent the strength of CO_2 sink (or source) communities, because lateral transport is an important linkage between communities in nature.

In order to compare metabolic rates (particularly the difference between production and respira-

tion) with erosional rates, we used the Revised Universal Soil Loss Equation (RUSLE) to model long-term erosion as a function of precipitation, soil erosivity, land cover/land use, and slope (Smith et al., 2007). This modeling has been undertaken with GIS. From data on soil organic carbon (SOC), we could also estimate the erosion rate of SOC. The studied watersheds eastward of Ensenada have 80% of the land with steep (erosive)

slopes and 20% with alluvial deposits. The areas with steep slopes lose carbon from erosion at a rate of at least 10 tons km^{-2} yr^{-1}. By comparison net ecosystem production (that is, vertical flux) is less than about 40 tons km^{-2} yr^{-1}. Therefore, the displacement of material by erosion can be of similar magnitude to net ecosystem production in areas (such as our study area) with complex topography. This can elevate the sequestration of

carbon at ecosystem scales, if there is less oxidation in depositional areas than in erosional areas.

We have also examined the carbon isotopic signature of sediments in Todos Santos Bay, in order to determine what portion of the organic carbon (OC) in those sediments is marine, and what fraction is terrestrial in origin (Smith et al., 2008). This becomes a measure of lat-

Lateral versus vertical carbon fluxes

eral transport of OC between land and the coastal ocean. We have learned that the sediments with maximum amount of terrestrial material are most removed from the coast, at the head of a submarine canyon. The composition of organic carbon in the bay is controlled by lateral transport and deposition as well as marine production and the oxidation of part of the terrestrial material.

In addition to those terrestrial and marine fluxes, we have analyzed fluxes (both lateral and vertical) of the urban area of Ensenada (Bullock et al., submitted). We considered issues such as the use of gasoline and other fuels, human metabolism and waste generation, and industrial processes such as cement production. In this case, this urban area is entirely supported by the import of materials and energy. The city of Ensenada emits about 6,400 tons C km^{-2} yr^{-1}. These emissions would require an area of 160 km^2 of shrublands to take up the carbon emitted from each km^2 of the city.

In order to understand the dynamics of vertical carbon fluxes in both the terrestrial and marine environments we are using the eddy flux technique. We installed two eddy flux towers in the study area. One tower is on shrubland, the most common natural vegetation of this region, while the other was installed on the fringe of a nearby island to measure marine fluxes. To our knowledge, apart from these two towers there are just other five towers in the whole coun-

try: one in Baja California Sur, two in Sonora, one in San Luis Potosi and one in Jalisco.

The terrestrial tower is located at Rancho "El Mogor" in Guadalupe Valley (Fig. 1). We began to collect data in July 2007. The study site has both evergreen and summer-deciduous shrubs. Preliminary analyses showed net ecosystem exchange to be of about the expected magnitude. March and April, just after the rain season (~332 mm of average annual rainfall), presented the higher diurnal amplitude of CO_2 absorption with maximum peaks of about 10 μmol CO_2 m^{-2} s^{-1}. In contrast, during September and October, when the soil was dry, diurnal carbon uptake had peaks of only about 1 μmol CO_2 m^{-2} s^{-1}. The marine tower was installed on Todos Santos Norte Island, about 20 km west of Ensenada (Fig. 2). We began collecting data in August 2008. Most coastal marine studies have been limited to transect studies of insufficient duration to capture temporal variation and event-scale forcing of CO_2 flux. Intensive research at single sites over multiple years is necessary to determine how the coastal ocean might adjust to changes in climate and watershed land use, in order to extrapolate over large areas. A

proper description of the spatial-scale variability of CO_2 exchange is still lacking. In coastal regions, in particular, various processes seem either to enhance or reduce gas exchange drastically. For example upwelling events (northwesterly winds, roughly parallel to shore) and "Santa Ana" events (onshore winds) are both common in the study area and will be of special interest.

Although pending more analyses of data from the two towers, our overall results suggest that lateral transfer and organic carbon oxidation along the lateral transfer pathway must be considered in an accounting of organic carbon mass balance both on land and in the ocean.

contact:
M. Escoto-Rodríguez
Centro de Investigacion Cientifica y de Educacion Superior de Ensenada [CICESE]

mescoto@cicese.mx

research team:
M. Escoto-Rodríguez
S.V. Smith
S.H. Bullock

> *"The underlying hypothesis is that a significant fraction of CO_2 fixed by autotrophic-dominated communities is transported as organic matter and oxidized outside the immediate uptake system.*

References

Smith, S.V., Bullock, S.H., Hinojosa-Corona, A., Franco-Vizcaíno, E, Escoto-Rodríguez, M., Kretzschmar, T.G., Farfán, L.M., Salazar-Ceseña, J.M., 2007. Soil erosion and significance for carbon fluxes in a mountainous mediterranean-climate watershed. Ecological Applications 17, 1379-1387.

Smith, S.V., Ibarra-Obando, S.E., Díaz-Castañeda, V., Aranda-Manteca, F.J., Carriquiry, J.D., Popp, B.N., Gonzalez-Yajimovich, O., 2008. Sediment organic carbon in Todos Santos Bay, Baja California, Mexico. Estuaries and Coasts 31, 719-727.

Bullock, S.H., Escoto-Rodríguez, M., Smith, S.V., Hinojosa-Corona, A., Submitted. Carbon flux of an urban system in Mexico.

CO$_2$ fluxes in semi-arid sites on carbonate substrates located in southeast Spain

Penélope Serrano-Ortiz, Enrique Pérez Sánchez-Cañete, Francisco Domingo, Ana Were, Luis Villagarcía and Andrew S. Kowalski

Arid and semi-arid lands comprise nearly a third of the total land surface (Okin, 2001). These water limited ecosystems are composed of patches of vegetation and bare soil that interact with each other (Domingo et al., 1999). Although such ecosystems are very sensitive to perturbations such as climate change or drought, little is known about their functional behavior, including processes of CO$_2$ exchange. Net CO$_2$ fluxes and their determinant processes are keys to characterizing the global carbon cycle and to assessing human impacts on ecosystems. In such research, CO$_2$ exchange has generally been interpreted as a biological flux (photosynthesis and respiration) neglecting other processes. However, some studies have revealed a contribution of geochemical processes to the net ecosystem carbon balance (NECB) (Emmerich, 2003; Mielnick et al., 2005). In addition, other recent publications (Kowalski et al., 2008; Serrano-Ortiz et al., 2009) demonstrate that abiotic processes can temporarily dominate terrestrial carbon exchange with the atmosphere in areas with carbonate substrates that occupy 12–17% of the Earth's land surface (Ford and Williams, 1989). Thus, further research is needed in order to understand the functional behavior of such ecosystems relating to CO$_2$ exchanges with the atmosphere to predict their response to climate change.

In this context, our team composed of researchers from the Desertification and Geoecology group (EEZA, CSIC, Almería) and GFAT (Atmospheric Physics Group, University of Granada) established three flux stations located in southeast Spain (Figure 1). The "Llano de los Juanes" flux site, located at 1600 m altitude and 25 km from the coast in the Sierra de Gádor (Almería; 36°55'41.7''N; 2°45'1.7"W), was installed in May 2004. It presents a mean annual temperature of 12°C and mean annual precipitation of ca. 475 mm. The dominant ground cover is bare soil, gravel and rock (49.1%). The vegetation is diverse but sparse, with predominance (% ground cover) of three perennial species, *Festuca scariosa* (18.8%), *Hormathophilla spinosa* (6.8%) and *Genista pumila* (5.5%). The other two sites ("Balsablanca" and "Amoladeras"), located near sea level and a few km from the coast in the "Cabo de Gata" Natural Park (Almería; 36°56' 26.0"; 2°1'58.8"W), were established in June 2006 and July 2007 respectively. They have a mean annual temperature of 18°C and
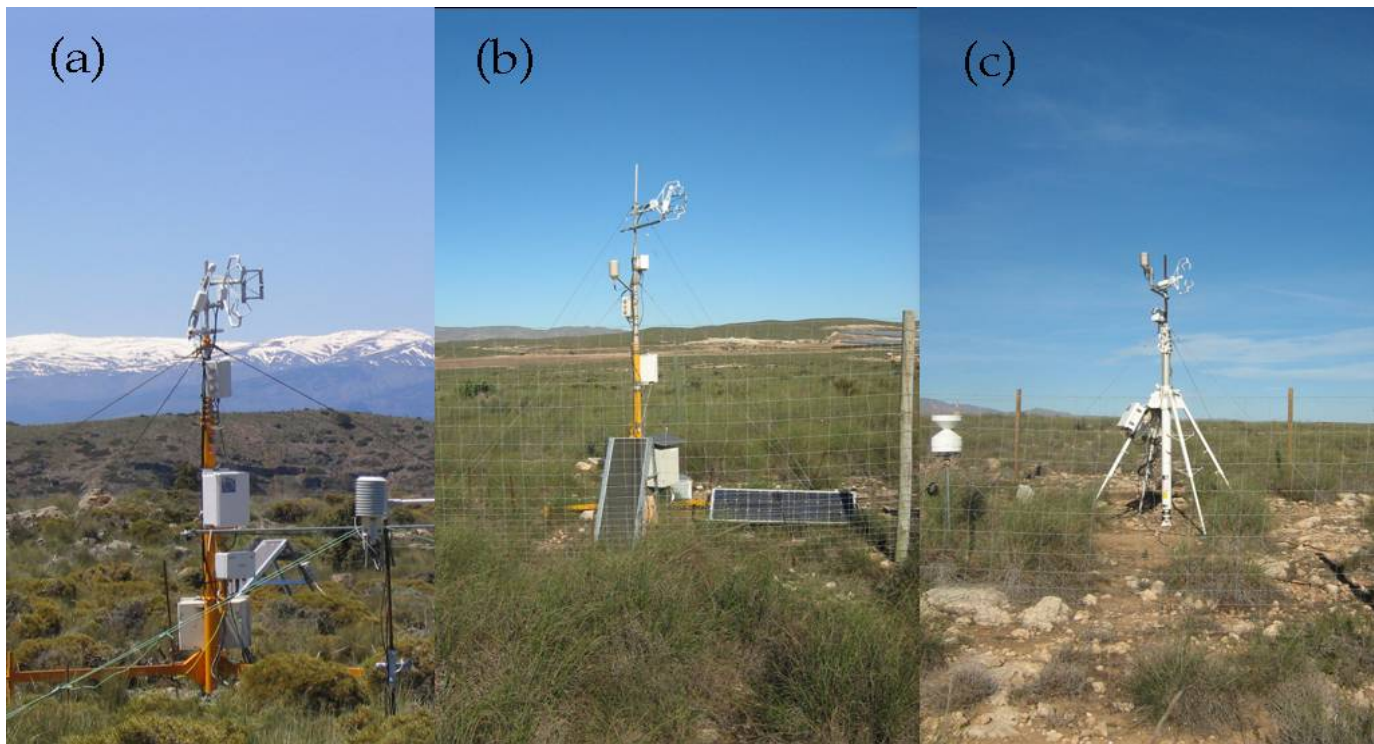

Figure 1. Flux stations located in southeast Spain in semi-arid ecosystems over carbonate soils: (a) Llano de los Juanes, (b) Balsablanca and (c) Amoladeras.

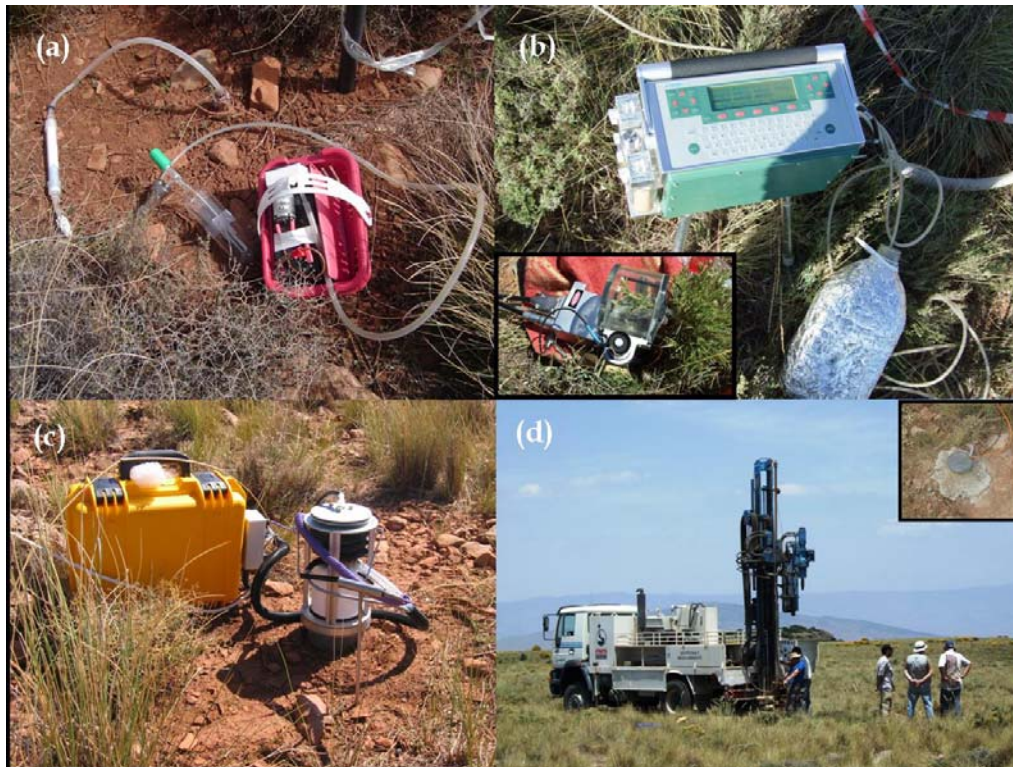# CO$_2$ fluxes in semi-arid sites on carbonate substrates

Figure2: Some examples of other techniques used in our study ecosystems: (a) taking soil air samples for stable isotopic analysis, (b) LI-6400 Portable Photosynthesis System for measuring leaf gas exchange and (c) LI-8100 Soil Chamber for measuring soil respiration and (d) drilling a borehole,

annual precipitation of 200 mm. At both sites, vegetation is dominated by *Stipa tenacissima* with presence of biological crust (20%), but "Balsablanca" has 63% of *Stipa tenacissima* and 10% of bare soil, gravel and rock, whereas the ground cover at "Amoladeras" is dominated by bare soil, gravel and rock (43%), with a 23% of *Stipa tenacissima*. All of these sites are characterized by summer droughts and asynchronous annual patterns of sunlight and precipitation.

The goals of making flux measurements at these sites are the quantification of the NECB and its interaction with the water balance, and the contribution of its determinant processes (biotic and abiotic). Taking into account that these processes act to-

gether, the eddy covariance technique and meteorological measurements cannot be applied alone to characterize the NECB over such ecosystems. In this context, several techniques are combined (Figure 2): (a) stable carbon isotopic analyses to discern among different processes involved in the NECB; (b) portable photosynthesis and (c) soil respiration systems to measure leaf gas exchange and soil emissions and estimate photosynthesis and respiration rates; (d) temporal variations of CO$_2$ and ^{222}Rn (quantitative index of the effects of natural ventilation) in soil and boreholes to determine the magnitude of CO$_2$ ventilated from the lithosphere to the atmosphere; and (e) biogeochemical modeling via coupling of existing models for biological

and geochemical processes, to separate net CO$_2$ fluxes into geochemical and biological components.

Flux measurements reveal two contrasting CO$_2$ exchange behaviors during two predominant periods: the growing and dry seasons. During growth periods, these sites act as net daily carbon sinks. Measured CO$_2$ fluxes are mostly correlated with light during daytime and can reach maximum CO$_2$ uptake of ca. 6 μmol m^{-2} s^{-1} (Figure 3a). However, during dry periods, they act as net daily carbon sources with CO$_2$ emissions correlating with atmospheric turbulence during daytime and reaching ca. 8 μmol m^{-2} s^{-1} (Figure 3b). Preliminary analyses regarding processes involved in such emissions during

dry period suggest that this behavior is not directly related to biological processes. Leaf gas exchange measurements together with soil chambers reveal that during dry periods most plants are senescent and soil respiration reaches minimum values. In addition, the WITCH geochemical model (Goddéris et al., 2006) estimates that geochemical precipitation processes are far from sufficient to explain the large magnitude of the daytime CO$_2$ emissions. Initial analyses suggest the importance of ventilation processes. This released CO$_2$ detected by the eddy covariance system is related to variations of CO$_2$ and ^{222}Rn in the soil and borehole. These preliminary results highlight the need to continue with these investigations in order to determine the importance of such processes in the NECB of semi-arid ecosystems over carbonate substrates.
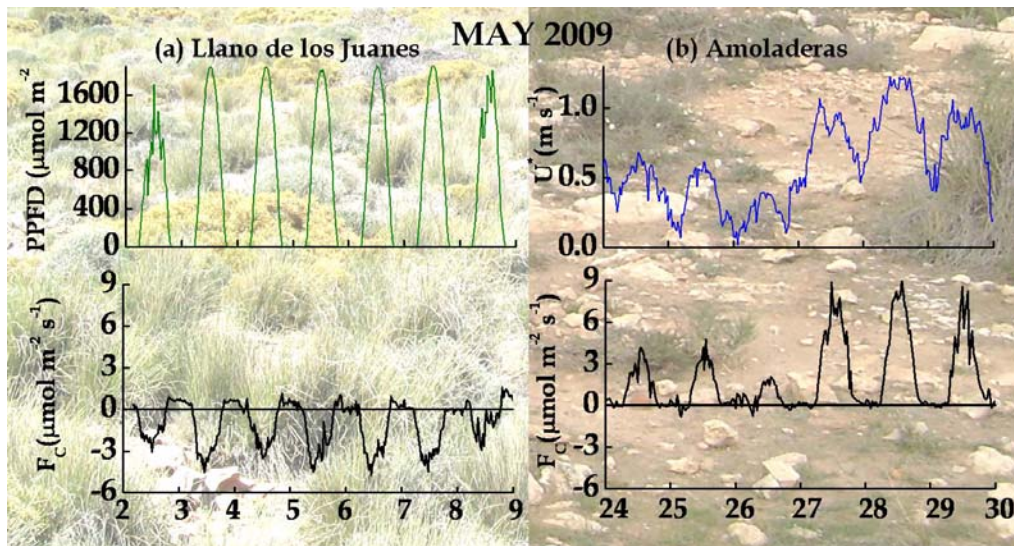
CO$_2$ fluxes in semi-arid sites on carbonate substrates

Figure 3: Carbon dioxide flux behavior (F_C, mmol m^{-2} s^{-1}) for two different ecosystems in May 2009. (a) Growing season for the "Llano de los Juanes" site with daytime F_C well correlated with incident photon flux density (PPFD, mmol m^{-2} s^{-1}); (b) dry season for "Amoladeras" site with daytime F_C well correlated with turbulence (u·, m s^{-1}).

Yakir and *Kadmiel Maseyk*, Weizmann Institute's]. Finally our research team is open to further collaboration with other scientists interested in this line of research.

contact:
Penélope Serrano-Ortiz

Universidad de Granada, Spain

penelope@ugr.es

References

Domingo, F., Villagarcía, L., Brenner, A.J. and Puigdefábregas, J., 1999. Evapotranspiration model for semi-arid shrublands tested against data from SE Spain. Agric. Forest Meteorol. 95, 67-84.

Emmerich, E.W., 2003. Carbon dioxide fluxes in a semiarid environment with high carbonate soils. Agric. Forest Meteorol.116, 91-102.

Ford, D.C. and Williams, P.W., 1989. Karst Geomorphology and Hydrology. Unwin Hyman, London, 601 pp.

Goddéris, Y., François, L.M., Probst, A., Schott, J., Moncoulon, D., Labat, D. and Viville, D., 2006. Modelling weathering processes at the catchment scale: The WITCH numerical model. Geochim. Cosmochim. Acta 70, 1128-1147, doi:10.1016/j.gca.2005.11.018.

Kowalski, A.S., Serrano-Ortiz, P., Janssens, I.A., Sánchez-Moral, S., Cuezva, S., Domingo, F. and Alados-Arboledas, L., 2008. Can flux tower research neglect geochemical CO2 exchange? Agric. Forest Meteorol. 148 (6-7), 1045-1054.

Mielnick, P., Dugas, W.A., Mitchell, K. and Havstad, K., 2005. Long-term measurements of CO2 flux and evapotranspiration in a Chihuahuan desert grassland. J. Arid Environ. 60, 423-436, doi:10.1016/j.jaridenv.2004.06.001.

Okin, G.S., 2001. Wind-Driven Desertification: Process Modeling, Remote Monitoring, and Forecasting (Charter 1). California Institute of Technology Pasadena, California, Pasadena, California, 12 pp.

Serrano-Ortiz, P., Domingo, F., Cazorla, A., Were, A., Cuezva, S., Villagarcía, L., Alados-Arboledas, L. and Kowalski, A.S., 2009. Interannual CO2 exchange of a sparse Mediterranean shrubland on a carbonaceous substrate. J. Geophys. Res. 114, G04015, doi:10.1029/2009JG000983.

New Mexico elevation gradient

Marcy E. Litvak and Andrew Fox

In the last few years, our group has combined existing tower infrastructure with several new funding opportunities to create a targeted network of tower sites in six of the major biomes that span much of the range in regional climate and plant functional types in Central and northern NM (Figure 1).

The two lowest elevation sites are in a C4 desert grassland (*Bouteloua eriopoda*) and a creosote shrubland (*Larrea tridentata*) at the Sevilleta National Wildlife Refuge and LTER site, 80 km south of Albuquerque. These sites were originally installed through the NASA-funded Big-Foot program as EOS Land Validation Core Sites in 2001 (http://www.fsl.orst.edu/larse/bigfoot/index/html). The two high elevation sites are in a ponderosa

pine woodland (*Pinus ponderosa, Quercus gambelii*) and a subalpine mixed conifer forest (*Picea engelmannii, Abies lasiocarpa*) in the Valles Caldera National Preserve. These towers were installed in 2006 through an award from the National Science Foundation, Science and Technology Center for the Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) to the University of Arizona (http://www.sahra.arizona.edu/). The two mid-elevation sites are newly established sites in a juniper savanna (*Juniperus monosperma, Bouteloua eriopoda*) (16 km south of Willard, NM on a private ranch) and a piñon-juniper woodland (*Pinus edulis, Juniperus monosperma*) on private land 8 km south of Mountainair, NM. The juniper savanna and

piñon-juniper systems were funded through NSF NM-EPSCoR and U.S. Forest Service and have been operational since May 2007 and November 2007, respectively. These six towers are in biomes that span 1500 m in elevation in the Southern Rocky Mountain-Mogollon Floristic Zone and together account for ~40% of the total land area in NM. Comparisons of long-term climate records, biomass and LAI estimates between the tower sites and 10 additional randomly chosen sites for each biome indicate that the tower sites are representative of these biomes across the state (Figure 2).

The eddy covariance instrumentation, micrometeorological sensors, and processing of all fluxes is identical for all sites. Our objectives with this net-

work are to:

1) **Quantify carbon, water and energy balance in six biomes that are broadly representative of the southwestern U.S. and specifically examine how carbon, water and energy partitioning varies as a function of vegetation type and climate across the elevation gradient.**

2) **Provide quantitative descriptions of the sensitivity of carbon, water and energy dynamics in these biomes to the principal environmental drivers, temperature and precipitation.** This is important given that climate models suggest that rising levels of CO_2 and other greenhouse gases will increase temperature by up to
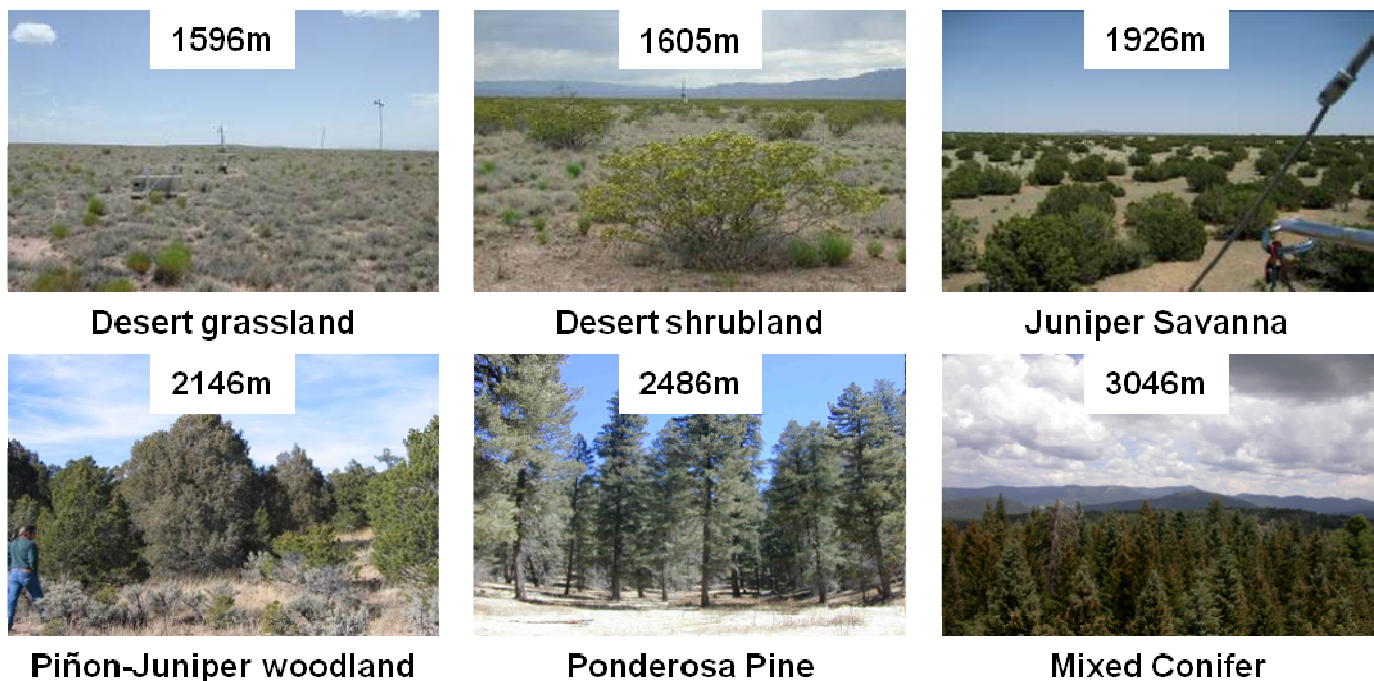

1596m — Desert grassland

1605m — Desert shrubland

1926m — Juniper Savanna

2146m — Piñon-Juniper woodland

2486m — Ponderosa Pine

3046m — Mixed Conifer

Figure 1: Biomes and locations at the New Mexico Elevation Gradient Network
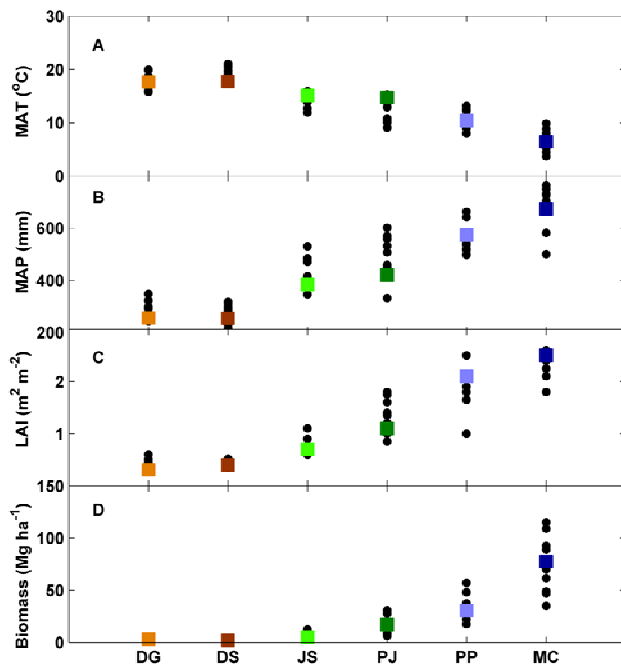
New Mexico elevation gradient

Figure 2: Auxiliary sites are used to evaluate the represenativeness of NMEG sites in terms of (a) mean annual temperature (MAT), (b) mean annual precipitation (MAP), (c) leaf area index (LAI) from MODIS, and (d) aboveground biomass. Black dots are auxiliary site data. NMEG sites are indicated by solid squares.

4°C by the end of this century, and alter precipitation patterns in the southwestern U.S. (IPCC 2007). Predicted deviations in the precipitation regime for this region include increased frequency and/or duration of extreme events (prolonged drought or above-average precipitation), changes in the frequency of rainfall events of different sizes, and shifts in the seasonal distribution of precipitation and snow cover (Allen et al. 2000, Cook et al. 2004, Seager et al. 2007, Wentz et al. 2007, Zhang et al. 2007, Leung et al. 2004).

3) **Quantify biome-specific patterns in how carbon storage and water use in semi-arid ecosystems respond to large scale changes in ecosystem structure.** The expectation is that predicted climate change scenarios will fundamentally alter the structure and dynamics of many ecosystems (Loik et al. 2004, IPCC 2007). Changes in the frequency and amplitude of precipitation or temperature fluctuations can eventually reach threshold or critical points that lead to a catastrophic shift in ecosystem state (Scheffer et al. 2009). In the SW U.S., such shifts are already common, often mediated by disturbances such as wildfire or insect/pathogen outbreaks whose probability increases as the ecosystem become increasingly stressed.

We are uniquely positioned with our network to take advantage of several natural disturbances that have triggered widespread changes in ecosystem structure across these biomes. In early 2009, a spruce budworm outbreak caused widespread defoliation throughout Central and northern NM, including at our tower site in the subalpine spruce-fir ecosystem in the Valles Caldera. In August 2009, a wildfire burned through the desert grassland eddy covariance tower site at the Sevilleta National Wildlife Refuge, and we installed an additional eddy covariance system 1 km away in Nov 2009 in unburned grassland to use as a comparison. We also initiated our own disturbance in a piñon -juniper woodland in a collaboration with Thom Rahn and Nate McDowell at Los Alamos National Laboratory, Mike Ryan and Rosemary Pendleton from the USFS and funding from DOE EPSCoR. In January 2009, we installed a second tower in a piñon-juniper woodland <2 km from the existing piñon-juniper tower, and girdled all of the piñon trees >7 cm dbh in early September (Figure 3) to simulate the widespread piñon mortality observed in piñon -juniper woodlands throughout the SW due to a combination of drought, bark beetles and pathogenic fungi in 2002-2005 (Allen and Breshears 1998, Breshears et al. 2005, 2009; McDowell et al. 2008). With these paired towers, we will be able to quantify the ecosystem consequences of widespread piñon mortality to carbon, water and energy balance in piñon -juniper woodlands.

Although occurring over a longer timescale, woody plant invasion in the southwestern US over the last 150 years, has triggered an equally dramatic change in the composition and structure of vegetation of the Sonoran and Chihuahuan deserts (Buffington and Herbel, 1965; Archer et al., 1988; Archer, 1989; Van Auken,

Figure 3: Panoramic view from flux tower showing piñon mortality subsequent to girdling

New Mexico elevation gradient

2000). Through a collaboration with Paolo D'Odorico, Stephan deWekker (both from University of Virginia), Jose Fuentes (Penn State University), Will Pockman and Scott Collins (both from University of New Mexico), we are using the desert grassland, creosote shrubland, and an additional tower in the grass-creosote ecotone at the Sevilleta to investigate how this increase in creosote impacts carbon, water and energy dynamics of desert ecosystems and if vegetation-microclimate feedbacks promote shrub encroachment in the Southwestern U.S.

With this existing network, we are able to quantify carbon, water and energy dynamics along an elevation gradient that represents the major biomes of the semiarid southwestern US. We encourage people who are interested in collaborating to contact us.

contact:
Marcy E. Litvak

University of New Mexico

mlitvak@unm.edu

References

Allen, M.R., P.A. Stott, J.F.B. Mitchell, R.Schnur, and T.L. Delworth. 2000. Quantifying the uncertainty in forecasts of anthropogenic climate change. *Nature*, **407**: 617-620.

Allen, C.D., Breshears, D.D., 1998. Drought-induced shift of a forest-woodland ecotone: rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences of the United States of America*, **95**: 14839-14842.

Archer, S., C. Scifres, C.R. Bassham, and R. Maggio (1988). Autogenic succession in a subtropical savanna: conversion of grassland to thorn woodland, *Ecol. Monogr.*, **58(2)**, 111-127.

Archer, S. (1989). Have southern Texas savannas been converted to woodlands in recent history? *Am. Nat.*, **134**, 545-561.

Breashears D., Myers O., Meyer C.W., Barnes F., Zou C., Allen C.D., McDowell N.G. and Pockman W.T. (2009). Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment*, **7**: 185-189.

Breshears D.D., Cobb N.S., Rich P.M., Price K.P., Allen C.D., Balice R.G., Romme W.H., Kastens J.H., Floyd M.L., Belnap J., Anderson J.J., Myers O.B. and Meyer C.W. (2005). Regional vegetation die-off in response to global-change-type drought. *PNAS*, **102**: 15144-15148.

Buffington, L.C. and C.H. Herbel (1965). Vegetation changes on a semidesert grassland range from 1858 to 1963. *Ecological Monographs* **35**:139-164.

Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle. 2004. Long term aridity changes in the western United States. *Science*, **306**: 1015-1018.

Intergovernmental Panel on Climate Change (IPCC). (2007) *IPCC Fourth Assessment Report – Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge.

Leung L.R., Qian Y., Bian X., Washington W.M., Han J. and Roads J.O. (2004). Mid-Century Ensemble Regional Climate Change Scenarios for the Western United States. *Climatic Change*, **62**: 75-113.

Loik, M.E., Breshears, D.D., Lauenroth, W.K. and Belnap, J. (2004) A multiscale perspective of water pulses in dryland ecosystems: climatology and ecohydrology of the western USA. *Oecologia*, **141**: 269–281.

McDowell N., Pockman W.T., Allen C.D., Breshears D.D., Cobb N., Kolb T., Plaut J., Sperry J., West A., Williams D.G. and Yepez E.A. (2008a). Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist*, **178**: 719-739.

Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M, Sugihara G. (2009). Early warning signals for critial transitions. *Nature* **461**: 53-59.

Seager R., Ting M.F., Held I., Kushnir Y., Lu J., Vecchi G., Huang H.P., Harnik N., Leetmaa A., Lau N.C., Li C.H., Velez J. and Naik N. (2007). Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **316**: 1181-1184.

Van Auken, O.W. (2000). Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics*, **31**: 197-215.

Wentz, F.J., L. Ricciardulli, K. Hilburn, and C. Mears. (2007). How much more rain will global warming bring? *Science*, **317**: 233-235.

Zhang, X., Zwiers, F.W., Hegerl, G.C., Lambert, F.H., Gillett, N.P., Solomon, S., Stott P.A., and Nozawa, T. (2007). Detection of human influence on twentieth century precipitation trends. *Nature*, **448**: 461-466.