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PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 11-1	FOR NSF USE ONLY
NSF 12-524 03/21/12	**NSF PROPOSAL NUMBER**

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DEB - Long-Term Ecological Research

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University of New Mexico	**1700 Lomas Blvd. NE** **Suite 2200, MSC01 1247,1 UNM** **ALBUQUERQUE, NM 87131-0001**
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University of New Mexico	**University of New Mexico** **NM ,871310001 ,US.**

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)	☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION	☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS	☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **LTERV: Long-term pulse dynamics in an aridland ecosystem**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 5,880,000	60 months	11/01/12	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ EAGER* (GPG II.D.2)   ☐ RAPID** (GPG II.D.1)
☒ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ___01/09/12___
   PHS Animal Welfare Assurance Number ___11-100768-MCC___

☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number _____
   Exemption Subsection _____ or IRB App. Date _____
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
   (GPG II.C.2.j)
   _____
☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT **Department of Biology**	PI/PD POSTAL ADDRESS **Castetter Hall**
PI/PD FAX NUMBER **505-277-5355**	**Albuquerque, NM 87131** **United States**

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME **Scott L Collins**	**PhD**	**1981**		
CO-PI/PD **Clifford N Dahm**	**PhD**	**1980**		
CO-PI/PD **Marcy Litvak**	**PhD**	**1998**		
CO-PI/PD **William T Pockman**	**PhD**	**1996**		
CO-PI/PD **Kristin L Vanderbilt**	**PhD**	**2000**		

Electronic Signature

Project Summary: This proposal requests funding to continue and expand our long-term research program in aridland ecology in and around the Sevilleta National Wildlife Refuge (SNWR). The original conceptual framework for the Sevilleta LTER was "Life on the Edge: Ecological Dynamics at a Biome Transition Zone." This proposal builds upon and broadens our original framework. The theme for Sevilleta LTERV is, "Abiotic pulses and constraints: dynamics and stability in aridland populations, communities and ecosystems." Although it is axiomatic that water is the key limiting resource in aridland ecosystems, most arid land soils are also chronically low in nutrients and organic matter. Nutrient availability is a function of the frequency and size of precipitation events as well as the time between events. As a consequence, net primary production and organic matter decomposition are often decoupled in space and time, and soil nutrient supply rate may limit net primary production during periods when soil moisture is sufficient for plant growth. In addition, arid and semiarid ecosystems worldwide are undergoing a state transition from grass- to shrub-dominated communities in response to multiple anthropogenic drivers. This life-form shift has important consequences for evapotranspiration, net primary production, carbon fluxes and biodiversity. Our research program integrates studies on multiple global change drivers and pulse precipitation dynamics to determine how they affect the rate at which this grass- to shrubland transition occurs. Together, our on-going and new research across multiple time and space scales will yield a comprehensive understanding of how key abiotic drivers affect pattern and process in aridland ecosystems.

   The goals of LTERV are to: **1) continue our diverse long-term datasets on ecosystem processes and dynamics developed over the past 24 years, 2) develop new observational and experimental projects and syntheses, 3) develop a more mechanistic understanding of belowground processes in aridland ecosystems, 4) develop, test, and contribute to general ecological theory, 5) enhance our information management system to meet standards for the LTER NIS, and 6) create a comprehensive program that integrates research with undergraduate and graduate education and training.** To accomplish these goals we will continue and expand our existing long-term datasets on climate, evapotranspiration and nutrient fluxes, net primary production and carbon fluxes, and plant and animal community composition and dynamics. We will add two new experiments that link soil moisture availability at depth with plant interactions and ecosystem processes, monitor the impacts of extreme events, model climate dynamics, species interactions and shrub encroachment, monitor water quality following disturbance events in the Rio Grande, and expand our studies of plant-consumer interactions.

<u>**Intellectual merit**</u>. The Sevilleta LTER Program (SEV) addresses ecological concepts and theory through comprehensive and interdisciplinary research in desert grassland, shrubland, forest and riparian habitats in central New Mexico. Our focal sites are the Sevilleta National Wildlife Refuge (SNWR) and the Middle Rio Grande (MRG). Our studies are linked by an overarching theme that considers **how abiotic drivers and constraints affect dynamics and stability in aridland populations, communities and ecosystems. <u>Broader Impacts</u>**. Our Schoolyard LTER, the Bosque Ecosystem Monitoring Program, reaches hundreds of middle and high school students annually in classroom and outdoor settings. Our Arts and Ecology REU Program brings together students from fine arts and ecology for an 11-week summer research and creative experience. We frequently interact and collaborate with staff of the SNWR, we actively participate in ESA SEEDS by hosting workshops and mentoring SEEDS Fellows, and we will participate in the newly developed UNM Biology Junior Scientist Outreach Program, which targets underserved Hispanic students in Albuquerque's south valley.

I. RESULTS FROM PRIOR SUPPORT

Intellectual merit. The Sevilleta LTER Program (SEV) addresses ecological concepts and theory through comprehensive and interdisciplinary research in desert grassland, shrubland, forest and riparian habitats in central New Mexico. Our focal sites are the Sevilleta National Wildlife Refuge (SNWR) and the Middle Rio Grande (MRG), and includes SEON – the Sevilleta Ecological Observatory Network – a network of flux towers and radio sondes throughout the middle Rio Grande basin (Fig 1). Our studies are linked by an overarching theme that considers **how abiotic drivers and constraints affect dynamics and stability in aridland populations, communities and ecosystems.**

Figure 1. Location of the Sevilleta National Wildlife Refuge in the Middle Rio Grande Basin in central New Mexico. Red symbols denote our network of flux towers and yellow symbols our network of radio sondes which make up SEON, the Sevilleta Ecological Observatory Network.
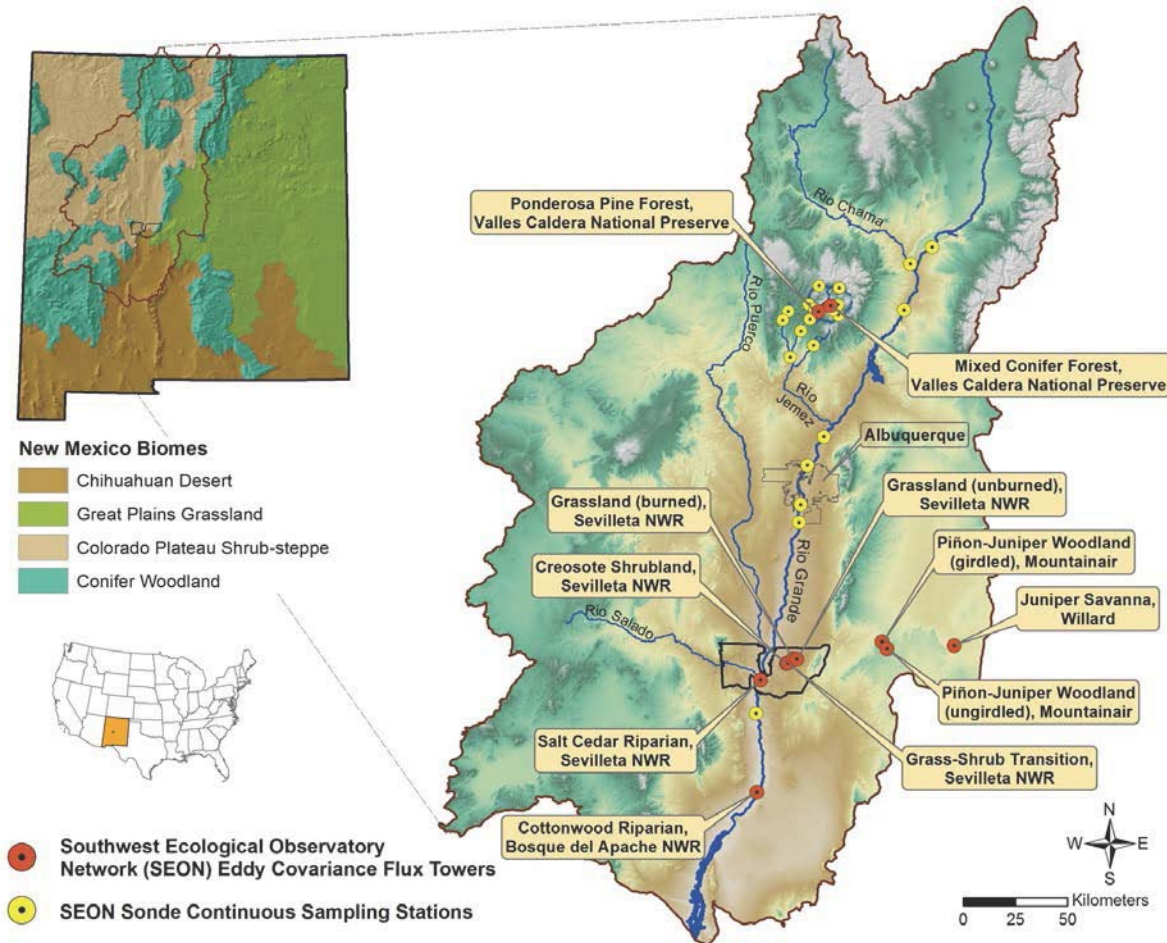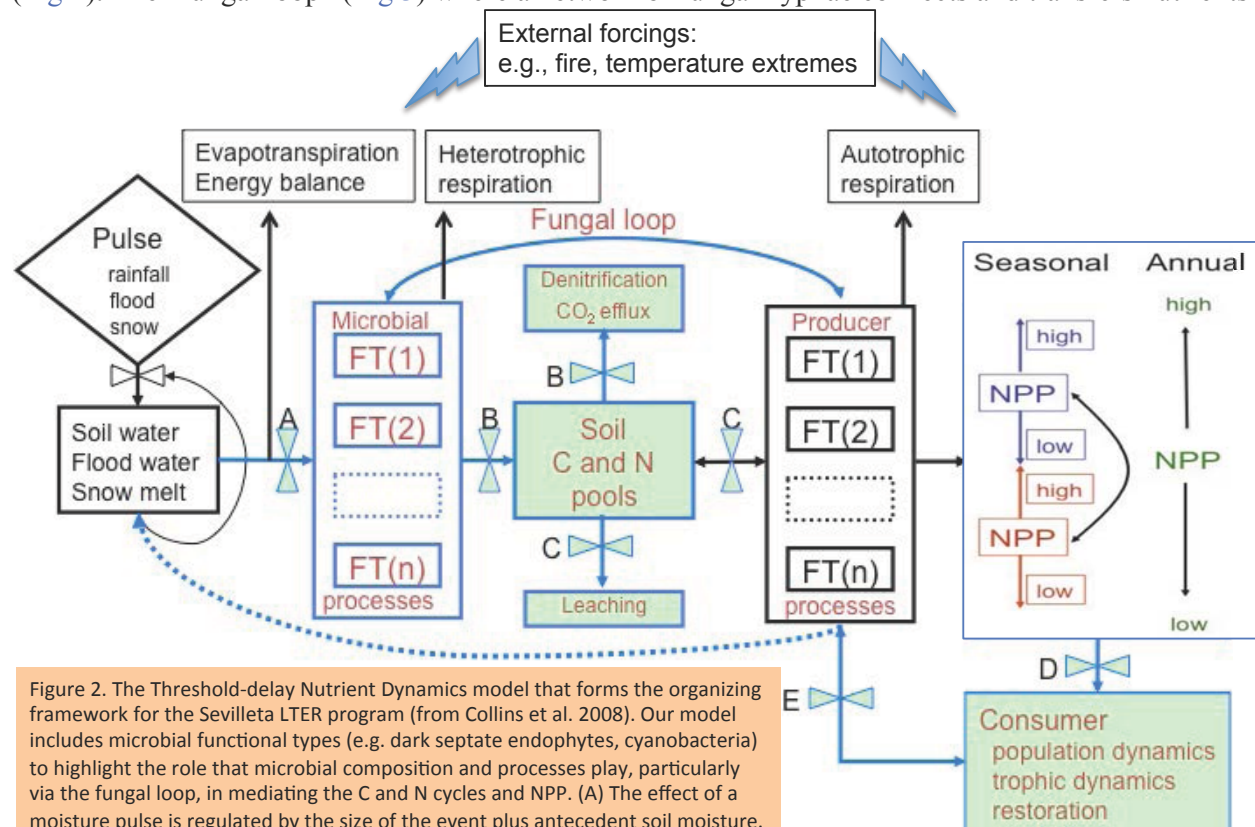

Broader Impacts. Our Schoolyard LTER, the Bosque Ecosystem Monitoring Program, reaches hundreds of middle and high school students annually in classroom and outdoor settings. Our Arts and Ecology REU Program brings together students from fine arts and ecology for an 11-week summer research and creative experience. We frequently interact and collaborate with staff of the SNWR, we actively participate in ESA SEEDS by hosting workshops and mentoring SEEDS Fellows, and we will participate in the newly developed UNM Biology Junior Scientist Outreach Program, which targets underserved Hispanic students in Albuquerque's south valley.

During LTERIV, SEV produced **204 publications** including **151 refereed journal articles**, **23 book chapters**, **24 dissertations and theses**, **6 miscellaneous publications** (proceedings, technical reports), and many other manuscripts are currently in press or in review. A complete list of publications can be found at: http://sev.lternet.edu. LTER funding supports our core activities, from

which we leverage additional funding to achieve our broader research objectives. Currently, over **$9.9M** in external funding (in addition to core LTER funding) contributes to SEV research. Here, we summarize selected results from LTERIV that span our research portfolio, including 10 of our "most significant" publications (cited in red). We start with our pulse dynamics conceptual framework, and then present our results in three integrated thematic areas: climate and abiotic drivers, ecosystem processes and biotic responses and feedbacks at multiple spatial and temporal scales.

Our conceptual framework is an extension of the original pulse-reserve paradigm for aridland ecosystems (Noy-Meir 1973). In the traditional pulse-reserve model a rain event triggers a pulse of activity that yields reserves (e.g., biomass) until moisture from that rain event is depleted. Reynolds *et al*. (2004) modified the original model to include plant functional types and time lags. We further modified the model (Collins *et al*. 2008a) to include contributions and feedbacks between soil moisture dynamics, microbial processes and functional types, soil nutrient pools and plant production (Fig 2). The "fungal loop" (Fig 3) where a network of fungal hyphae connects and transfers nutrients

Figure 2. The Threshold-delay Nutrient Dynamics model that forms the organizing framework for the Sevilleta LTER program (from Collins et al. 2008). Our model includes microbial functional types (e.g. dark septate endophytes, cyanobacteria) to highlight the role that microbial composition and processes play, particularly via the fungal loop, in mediating the C and N cycles and NPP. (A) The effect of a moisture pulse is regulated by the size of the event plus antecedent soil moisture. (B), the moisture pulse is sufficient to drive microbial processes (C-fixation by cyanobacteria, denitrification) but it is not sufficient for uptake by plants. (C), moisture is sufficient for plant growth, and potentially soil leaching. (D) NPP regulates consumer populations that then feedback to alter producers (E). FT, functional type.

between biological soil crusts (BSCs) and patches of vegetation (Green *et al*. 2008) is embedded within our model. *Together, our Threshold-Delay-Nutrient Dynamics (TDND) model and its integrated fungal loop hypothesis form the conceptual framework for the Sevilleta LTER research program, and our on-going and proposed new research in LTERV explicitly address key components of this framework.*

A. Climate and abiotic drivers. Climate is the key driver of pulse dynamics at scales ranging from a single rainfall event to decadal variation in precipitation across the US Southwest. Regional climate

Figure 3. Fungal loop model (Collins *et al.* 2008) showing hyphal connections and nutrient transfers between soil crusts and grass tussocks.
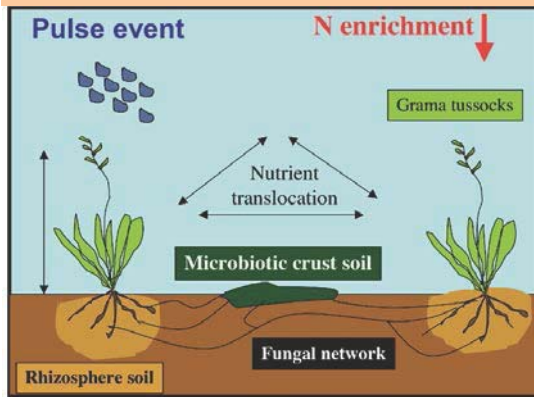
dynamics are driven by nonlinear interactions among the Pacific Decadal Oscillation, the El Niño Southern Oscillation, and the North American Monsoon. Together these drivers create a spatially and temporally variable local and regional precipitation regime (Gutzler & Robbins 2011, Notaro *et al.* 2010). Using data, models and satellite imagery, Notaro *et al.* (2010) found that peak vegetation greenness occurs in a clockwise pattern across the southwestern US, beginning in spring in the Sonoran Desert following winter rains, then in Utah-Colorado with snowmelt/summer rains, and finally in New Mexico with late summer monsoon rains. A bimodal seasonal pattern exists, characterized first by the accumulation of soil moisture during synoptic winter storms, followed by a dry late spring when soil moisture is depleted, and later by responses to summer monsoon storms that lead to green-up. This pattern supports our net primary production submodel of the TDND model (Muldavin *et al.* 2008, Fig 2) in which summer (but not winter) rains create discrete precipitation pulses that drive community structure and most ecosystem processes.

Monsoon precipitation accounts for 60% of annual precipitation at SEV. Precipitation timing, magnitude, and intensity influence most ecosystem processes, but temporal change in the magnitude and variation of these properties have not been assessed in our region. We used daily precipitation data from the Historical Climate Network to assess differences in precipitation timing and magnitude for the Northern Chihuahuan Desert region (Petrie *et al. in prep*). Results show an increase in frequency of rain events, along with a small decrease in average event size (Fig 4) resulting in no

Figure 4. During the past 100 years, number of rainfall events during the summer monsoon has increased significantly over time, while there has been a slight decrease in the mean size of precipitation events (Petrie et al. in prep). The net result has been no directional change in total precipitation over this time period.
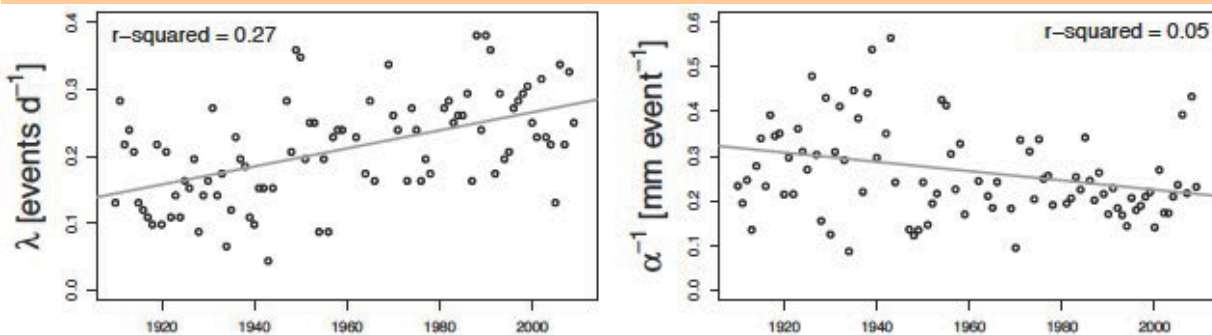
overall long-term trend in seasonal precipitation. Size and frequency of rain events influences key processes such as net primary production (NPP) and soil respiration (Rs) (Thomey *et al.* 2011, Vargas *et al.* 2012; see below), while periodic chronic droughts profoundly alter the distribution and abundance of species in the region.

Chronic droughts have caused regional-scale forest mortality worldwide and climate change is likely to enhance mortality events in the future. The southwestern US experienced a severe drought from 1998-2003 that resulted in widespread mortality of piñon pine (*Pinus edulus*, Breshears *et al.* 2005). McDowell *et al.* (2008) developed a hydraulically based theory considering C balance and insect resistance in tree survival and mortality. Multiple mechanisms, including C starvation in isohydric species, may cause mortality during drought and create a cascade of effects that reduce resistance to biotic agents, such as fungal pathogens and bark beetles. Wet phases of multidecadal climate oscillations and atmospheric N deposition (Allen *et al.* 2010) may increase plant

susceptibility to drought-induced mortality by stimulating shifts in hydraulic architecture, effectively predisposing plants to water stress. Mechanisms of water potential regulation may partition tree species between survival and mortality, thus ecophysiological research at SEV may help to improve models of plant survival and mortality under future climate scenarios.

B. Ecosystem processes. Shrub encroachment, like drought-associated conifer mortality, is one of the major manifestations of regional climate change. Understanding the causes and consequences of shrub encroachment remains one of the long-term goals of the SEV LTER. One consequence of shrub encroachment is nutrient loss during storms. Turnbull *et al.* (2010a,b,c) investigated runoff-driven erosion and the redistribution and loss of dissolved and particulate-bound N and P during natural runoff events over a gradient from grassland to shrubland at SEV. They found an overall increase in runoff and erosion across the transition as a result of increased connectivity of bare areas. During high-magnitude rains, the output of N and P greatly exceeded annual N and P inputs, particularly over shrub-dominated areas where erosion rates are higher. This loss of soil nutrient reserves appears to be a major consequence of shrub encroachment.

Ravi *et al.* (2010b) summarized the interactions between fires and soil erosion, and the implications of these interactions for shrub encroachment, nutrient fluxes and management of rangelands. Shrub encroachment leads to resource heterogeneity and the development of islands of fertility surrounded by patches of unvegetated soil (Schlesinger *et al.* 1990). However, Ravi *et al.* (2009) proposed that fire, through alterations in soil hydrophobicity and enhanced surface erosion, can potentially reverse the development of fertility islands. To do so requires burning at a key transition stage before the system passes a threshold of shrub encroachment and loss of grass cover (Ravi *et al.* 2009). This analysis has important management implications for restoring and maintaining grassland in arid systems where shrub encroachment is occurring.

Another consequence of shrub encroachment is feedback to local microclimate. Analyzing long-term temperature data from sites near SEV and local temperature data across the grassland to shrubland ecotone, D'Odorico *et al.* (2010) found that nighttime low temperatures during winter were approximately 2°C warmer in shrub-dominated areas than in adjacent grassland. Given known tolerances of seedlings to freezing (Medeiros & Pockman 2011), this pattern suggests that shrub encroachment by *L. tridentata* creates a warmer microclimate, enhancing seedling survival and further facilitating invasion by *L. tridentata*. As shrubs invade and replace C_4 grasses, vegetation cover decreases from 60% to as low as 25%. Tower measurements of energy balance in grassland, shrubland and ecotone (He *et al.* 2010) showed that nighttime low temperatures are warmer in shrubland than in grassland because the larger area of exposed soil absorbs more heat during the day and releases it at night, particularly during calm, clear winter nights.

Rainfall and temperature patterns regulate regional net ecosystem exchange (NEE) and C storage potential. Anderson-Teixeira *et al.* (2011) compared patterns of NEE and C storage along a 1500-m elevation gradient that includes six vegetation types in New Mexico, including desert grassland and shrubland, juniper savanna, piñon-juniper woodland, ponderosa pine and mixed conifer ecosystems. They found that subalpine forests annually sequestered 10 times more C than desert grassland and shrubland. High-elevation ecosystems have a longer growing season, more reliable rainfall distribution throughout the year, and lose a lower fraction of incoming C as respiration—leading to a more positive NEE than desert grasslands and shrublands. The results suggest that as climate change and disturbances (fire, beetle outbreaks) alter species composition throughout the region, C sequestration may be destabilized, likely converting C sinks into sources.

Regionally, pulse events episodically connect terrestrial and aquatic ecosystems by routing runoff from uplands to rivers and through human distribution systems that move river water into irrigation canals. The 300-km reach of the Middle Rio Grande is routed into 2100 km of irrigation canals. Van Horn (2010) conducted synoptic sampling of nutrients and dissolved oxygen (DO) in the

Rio Grande as it flows through the City of Albuquerque to the Sevilleta. The North Channel Diversion is a concrete channel that carries storm water from urban Albuquerque into the Rio Grande after storm pulses, resulting in dramatically increased flow that brings organic matter, detritus, contaminants and chemically reduced solutes into the river. The resulting pulses of oxygen-depleted (DO< 2 mg/L) river water move downstream toward the intake pipe that draws surface water for domestic use (Fig 5). In addition, nutrient-enriched water from wastewater treatment plants elevates

Figure 5. Discharge from a monsoon storm event through the Albuquerque North Channel Diversion into the Rio Grande. Such pulse events move significant quantities of organic matter into the river causing a pulse of low DO water to move downstream (Van Horn 2010).
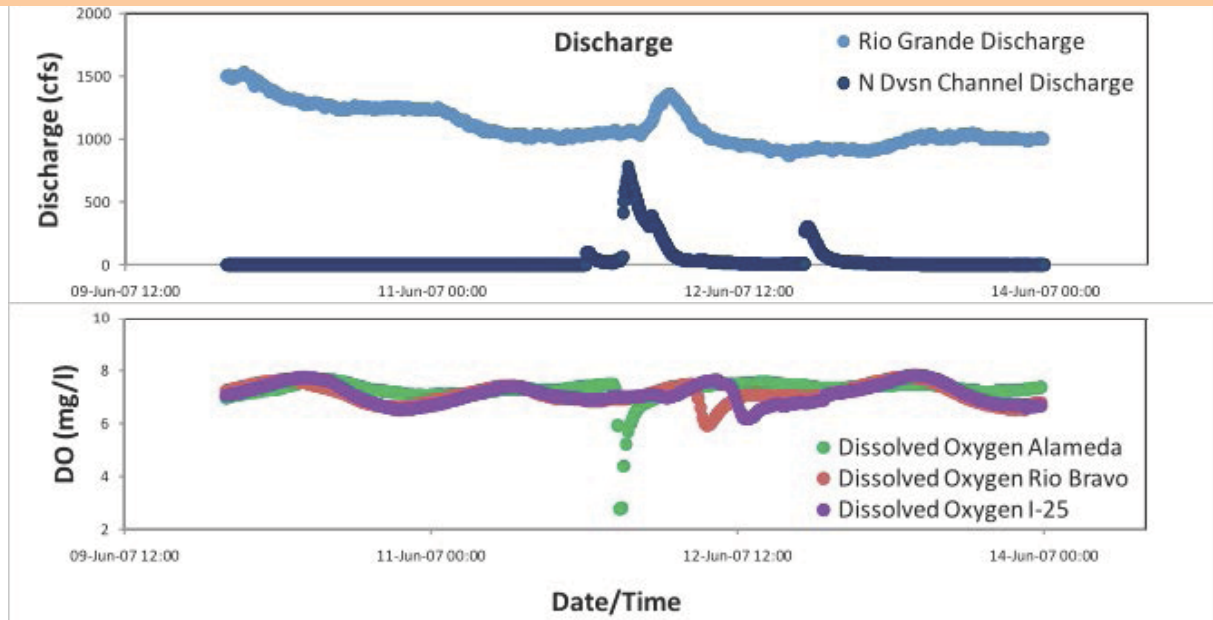
NO_3 and NH_4 concentrations in the Rio Grande below Albuquerque. This water is used for agricultural irrigation, which effectively removes nutrients from solution and improves water quality downstream of urbanized reaches of the Rio Grande.

C. Biotic responses and feedbacks. Accumulating evidence suggests that the symbiotic fungal communities of arid ecosystems support plant community composition and NPP through nutrient transformation and translocation, and by mitigating the effects of heat and drought on primary producers. These observations are the basis for our fungal loop model. These services are provided by relatively few microbial taxa. Porras-Alfaro et al. (2010) characterized diversity and structure of soil fungal communities in SEV grasslands. Approximately 40% of soil operational taxonomic units (OTUs) were considered novel. The dominant organisms were dark-septate ascomycetes in the order Pleosporales. The fungal communities of rhizosphere soil and crusts overlapped substantially in composition. Grama grasses are heavily colonized by endophytic fungi from at least 10 different orders, but are dominated by dark septate ascomyctes (Porras-Alfaro et al. 2008). Herrera et al. (2011 – funded partly through an ROA supplement) observed that root associated fungi increased under both infrequent large and frequent small rainfall events. These same fungi dominate the decomposer communities of litter (Gallo et al. 2009). Glomeromycota, which form arbuscular mycorrhizae, and filamentous Basidiomycota, which dominate litter decomposition in forest ecosystems, are rare. Of note, the dominant Ascomycota include taxa known for their capacity to denitrify, which may explain the apparent fungal dominance of this key ecosystem process (Crenshaw et al. 2007).

Ecosystem processes respond to rainfall variability. The "bucket model" (Knapp et al. 2008a) predicts that increased precipitation variability will have a positive impact on processes in arid ecosystems. To test this model, we experimentally increased rainfall variability during the summer

monsoon without changing the total amount of rain, and measured leaf gas exchange, NPP and Rs (Thomey *et al*. 2011; Vargas *et al*. 2012). A small number of large events increased mean soil water content throughout the monsoon season to a greater extent than did a larger number of small events. Higher mean soil moisture led to higher photosynthetic rates, higher Rs and increased NPP of *B. eriopoda*. Although this pattern was consistent over two years, the degree of response varied across years as a function of total rainfall. Thus, Thomey *et al*. (2011) revised the bucket model to account for year-to-year differences in seasonal precipitation. These results illustrate how climate variability may alter key ecosystem processes in aridland ecosystems.

NPP is a key integrating process in terrestrial ecosystems (McNaughton *et al*. 1989). Our TDND model links NPP to variable precipitation patterns contingent on hydrology, soil moisture dynamics, functional types, and landscape context. Muldavin *et al*. (2008) examined a 6-yr, seasonal record of

Figure 6. Aboveground net primary production in grassland and shrubland from 1999-2010
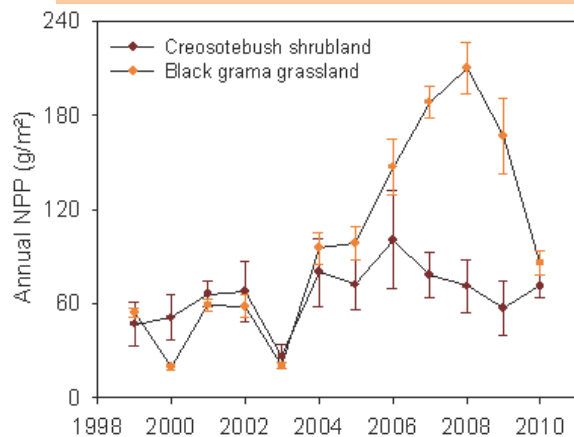
NPP with respect to precipitation, soil moisture, and functional groups in grassland and shrubland at SEV. During this period, NPP was quite low (grassland = 51.1 g/m^2; shrubland = 59.2 g/m^2) and positively correlated with soil moisture. Since 2004, NPP has increased significantly in grassland, but not in shrubland (Fig 6). Annual plants respond strongly to seasonal variation in soil moisture (Xia *et al*. 2010) whereas C_4 grasses respond to large, transient summer storms. In contrast, NPP in shrubland occasionally responds to summer moisture, but the predominant pattern is slow, persistent non-pulsed growth of C_3 shrubs during spring in response to accumulated winter soil moisture (see also Sponseller *et al*. 2012)—a mechanism that may promote shrub dominance following chronic droughts that occur every 50-60 years in this region (Milne *et al*. 2003).

Climate variability occurs in conjunction with other environmental changes, including atmospheric N deposition. Although increased N availability typically increases NPP in mesic systems, the impacts of N additions on semiarid ecosystems remain unclear (Hall *et al*. 2011). Ladwig *et al*. (2012) examined above- and belowground NPP in response to long-term N addition in desert grassland at SEV. Differences in aboveground NPP between fertilized and control treatments occurred in response to two pulse events: a prescribed fire (2003) and a year with double the average monsoon precipitation (2006). The greatest pulse in belowground NPP occurred the year following the wettest summer, decreasing gradually thereafter. Belowground production was unrelated to aboveground production within years and unrelated to N enrichment. These results are contrary to most N-addition studies that find increased aboveground biomass with N fertilization. It appears that disturbance regimes, such as fire or drought, play a stronger role in shaping production dynamics than soil fertility in this arid grassland.

Our on-going nighttime warming, N deposition, winter rainfall experiment explicitly assesses the interactions among key environmental presses and pulses (Smith *et al*. 2009) at SEV. Collins *et al*. (2010) reported that nighttime warming and low-level N fertilization led to rapid responses among dominant species following the first year of treatments. Specifically, *B. gracilis* increased with N addition, but not warming; *B. eriopoda* increased with nighttime warming but not N addition; and *Gutierrezia sarothrae*, a C_3 shrub, also increased with warming. These initial results changed over time. Although *B. eriopoda* and *B. gracilis* responses remained consistent, *G. sarothrae* declined likely because of increased competition from the dominant C_4 grasses suggesting that shrub

encroachment may slow in the absence of grazing and under warmer, wetter monsoon conditions that favor the C_4 grasses (Fig 7).

Figure 7. Grow pulses of dominant plants, *Bouteloua gracilis, B. eriopoda, Gutierrezia sarothrae*, and other subshrubs and forbs in response to nighttime warming, N addition and increased winter precipitation.
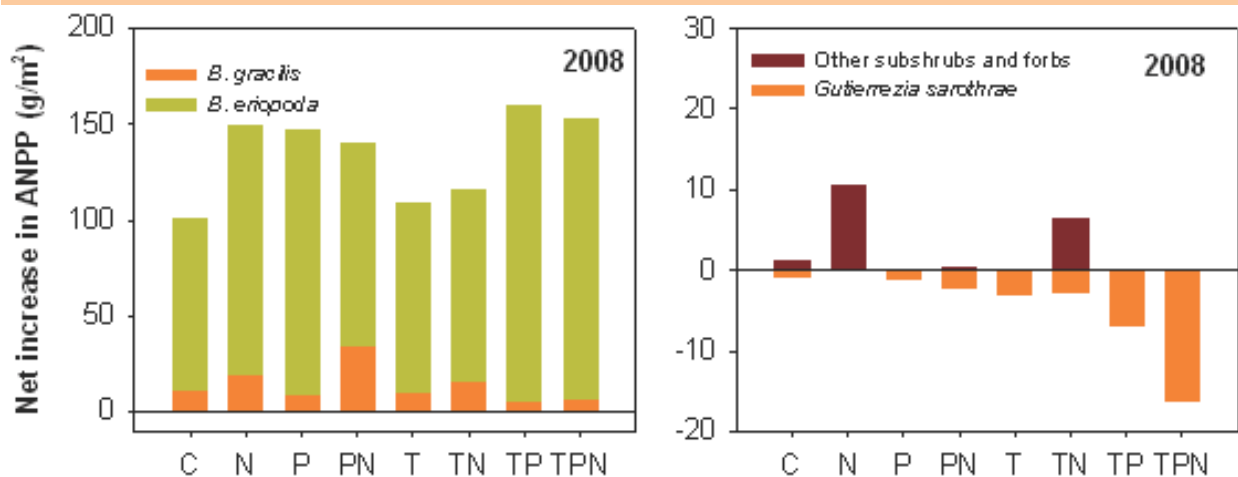
Temporal dynamics of consumers are strongly related to rainfall pulses and plant production (Ernest *et al*. 2000, Yates *et al*. 2002, Báez *et al*. 2006, Warne *et al*. 2010b). Indeed, Báez *et al*. (2006) concluded that trophic interactions at SEV were strongly driven by bottom-up processes. Warne *et al*. (2010b) assessed the impacts of interannual climate variability on C_3 and C_4 plants, grasshoppers, and lizards at SEV. They found that consumers used an increasing proportion of monsoon-derived C_4 resources over the growing season during average rainfall years. However, consumers relied on C_4 resources that were likely carried over from previous year's production during a spring with below-average precipitation, demonstrating the degree of diet flexibility that consumers need to survive under future patterns of increased climate variability.

D. Informatics. Vanderbilt *et al*. (2010) discussed the significant barriers to creating and using common EML protocols and keywords in an international context. The ILTER Network has agreed to provide EML in English, but translation remains the burden of data providers for whom English may be a second language. In many cases, there are no direct translations between languages making the use of EML challenging globally. Vanderbilt *et al*. (2010) laid out a roadmap to address the difficulties of multilingual translation and facilitate the development of an international EML framework that will benefit data synthesis globally. Development of this EML roadmap was funded through supplement funding from OISE.

In summary, these studies highlight the breadth of our current LTER activities, address the LTER core areas of research, and illustrate the range of on-going studies of climate and abiotic drivers, ecosystem processes and biotic responses and feedbacks at SEV, all of which are integrated in our model of pulse dynamics. Together, these and other studies serve as the foundation for our ongoing and new research activities described in Section II of our proposal.
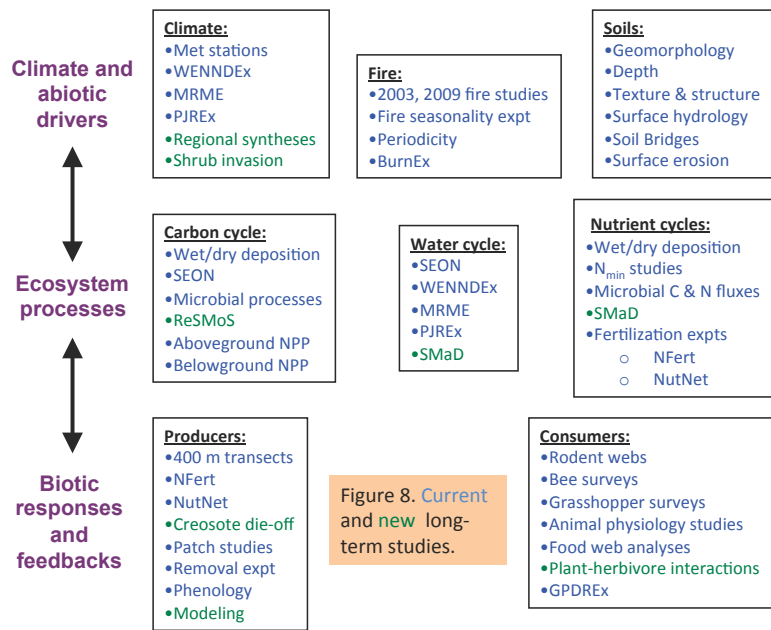
II. PROJECT DESCRIPTION

A. Introduction and Background. The Sevilleta LTER (SEV) supports a long-term, integrated, interdisciplinary research program addressing key hypotheses on pattern and process in aridland ecosystems. SEV research includes studies in desert grassland and shrubland communities, and riparian ('bosque') and mountain forests, emphasizing pulse driven processes in space and time. Key drivers (e.g., climate, fire, water, resource availability) govern dynamics in each landscape

component. Our focus on how biotic and abiotic drivers affect spatial and temporal dynamics of aridland ecosystems allows us to conduct long-term research that addresses important basic theories and yet has significant relevance to regional, national and international research priorities.

The Sevilleta LTER includes the Sevilleta National Wildlife Refuge (SNWR) and the middle Rio Grande Basin, central New Mexico. The SNWR (managed by the US Fish and Wildlife Service) and its surroundings are positioned at the intersection of several major biotic zones: Chihuahuan Desert grassland and shrubland, Great Plains grassland, piñon-juniper woodland and montane forest, Colorado Plateau shrub-steppe, and riparian ecosystems along the Rio Grande (Fig 1). Because of the confluence of these major biotic zones, the SNWR and the Middle Rio Grande Basin present an ideal setting to investigate how environmental change and climate variability interact to affect ecosystem dynamics within, and at the boundaries of, major southwestern biomes.

B. History and Growth of the Sevilleta LTER Program (SEV). The research theme for **LTERI** (1988-1994) was "Life on the Edge," because transition zones are known to be highly dynamic in response to environmental drivers. The foundations for our understanding of how interannual climate variability, particularly the El Niño Southern Oscillation (ENSO), effects the distribution, abundance and dynamics of populations and communities were developed during this period (e.g., Molles & Dahm 1990, Dahm & Molles 1992, Molles *et al*. 1992). In addition, linkages between ENSO, net primary production (NPP), small mammal populations and hanta virus outbreaks were found (Yates *et al*. 2002). **LTERII** (1994-2000) included more focused research on how interannual rainfall patterns affected patch structure and dynamics, particularly across the grassland to shrubland ecotone (e.g., Gosz *et al*. 1995, Peters 2000, Anand & Li 2001). During **LTERIII** (2000-2006) we developed a conceptual framework for patch dynamics (Peters *et al*. 2006a), and started experiments, measurements and modeling of patch structure and change (e.g., Peters 2000, 2002a,b, Rastetter *et al*. 2003, Kröel Dulay *et al*. 2004, Hochstrasser *et al*. 2004, Chen *et al*. 2005, Peters *et al*. 2006b) along the grassland to shrubland ecotone. In addition, we started new research on ecohydrology (Kurc & Small 2004, 2007, Dahm *et al*. 2002, Ravi *et al*. 2007, Pockman & Small 2010), expanded our measurements of NPP (Muldavin *et al*. 2008, Xia *et al*. 2010, Ladwig *et al*. 2012), and added a new restoration experiment on Gunnison's prairie dog. During **LTERIV** (2006-2012) we placed a greater emphasis on interactions among key processes and drivers of change in aridland ecosystems (McDowell *et al*. 2008, Collins *et al*. 2010, Thomey *et al*. 2011, Vargas *et al*. 2012), expanded our ecohydrological work (Turnbull *et al*. 2008, 2010a,b,c, Ravi *et al*. 2009, 2010a,b), initiated a new focus on microbial ecology (Stursova *et al*. 2006, Zeglin *et al*. 2007, Green *et al*. 2008, Porras-Alfaro *et al*. 2008, 2009, Herrera *et al*. 2011), added new ecophysiological studies of key producers and consumers (Engel *et al*. 2009, Warne *et al*. 2010b, Medeiros & Pockman 2010, 2011), added a flux tower network to compare ecosystem processes across upland and riparian biomes (Martinet *et al*. 2009, Anderson-Teixera *et al*. 2011), and formalized our organizing framework (Collins *et al*. 2008a). In **LTERV** (2012-2018) we will continue to build on our organizing framework, with particular emphasis on climate change and pulse dynamics, interactive biotic and abiotic drivers, plant-herbivore studies, and linkages between aboveground-belowground systems. We believe our ever-evolving organizing framework effectively integrates the LTER core areas with our research program, and allows us to test important hypotheses of general ecological interest.

SEV research investigates the individual and interactive effects of three integrated thematic areas: abiotic pulses and constraints, ecosystem processes, and biotic responses and feedbacks (Fig 8). The main abiotic *pulses* and *constraints* are (1) seasonal, annual, and decadal variations in climate, (2) geomorphology, soil texture, structure and depth, and surface and subsurface hydrology, and (3) season, periodicity, and intensity of fire and drought. These abiotic factors affect *ecosystem processes* including (1) biogeochemical pools and cycles, (2) soil water distribution, storage, use and loss, (3) patterns and controls on NPP, and (4) C storage and fluxes. *Biotic responses and feedbacks*

Climate and abiotic drivers

Climate:
•Met stations
•WENNDEx
•MRME
•PJREx
•Regional syntheses
•Shrub invasion

Fire:
•2003, 2009 fire studies
•Fire seasonality expt
•Periodicity
•BurnEx

Soils:
•Geomorphology
•Depth
•Texture & structure
•Surface hydrology
•Soil Bridges
•Surface erosion

Ecosystem processes

Carbon cycle:
•Wet/dry deposition
•SEON
•Microbial processes
•ReSMoS
•Aboveground NPP
•Belowground NPP

Water cycle:
•SEON
•WENNDEx
•MRME
•PJREx
•SMaD

Nutrient cycles:
•Wet/dry deposition
•N_{min} studies
•Microbial C & N fluxes
•SMaD
•Fertilization expts
  o NFert
  o NutNet

Biotic responses and feedbacks

Producers:
•400 m transects
•NFert
•NutNet
•Creosote die-off
•Patch studies
•Removal expt
•Phenology
•Modeling

Figure 8. Current and new long-term studies.

Consumers:
•Rodent webs
•Bee surveys
•Grasshopper surveys
•Animal physiology studies
•Food web analyses
•Plant-herbivore interactions
•GPDREx

include the dynamics of plant-environment, plant-plant and plant-animal interactions. These focal components and activities directly address the five LTER Network core research areas. Essentially, our LTER research links climate dynamics, disturbances, and soil processes with soil nutrient and water fluxes to understand seasonal and annual variability in NPP, and how that variability ultimately affects the dynamics, distribution, abundance and interactions of key populations of aridland producers and consumers.

To accomplish these goals, SEV research is organized into three integrative thematic areas (ITAs): *Climate and abiotic drivers*, *Ecosystem processes* and *Biotic responses and feedbacks*. These ITAs are not mutually exclusive, but serve as an effective mechanism to organize and synthesize our research. Sevilleta scientists interact within and across these ITAs. New and continuing research includes a variety of activities in each ITA. These ITAs, along with our conceptual model on multi-scale pulse dynamics in aridland ecosystems described below, form the structural basis of this renewal proposal. Many of our continuing and new activities build on recommendations made by the 2009 site visit team. Major recommendations included the need for more field-based quantification of N cycle components, stronger cross-system comparisons (e.g., grassland-woodland), increased attention to the role of consumers, further analyses related to the fungal loop model, and overall quantification of our pulse-dynamics model. We have taken these recommendations seriously, and the new activities described below reflect our attempts to incorporate the review team's major recommendations. Doing so, however, is a long-term goal that we will continue to strive for over this and future funding cycles.

C. General Conceptual Model: Threshold-Delay Nutrient Dynamics (TDND). In mesic environments, the hydrologic cycle couples biological processes (e.g., C and N dynamics, NPP) in ecosystems. Water transports nutrients, sustains biotic activity, and drives microbial processes, thereby linking production, decomposition and storage of organic matter (OM), and controls the rates of reactions that drive community structure and ecosystem processes. Organic nutrient pools accumulate in mesic environments over time and most of the N required for primary production and trophic interactions comes from OM decomposition. Where moisture is predictable and sufficient, C and N cycles are more or less closed and tightly coupled through production and decomposition of OM (Asner *et al.* 1997).

More than 40% of continental land area is arid or semiarid, with interannual rainfall variability ranging from 25-100% (Reynolds *et al.* 2007, Schimel 2010). Like mesic systems, water controls most biological processes in arid ecosystems, but high temperatures and erratic water inputs impose a pulsed pattern on biological activity (Loik *et al.* 2004, Belnap *et al.* 2004, Knapp *et al.* 2008a). Because water is only available sporadically, nutrients accumulate in dry periods when plant and microbial growth are suspended (Austin *et al.* 2004, White *et al.* 2004, Welter *et al.* 2005, Hall *et al.* 2011). Rainfall events of varying magnitude selectively trigger temperature-dependent biological activities, including plant and microbial nutrient uptake, respiration and growth, as well as

biogeochemical processes such as decomposition and denitrification. Large, rare rain events can lead to vertical and horizontal nutrient loss through leaching and runoff (Schlesinger *et al*. 1999, Walvoord *et al*. 2003, Ludwig *et al*. 2005, Turnbull *et al*. 2010a,b). Processes such as decomposition and nitrogen transformations in arid ecosystems are also driven by abiotic factors. Sunlight strongly affects the rate of litter decomposition (Austin & Vivanco 2006, Gallo *et al*. 2009, Brandt *et al*. 2010, Austin 2011), and high soil temperatures may lead to considerable gaseous losses of N (Peterjohn & Schlesinger 1990, McCalley & Sparks 2009). These abiotic drivers in concert with limited rainfall delivered in events of variable timing and magnitude not only restrict biotic processes to episodic pulses, but also leave NPP, nutrient fluxes and decomposition uncoupled much of the time (Huxman *et al*. 2004b, Augustine & McNaughton 2004, Austin & Vivanco 2006, Collins *et al*. 2008a).

Like other regions, the arid Southwest is experiencing climatic change (Karl et al. 2009) and increasing rates of atmospheric N deposition (Fenn *et al*. 2003, Báez *et al*. 2007). The consequences of increased N loading and climate change for community structure and ecosystem processes in arid lands are poorly understood, and likely related to seasonal timing, microbial and plant functional types, and precipitation (Zeglin *et al*. 2007, Porras-Alfaro *et al*. 2008, Hall *et al*. 2011, Ladwig *et al*. 2012). Our overarching conceptual framework is designed to understand the mechanistic interactions of climate change and chronic resource alterations (Smith *et al*. 2009), particularly increasing N availability, on community and ecosystem processes in aridland ecosystems. We emphasize the degree to which interactions and processes are coupled in time: coupled-decoupled interactions range across scales from the timing of microbial decomposition and plant nutrient uptake to periodic hydrologic linkages between landscape components (Van Horn 2010). Thus, our research on pulse dynamics and coupled-decoupled processes integrates the principal structural and functional elements of aridland ecosystems across multiple spatial and temporal scales, and determines how those elements will respond to global change drivers.
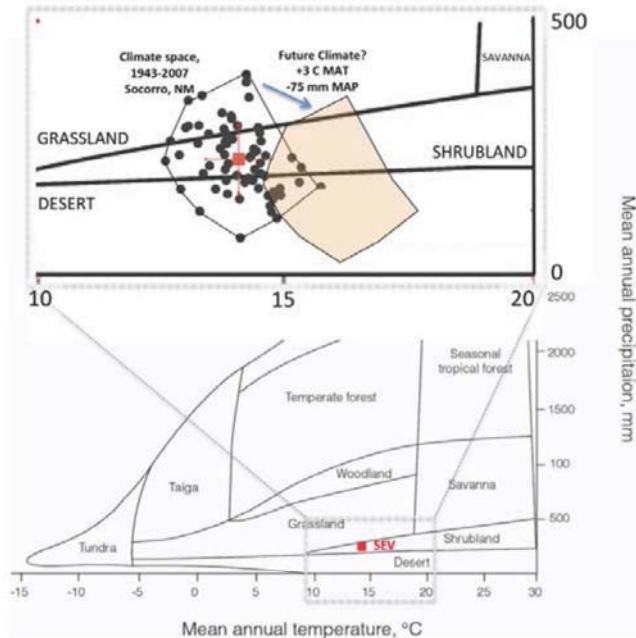
The pulse-reserve paradigm (Noy-Meir 1973) was developed to describe aridland responses to individual precipitation events. Each event triggers a pulse of growth that yields reserves (energy, seeds, biomass) until moisture from the rain event is depleted. Focusing only on individual rain events, however, may limit our understanding of aridland ecosystem processes. Reynolds *et al*. (2004) modified the pulse-reserve model such that pulses of precipitation generate and/or add to existing soil moisture, leading to production responses that may vary among plant functional types depending on prior conditions, seasonality, etc. The direct linkage between antecedent soil moisture and plant functional types allows for variable rates of production in response to variation in size, timing and seasonality of events. The Reynolds *et al*. (2004) model significantly improved the original model, but it lacked explicit inclusion of pulse-driven microbial processes (fixation and transformation of C and N, decomposition, nutrient storage and translocation) whose thresholds and response intervals differ substantially from plants. We modified the Reynolds *et al*. model (Collins *et al*. 2008a) to include contributions and feedbacks between soil moisture dynamics, microbial functional types, soil nutrient pools and plant production (Fig 2). *This Threshold-Delay-Nutrient Dynamics (TDND) model is the conceptual framework for the Sevilleta LTER research program. Current and proposed research explicitly addresses all components of this framework.*

Although the original pulse reserve model is primarily terrestrial, pulse dynamics applies to riparian and riverine processes as well (Belnap *et al*. 2005). For example, storms are relatively discrete pulses that affect microbial activity, nutrient availability, and producer and consumer dynamics in riparian systems (Molles *et al*. 1998, Valett *et al*. 2005, Martinet *et al*. 2009, Van Horn 2010, Harms & Grimm 2010). Thus, our general conceptual model can be applied in all of the core landscape units at SEV. The pulse-reserve model as developed here is spatially static in that it describes local-scale processes in time. A related concept, the Trigger-Transfer-Reserve-Pulse (TTRP) model (Ludwig *et al*. 2005), was developed to link trigger events, such as rainfall, with reserve processes through spatial transfer of nutrients and water (runoff–runon, flood spates) in areas

with complex topography (Belnap *et al.* 2005, Turnbull et al. 2010a,b). It is these large-scale but infrequent events that couple terrestrial and aquatic landscapes at SEV (e.g., Fig 5).

In addition to spatial connectivity, temporal changes in the frequency, intensity, and seasonality of abiotic drivers will have a significant impact on community structure and ecosystem processes (Gerten *et al.* 2008, Luo *et al.* 2008, Knapp *et al.* 2008a, Diffenbaugh *et al.* 2008). Based on mean annual temperature and precipitation, SEV could support grassland, shrubland or desert. Given predictions of increasing aridity under most climate change scenarios (Seager et al. 2007, Gutzler & Robbins 2011) ecosystems at SEV are likely to be driven toward shrubland and desert (Fig 9). Our existing long-term measurements and experiments along with our proposed new research are designed to understand how aridland ecosystems will change in response to alterations in the spatial and temporal dynamics of key abiotic and biotic drivers. For example, regional climate is predicted to become even more variable in the future (Diffenbaugh *et al.* 2008, Schoof *et al.* 2010, Min *et al.* 2011). Surface and subsurface hydrological processes (evapotranspiration [ET], surface flow rates, ground water recharge) are likely to change in upland areas as shrubs encroach on former grasslands (Turnbull *et al.* 2010a, b, c), and drought mortality, bark beetles and N deposition combine to reduce tree abundance in piñon-juniper woodlands (Breshears *et al.*

Figure 9. Location and variation of Sevilleta in climate space defined by current mean annual temperature and precipitation. Sevilleta is currently on the boundary between grassland, shrubland and desert, and climate change will likely increase aridity and drive the system toward shrubland and desert.

2005, McDowell *et al.* 2008, Allen *et al.* 2010, Shim *et al.* 2011). River regulation and invasive species have altered groundwater availability, hydrological flow regimes, nutrient dynamics and groundwater-riparian coupling in the Middle Rio Grande (Tibbetts & Molles 2005, Follstad Shah & Dahm 2008, Harner *et al.* 2009, Follstad Shah *et al.* 2010). Atmospheric N deposition and runoff are increasing the amount of seasonally available soil N in historically N-poor terrestrial and aquatic ecosystems (Fenn *et al.* 2003, Báez *et al.* 2007, Van Horn 2010, Hall *et al.* 2011). Climate change has the potential to alter long-term precipitation regimes contributing to the replacement of C_4 grassland by C_3 shrubs (Van Auken 2000, 2009, Geist & Lambin 2004, Báez & Collins 2008, Knapp et al. 2008b, Báez *et al. in revision*). Such changes in plant species composition and functional types will alter habitat structure, resource availability, trophic interactions, and C storage and fluxes. Thus, our goal of understanding how changes in key abiotic drivers and constraints (climate, water, soils) interact with ecosystem processes (NPP, NEP, biogeochemistry) to affect the dynamics, stability, and interaction of key producers and consumers integrates SEV research.

D. Continuing and new research activities.
D1. Continuing activities. We summarize below our continuing research activities, our general goals for each activity, and how each project addresses components of our TDND model. Details regarding methods and hypotheses can be found in publications and in on-line project metadata.
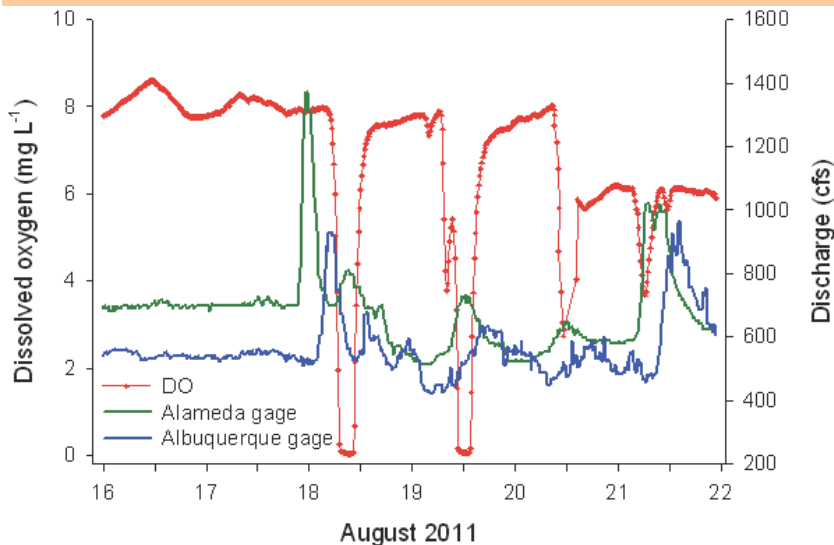**D1a. ITA1: Climate and abiotic drivers**

I. Monitoring studies. Our monitoring studies quantify ecosystem responses to natural pulse events at large spatial and multiple temporal scales (single events to decades).

A. Meteorological monitoring. Climate is the key driver of ecosystem processes in aridland environments at daily, seasonal, interannual and decadal time scales (North American Monsoon, ENSO, the Pacific Decadal Oscillation) (Gutzler *et al.* 2002, Milne *et al.* 2003). We maintain 10 comprehensive meteorological stations, three partial stations and nine Hobo rain gauges across the SNWR. Comprehensive met stations measure precipitation, N deposition, air and soil temperature, wind speed and direction, solar radiation, relative humidity and soil moisture. Meteorological and soil measurements are saved hourly and reported daily on the SEV website and ClimDB. These stations, along with the NOAA CRN site, the NRCS SCAN station, and met data recorded at some experiments allow us to gather spatially extensive meteorological data in all major habitats at SEV.

B. SEON: Riparian/river dynamics. As noted above, terrestrial and aquatic components of the landscape are periodically coupled through trigger-transfer events (Ludwig *et al.* 2005). **The goal of our river and riparian measurements is to understand how pulse events (fires, floods) move materials from terrestrial to aquatic components of the landscape affecting water quantity and quality in the Middle Rio Grande.** Continuing activities include a sonde network that measures temperature, pH, conductivity, turbidity, and dissolved oxygen at 27 locations from the Valles Caldera through the Jemez River to the Rio Grande south of SEV (Fig 1). The sonde network, which is part of an extensive network of in-stream monitoring sensors and flux towers located throughout the middle Rio Grande, which we refer to as SEON - Sevilleta Ecological Observatory Network, is a partnership between SEV, EPSCoR, the Valles Caldera National Preserve and the US Army Corp of Engineers. A second major focus linked to EPSCoR and SEON is the deployment and testing of continuous measurements of nitrate and phosphate in river water along with sonde data. Currently, we are documenting the effects of the Las Conchas Fire that burned from June-August 2011 in the Jemez

Figure 10. Rio Grande dissolved oxygen at the Bernalillo research site and discharge at the USGS Alameda and Albuquerque gages, 16--22 August, 2011. The drop in DO was caused by organic matter pulses washed into the Rio Grande by monsoon storms following the Las Conchas Fire near Los Alamos, NM.

Mountains north of SNWR. Pulses of organic matter following the fire were moved into the Rio Grande and its tributaries at the start of monsoon rains. Theses pulses of organic matter resulted in dramatic declines in DO and abundant fish kills in the river (Fig 10).

C. SEON: Flux towers. The varied topography and large elevational gradients that characterize central New Mexico create a wide range of climatic conditions – and associated communities – within relatively short distances, providing an ideal study system to determine the effects of climate variability on ecosystem dynamics. Such studies are critical given that our region has already experienced altered precipitation patterns (Mote et al. 2005, Petrie *et al. in prep*), and will likely experience a more arid and variable climate in the future (Seager *et al.* 2007; Ting *et al.* 2007,

Gutzler & Robbins 2011). To predict regional changes in C storage, hydrologic partitioning, and water resources in response to climate change, SEV maintains a network of 11 eddy covariance towers as part of SEON which includes nine towers in the New Mexico Elevation Gradient: 2 grassland sites, creosote shrubland, grass-shrub transition, juniper savanna, 2 piñon-juniper woodland sites, ponderosa pine, mixed conifer (Kurc & Small 2004, 2007, Anderson-Teixeira *et al*. 2011), and 2 riparian sites (Cleverly *et al*. 2006)(Fig 1). Measurements at each tower site include the exchange of C, water and energy between each ecosystem and the atmosphere, and relevant meteorological variables. **The primary goal of our flux tower network is to use the elevation gradient in central New Mexico – ranging from hot and arid at low elevations to mesic riparian or cool, high-elevation forests – to determine how processes in these climate-controlled ecosystems will respond to climate change.** In particular, we are focusing on the interactive effects of temperature and soil moisture pulses on ecosystem processes, as temperature decreases and soil moisture increases up the gradient and both change within sites over time. Results to date demonstrate the key role of upper elevation conifer forests in C storage (Anderson-Teixeira *et al*. 2011) and demonstrate how increasing aridity will likely reduce C storage across the region in the future.

II. Manipulative experiments. We experimentally alter precipitation pulses seasonally, the drivers of our TDND model, to gain a mechanistic understanding of the consequences of increased climatic variability and extreme events on ecosystem processes and biotic responses.
A. Monsoon rainfall manipulation experiment (MRME). Global change models predict more variable precipitation regimes in the future (IPCC 2007, Diffenbaugh *et al*. 2009). We established MRME to experimentally manipulate the amount and timing of monsoon precipitation events. **The primary goal of MRME is to determine how changes in the temporal pattern of summer precipitation affect plant and microbial community structure and interactions, and ecosystem processes in desert grassland.** MRME contains five replicate plots (9mx14m) of the following treatments imposed from July through September: 1) ambient plus a weekly addition of 5mm rainfall, and 2) ambient plus a monthly addition of 20mm rainfall. At the end of each monsoon season, each experimental treatment has received the same total amount of precipitation, but in events that differ in size and frequency. In addition, three plots receive only ambient precipitation. Plots are instrumented with soil temperature, moisture and CO_2 probes, minirhizotrons, and root donuts (belowground NPP). Subplots in each plot receive $5gN\ m^{-2}y^{-1}$ as NH_4NO_3 prior to the monsoon season. Plant species composition and NPP are measured twice per year. These treatments create distinctly different patterns of rainfall that mimic future scenarios for climate change in our region (Gutzler & Robbins 2011). Results thus far support predictions (Knapp *et al*. 2008a) that arid ecosystem processes will exhibit positive responses to increased climate variability (Thomey *et al*. 2011, Vargas *et al*. 2012). In addition, in 2011 soils were collected from all replicates for metagenomic analysis to determine how precipitation variability alters microbial community composition, structure and functioning.

B. Warming-El Nino-Nitrogen Deposition Experiment (WENNDEx). Climate change coupled with increased resource availability alters plant growth and potentially drives long-term shifts in community composition and ecosystem processes (LeBauer & Treseder 2008, Smith *et al*. 2009, Allen *et al*. 2010). **The primary goal of WENNDEx is to determine how nighttime warming, winter precipitation pulses, and N deposition affect plant and soil microbial communities, Rs, and NPP in desert grassland.** WENNDEx is a multi-factorial, fully crossed (n=5) field experiment. Treatments include increased nighttime temperatures (1.5-2.0C during winter), N deposition ($2gN\ m^{-2}y^{-1}$ as NH_4NO_3) and winter precipitation (+50% of long-term average). Plots (2mx3m) are instrumented with soil temperature, moisture, and CO_2 sensors, and air temperature probes.

Treatments mimic conditions expected to occur 75-100 years from now. Although warming should favor the desert grass, *B. eriopoda*, N deposition and increased winter precipitation may favor the northern grass *B. gracilis* and C_3 species. How these contrary forces will interact over the long term to affect community composition is unknown. Initial results show that the desert grass increases under warmer conditions (Collins *et al.* 2010); however, this experiment was burned in the 2009 wildfire and we are now tracking post-fire ecosystem reconstruction under this environmental change scenario. Also, in 2011 soils were collected from all replicates for metagenomic analysis to determine how these drivers alter microbial community composition, structure and functioning.

C. Piñon-Juniper Rainfall Experiment (PJREx). Warmer temperatures, increased precipitation variability and chronic droughts may create conditions that exceed the physiological tolerances of some species while increasing productivity and abundance of others. Large-scale vegetation change could occur as catastrophic mortality during climate extremes removes some dominant species and alters growth and reproduction of others. For example, in the southwestern US, piñon pine (*Pinus edulis*) recently experienced 40-95% mortality regionally while co-occurring juniper (*Juniperus monosperma*) experienced lower (2-25%) mortality (Breshears *et al.* 2005, 2009). This differential mortality decreased woody plant cover, altering species distributions and key ecosystem functions like C uptake and water balance. **The primary goals of PJREx are to determine the causes of pine mortality under chronic drought and the potential for pine to outperform juniper under conditions of increased annual precipitation.** PJREx is a long-term manipulative experiment to study the mechanistic basis of responses of piñon-juniper woodland to either chronic drought (-45% of annual precipitation) or years of increased (+50% of the long-term average) rainfall. Plots are 40mx40m (n=4 per treatments). In the 45% rainfall exclusion treatment, we use a hydraulic model (Sperry *et al.* 1998, 2002) to evaluate water transport limitations in piñon and juniper during severe drought (McDowell *et al.* 2008). The +50% of mean annual precipitation treatment allows us to measure the effects of increased rainfall. Measurements include soil moisture, temperature, Rs, and piñon and juniper sap flow. Our goal is to distinguish among hypothesized mechanisms for the observed differential mortality during drought and responses during periods of above-average rainfall that may pre-dispose the system to more catastrophic responses during drought. Results to date suggest that C starvation is a likely factor in pine mortality during periods of prolonged drought.

D1b. ITA2: Ecosystem processes. Our long-term monitoring and experimental manipulations are designed to determine the extent of N limitation in desert grassland and how shrub encroachment feeds back to alter the spatial distribution and quantity of soil resources.
I. Monitoring studies.
A. Ecohydrology. The island of fertility model (Schlesinger *et al.* 1990, 1996) describes a positive feedback loop between plant cover and resource accumulation, leading to patches ("islands") of higher resource availability under plant canopies. Recent work at SEV suggests that differences between resource islands, such as microtopographic variation and the concentration of resources beneath plant canopies compared with open areas, decrease following fire and drought (Ravi *et al.* 2007, 2009). Thus, resource islands are more dynamic than previously thought, because prolonged drought and/or fire decrease spatial variability and alter patch structure (Ravi *et al.* 2009, 2010a,b). One large-scale consequence of shrub invasion is a decrease in vegetation cover and an increase in surface runoff that transports nutrients and soil particles downslope (Turnbull *et al.* 2010a, b, c). **The goal of our ecohydrological monitoring is to determine how rainfall pulses and fire affect nutrient, water, and soil particle transfers as shrub encroachment alters local surface hydrology and nutrient availability.** Four 10mx30m flumes were established in 2005 across the grass-shrub ecotone to monitor nutrient and sediment content and amounts in runoff triggered by

monsoon precipitation events. Measurements include surface particle size distribution, soil organic matter, total N and C, and soil bulk density. Results to date show significantly higher transfer of soil particles, N and C in shrub- compared to grass-dominated areas (Turnbull *et al.* 2010a,c).

II. Manipulative experiments.
A. Nitrogen fertilization experiment (NFert). Nitrogen deposition is altering ecosystem structure and function globally (Stevens *et al.* 2004, Suding *et al.* 2005, LeBauer & Treseder 2008) and N availability is a key component of our TDND model (Fig 2). **Specifically, the goals of NFert are to determine the effects of chronically elevated N availability on microbial community composition and structure, plant-fungal interactions, plant community composition and dynamics, and above- and belowground NPP.** NFert contains 20 5mx10m plots, 10 controls and 10 plots that receive 10 gN m^{-2}yr^{-1} as NH_4NO_3. Minirhizotrons and root donuts (Milchunas *et al.* 2005) are installed in all plots (Corkidi *et al.* 2002, Johnson *et al.* 2003). Annual measurements include above- and belowground NPP and plant species composition (Ladwig *et al.* 2012). Periodic measurements include soil N availability, extracellular enzyme activities (Stursova *et al.* 2006, Zeglin *et al.* 2007), and comparative molecular analyses of fungal and cyanobacterial community composition (crusts), soil microbes, and fungal endophytes (Porras-Alfaro *et al.* 2008, 2009). Results to date show that soil, rhizosphere and endophyte microbial communities differ in response to N deposition (Porras-Alfaro *et al.* 2008). Also, above- and belowground NPP are uncorrelated. Aboveground NPP only increased in years of above average precipitation whereas belowground NPP had a lagged and multi-year pulse response to a summer of very high rainfall (Ladwig *et al.* 2012).

B. NutNet. SEV is a participant in the international Nutrient Network Collaboration (Firn *et al.* 2011, Adler *et al.* 2011). We have 5 replicates of each annual nutrient addition treatment (N, P, K singly and all combinations). Plots are 5mx5m. Soil nutrients are measured every three years, and plant community composition and aboveground NPP are measured twice per year.

## D1c. ITA3: Biotic responses and feedbacks.
I. Monitoring studies. Our monitoring studies assess how populations, communities and processes respond to long-term climate variability, and determine important feedbacks between consumer and producer populations, all of which are components of the TDND model, as well as LTER core areas. *A. Producers.* Plant community composition and NPP are governed by seasonal and interannual variation in precipitation. **The goals of our producer studies are to quantify above- and belowground NPP, and plant community composition, structure and dynamics in response to climate variability, and to measure grassland recovery following the 2009 wildfire.** NPP is a key integrating variable (McNaughton *et al.* 1989) and understanding pattern and control of NPP is required of all LTER sites. Our TDND model includes drivers that affect NPP (Muldavin *et al.* 2008). We measure seasonal aboveground NPP at our core blue grama, black grama and creosote sites, NFert, WENNDEx, MRME, in burned and unburned mixed grassland, in burned and unburned grassland-shrubland transition areas, and in understory vegetation in piñon-juniper woodland. We use a non-destructive allometric approach (Huenneke *et al.* 2001, Muldavin *et al.* 2008) that allows us to measure aboveground NPP by species at the same point over time. Results from our long-term NPP studies show that grassland productivity is highly variable over time and poorly correlated with seasonal precipitation or soil moisture. Production in creosote-dominated areas is much less variable, and related to spring soil moisture (Muldavin *et al.* 2008).

Starting in 2005, belowground net primary production (BNPP) has been measured using root ingrowth donuts (Milchunas *et al.* 2005, Milchunas 2009) at NFert, in burned and unburned mixed grass sites, at the creosote core site, and starting in 2011 at MRME. Donuts are harvested yearly at two depths, 0-15 cm and 15-30 cm. Newly collected soil from adjacent areas is then sifted and used

to reconstruct the root ingrowth donut for the next annual harvest. In addition to BNPP, we have greatly increased studies of other belowground processes including soil respiration, decomposition,

Figure 11. Patch boundaries of *Bouteloua eriopoda* and *B. gracilis* along a 400 m transect showing stable (red) shifting (green) and directional (purple) patch boundaries from 1989-2008.
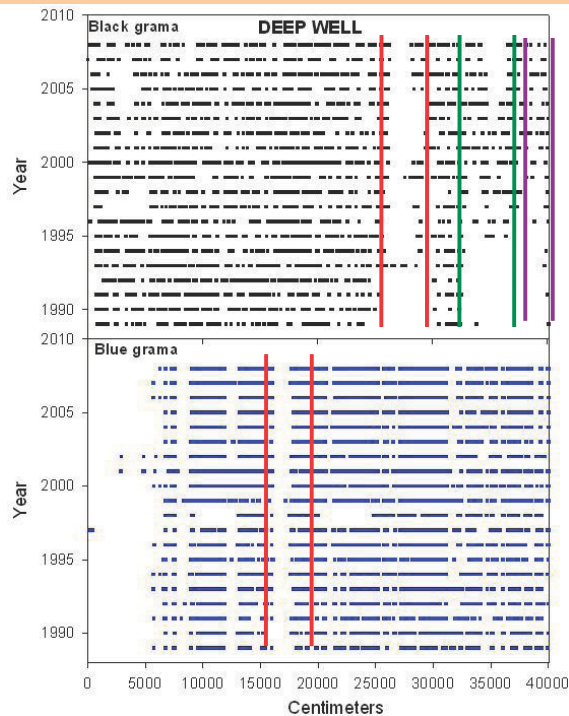
and microbial community composition (Stursova *et al.* 2006, Crenshaw *et al.* 2007, Zeglin *et al.* 2007, Green *et al.* 2008, Porras-Alfaro *et al.* 2007, 2008, 2010, Brandt *et al.* 2010, Vargas *et al.* 2010, 2012, Pockman & Small 2010, Ladwig et al. 2012). We will continue seasonal measurements of fungal hyphae and fine root dynamics in minirhizotrons located in mixed black grama-blue grama grassland, creosote shrubland, MRME, and NFert, along with periodic measurements of microbial composition and functioning.

Differences in winter vs. summer precipitation regimes are reflected in species, functional group, and community responses as mediated by soil water content, both of which affect consumer abundance and dynamics (see below). We measure vegetation composition and structure seasonally each year at 1-cm resolution along two 400-m, permanently located line-intercept transects. One of these transects was burned in 2009. Prior to the fire (1989-2008), these data supported our patch boundary model (Peters *et al.* 2006) that predicts boundaries to be either dynamic, static, or shifting based on species interactions or environmental constraints, leading to a large-scale patch mosaic that changes (pulses) at different rates over time (Collins & Xia *in prep*, Fig 11).

B. Consumers. Consumer populations integrate multiple pulse events (seasonal and interannual), creating lag effects between precipitation and population dynamics (Yates *et al.* 2002, Chesson *et al.* 2004, Warne *et al.* 2010b). The Sevilleta ecosystem is strongly driven by bottom-up processes (Baez *et al.* 2006) and heavily dependent upon seasonal patterns of NPP. **The goals of our consumer studies are to quantify population abundance, interannual variability, and physiological responses of key taxa (small mammals, native bees, grasshoppers) in response to seasonal and interannual variation in precipitation and fluctuations in resource availability.** Mammal trapping webs were established in black grama grassland and creosote shrubland in 1989 (Parmenter *et al.* 2003). Populations have been monitored twice each year (spring, fall), but in LTERV we will add a third trapping period each year to better quantify population dynamics (Ernest *et al.* 2000). Grasshoppers, another key consumer in aridland ecosystems (Ritchie 2000), have been shown to vary along spatial and elevational gradients at SEV (Rominger *et al.* 2009). To determine distribution and abundance of these important consumers, grasshopper abundance and community composition are measured annually along survey transects adjacent to the mammal trapping webs. Numerous populations of native bee species occur at SEV where the rarity of *Apis mellifera* makes SEV ideal for the study of native pollinators. Blue and yellow funnel traps located near the trapping webs have been used to sample bees every two weeks from March through October since 2002. Traps are located at core blue grama, black grama, and creosote sites. Bee composition and abundance are related to temporal pulses in the abundance of plant populations (Mulhouse *et al. in prep*) along with high interannual variation in floral phenology (Wetherill *et al. in revision*).

SEV provides an excellent venue for understanding how changing climates may affect producer–consumer interactions and population dynamics. Our studies explicitly couple rainfall pulses and NPP with consumer trophic structure in our TDND model. Variation in winter rainfall patterns and inputs directly influences the biomass of C_3 species (Muldavin *et al*. 2008, Xia *et al*. 2010) whereas C_4 productivity is largely driven by the summer monsoon. These differences in photosynthetic pathways among plant functional groups, and hence C isotope ratios, allow us to partition, quantify, and track C (and by proxy N and energy) movements from producers into consumers at a variety of trophic levels. Climate change is likely to differentially influence seasonal patterns of precipitation, and these changes will undoubtedly alter NPP among plant functional types. As a consequence, insight into how consumers interact with specific resource systems (C_3 vs. C_4 functional types) is critical to understanding how climate change might influence the structure and abundance of consumer populations. Grasshoppers and ants are among the most important primary consumer groups at SEV and provide significant biomass to higher tropic levels. We make monthly collections of grasshoppers and ants during the growing season. Using TDL, we measure the C, N and O isotope ratios of consumer "breath" (Martinez del Rio & Wolf 2005, Engel *et al*. 2009, Warne *et al*. 2010a,b) to assess water stress and determine the relative importance of C and N derived from C_3 vs C_4 plant production associated with winter or summer rainfall. Also, we periodically measure isotope ratios in prairie dogs to assess their health and status during the colony restoration process.

II. Experimental manipulations. On-going experiments are designed to understand interactions among dominant plant functional types in our model, as well as how external forces (e.g., fire) affect plant community composition and structure.
*A. Producers*
Removal experiment. At the patch scale, we measure cover and composition of vegetation on 3mx4m plots established in 1995, where we annually remove aboveground biomass of dominant species. Replicate and control plots are located in areas dominated by blue grama, black grama or creosote or in communities co-dominated by blue and black grama, and black grama and creosote. This long-term experiment provides information on the dynamics of dominant species at SEV. Results thus far show that dominant C_4 grasses exert strong controls on forb abundance and diversity (Peters & Yao 2012).

Seasonal fire experiment. In 2007, we established a replicated experiment to determine the effects of fire seasonality on grassland community composition. Plots are 20mx30m (n=4) and replicates were burned in November 2007, March 2008 and June 2008. Species composition is measured annually in permanent subplots nested in each replicate. Seasonal burns will be repeated once every 6-8 years. Results thus far show that summer fires result in highest post-fire plant species diversity but that these effects are highly transient (Ladwig *et al*. *in prep*).

B. Consumers.
Gunnison's prairie dog restoration experiment (GPDREx) Population dynamics of native consumers have been dramatically altered during the past century, including local extirpation of Gunnison's prairie dog (*Cynomys gunnisonii*). Prairie dogs are keystone species that physically alter soil structure and nutrient content, and create habitat patches high in biodiversity (Fahnestock & Detling 2002, Davidson & Lightfoot 2006, 2007, 2008a.b). In 2005, we initiated an experimental restoration of Gunnison's prairie dogs at SEV. **The primary goals of GPDREx are to determine how prairie dog colonies influence plant community structure and ecosystem processes, and how changes in community structure affect consumer resources within and among seasons.** Since 2005 prairie dogs periodically have been added to replicate colonies. Prairie dog population size is estimated each year through trapping and observation towers. Plant species composition and abundance are collected

Figure 12. Gunnison's prairie dog restoration project showing 1 ha control and treatment plots. White dots are currently active mounds on the three colonies started in 2005.
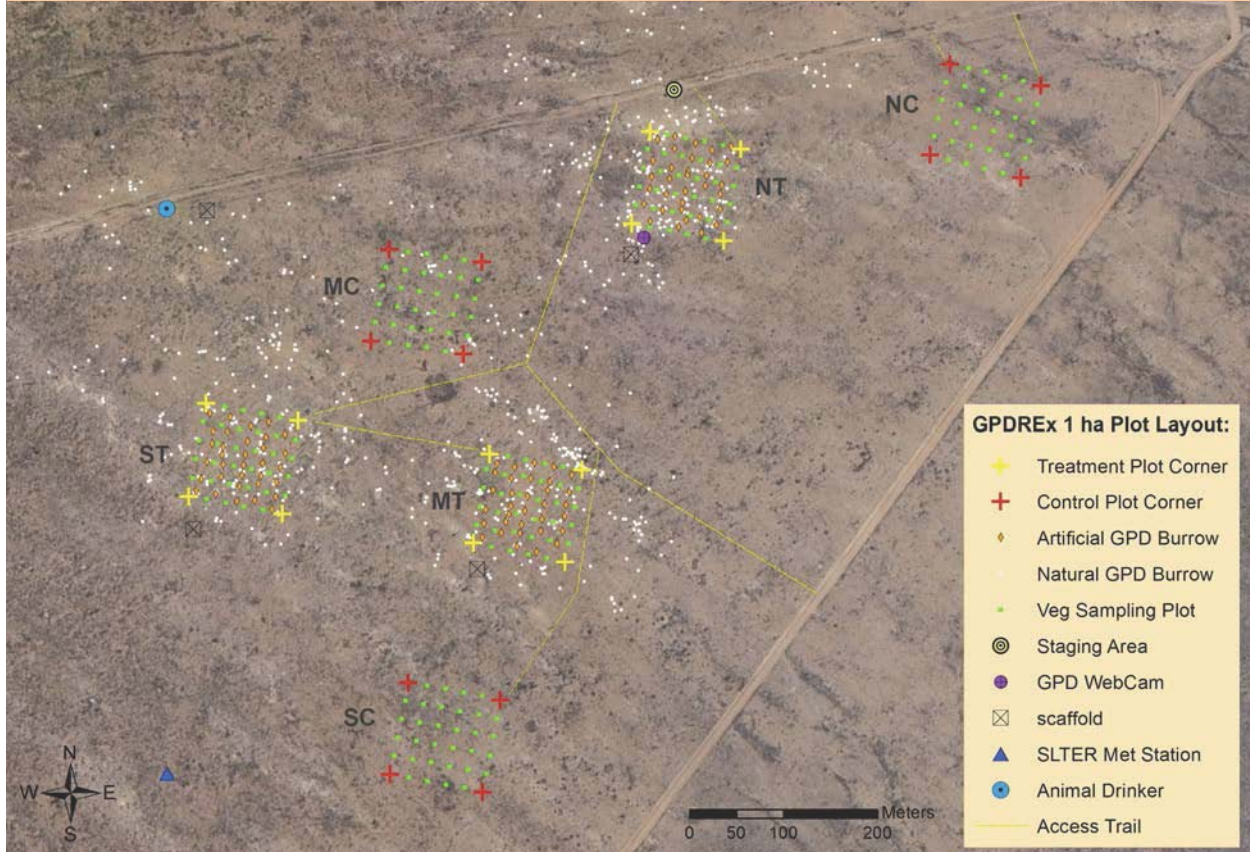
twice each year at 36 permanent points within a 50mx50m grid centered on each experimental colony or paired non-colony area. Vegetation standing crop is estimated each year by clipping all vegetation rooted in a 1-m^2 plot near each permanent sampling point. Active mounds are mapped every fall (Fig 12). This design allows us to track spatial and temporal changes in community composition, resource availability and ecosystem dynamics as burrows are abandoned and new burrows are colonized.

D2. New Research

Our new research builds on the foundation of our existing observational and experimental activities and addresses key components of our TDND model. Belowground processes and interactions will receive increasing attention during LTERV, an emphasis that began following our 2003 site visit, and continues based on advice from our site visit in 2009. Specifically, we will determine the effects of climate change and soil moisture availability on soil microbial populations and processes using two new manipulative experiments. We have added two new modeling studies on grassland-shrubland transition, one on pulse-driven biotic changes and the other on regional climate impacts of shrub encroachment. Finally, we expand our consumer studies through experiments that directly address how plant-herbivore interactions affect species distributions along environmental gradients.

D2a. ITA1 and ITA2: Climate and abiotic drivers/Ecosystem processes.
I. Manipulative experiments
A. Soil Moisture at Depth (SMaD). Two types of SMaD experiments will be conducted during LTERV. The first, SMaD-Rs, will test mechanistic hypotheses about nutrient transfers, the fungal
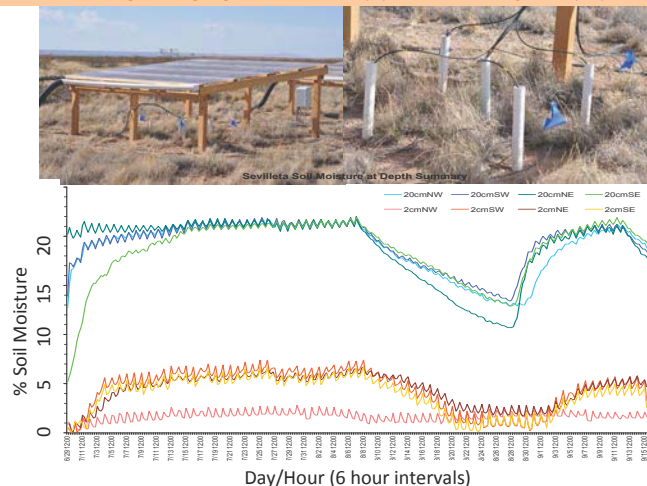
loop, and controls on soil respiration (Rs). The second, SMaD-Ecotone, will address competition for water and N between grasses and shrubs in the grass-shrub ecotone.

SMaD-Rs. Our previous studies established that the functional characteristics, spatial organization and taxonomic composition of soil microbial communities in SEV grasslands are highly responsive to variation in precipitation patterns and nutrient availability (Zeglin *et al*. 2007, Porras-Alfaro *et al*. 2008, 2011, Green *et al*. 2008, Herrera *et al*. 2011). Prevailing edaphic and climatic conditions sustain a distinctive N cycle in which Ascomycota dominate the fungal communities of biocrusts, plants, soil and litter, and the processes of N transformation and translocation. With no large reservoirs of soil C, little is known about the C acquired through symbiotic associations with perennial grasses and cyanobacterial crusts that fuel these fungal pathways and soil respiration. Because many Ascomycetes can grow at low water potential and high temperature, their metabolism may be temporally disconnected from that of plants and cyanobacteria through variation in the size of rain events. This disconnect may mitigate plant-microbe competition for N and create a microbial reservoir of N in fungal biomass. At times, flooded soil surfaces may support a microbial food web similar to those of benthic mats, and occasionally there is sufficient infiltration to support bacterial metabolism in subsurface soils. Most previous studies of microbial community organization and N transformation in arid ecosystems have focused on individual ecosystem components (e.g., rhizosphere, biocrusts, bulk soil, plant production), rather than linkages among these components.

Microbial composition and nutrient transfers interact with rainfall pulses to affect soil respiration, plant growth and ecosystem productivity. Field measurements demonstrated that photosynthesis (Anet) by desert grasses responds to small (5mm) as well as large (20mm) rain events (Thomey *et al*. 2011, *in prep*), and soil respiration (Rs) was closely tied to plant growth as pulse size increased (Vargas et al. 2012). Over the growing season, NPP (Thomey *et al*. 2011) and Rs (Vargas *et al*. 2012) were significantly higher in response to a small number of large rainfall pulses, which result in deeper infiltration and prolonged soil moisture availability relative to a large number of small events. NPP also increased with N addition when soil moisture was available indicating N limitation (Ladwig *et al*. 2012). Yet, at the ecosystem scale, these grasslands have been a net C source over the past few years (Anderson-Teixeira *et al*. 2011). Together, these results demonstrate that local processes (Anet, Rs) in this grassland are highly sensitive to soil moisture and N, that Anet is correlated with Rs, yet at larger scales, NPP is not well correlated with NEE.

Therefore, in the context of seasonal and interannual rainfall variation and anthropogenic N enrichment, we propose to experimentally evaluate four hypotheses derived from the TDND model that will integrate soil moisture, microbial, plant and ecosystem responses using *in situ* soil moisture arrays developed at the Sevilleta that give us unprecedented control of the frequency, synchrony, and duration of surface pulses, subsurface soil moisture and soil resource availability (Fig 13).

Over the next six years we will test the following four hypotheses 1) *Small surface rainfall pulses (1-2mm) stimulate biocrust processes of C and N fixation and fungal growth, leading to the storage of C and N, which are accompanied by ephemeral pulses of respiratory CO_2 efflux. The availability of these reserves for plants varies with season and availability of sufficient antecedent moisture to support*
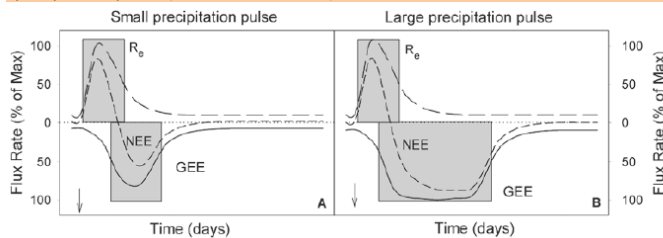

Figure 13. Soil moisture array. Complete rainout shelter (upper left), PVC inserts with irrigation hose and emitters (upper right), and soil moisture at 20 cm (blue, green) and 2 cm (orange, red) depths. Soil moisture probes are located midway between the center and corner PVC inserts which are 40 cm apart. The pump was turned off on 8/8/11 and restarted again on 8/20/11.

plant growth. This hypothesis builds on the "mantle of fertility" concept of Belnap *et al*. (2003), which proposes that biocrusts are the principal mediators of ecosystem C and N exchange in arid environments. 2) *Consistent soil moisture in the rooting zone will stimulate competition for nutrients between plants and microorganisms, leading to greater translocation of N and C between rhizospheres and biocrusts accompanied by a gradual increase in soil CO_2 efflux that will peak and then decline gradually over time as low soil organic matter content limits C supply for soil respiration.* This hypothesis is based on evidence suggesting that soil CO_2 efflux declines in desert soils before the end of a soil water pulse as a consequence of C limitation (Sponseller 2007). Alternatively, soil CO_2 efflux will peak within five days of the start of a prolonged soil moisture event, and remain high throughout the event through photosynthetically derived C provided to microbes by root exudation (Vargas *et al*. 2011, 2012). 3) *Peak surface and subsurface CO_2 efflux*

Figure 14. Hypothetical response of soil respiration, NEE and GEE to large and small precipitation pulses (Huxman et al. 2004b) to be tested with SMaD-Rs.

rates are temporally displaced following rainfall pulses. The duration of subsurface efflux changes with size of a precipitation event, whereas surface efflux rates are unaffected by event size. This hypothesis is a direct test of the model presented in Huxman *et al*. (2004a,b, Fig 14). Alternatively, both surface and subsurface CO_2 production will be positively correlated with rainfall event size and duration of soil moisture availability. 4) *Longer moisture availability in soils will enhance soil CO_2 production and total NPP (both belowground and aboveground).* Thus, large pulses of ecosystem respiration could be counterbalanced by large pulses of gross primary productivity (GPP), which result in neutral C balance in the ecosystem (i.e., NEE near zero). Alternatively, greater ecosystem respiration as a response of differential moisture availability will outpace GPP and result in net ecosystem C losses (i.e., positive NEE).

To test these hypotheses, we will establish replicate soil moisture manipulation plots that will allow us to control soil moisture in the rhizosphere (20-25 cm), soil surface, or both. Each plot is 1x1 m (N=10). To control *subsurface* soil moisture, five PVC tubes are buried vertically to a depth of 25 cm. One is located in the center of the plot and the remaining four tubes are located ~40 cm north, south, east and west of the central tube (Fig 13). Holes drilled in the bottom of each PVC tube allow water to diffuse into the soil. Irrigation tubing connected to a pump and water tank is inserted into each tube. A solenoid-controlled on/off valve controls the pump, which automatically regulates soil moisture content. Preliminary tests confirm that we can maintain soil water around 20% VWC at depth in the area between the PVC tubes for several weeks without elevating soil water content at the soil surface (Fig. 13). To control *surface* moisture, we apply small rainfall events (1-2mm) using a backpack sprayer at predetermined time intervals depending on which hypothesis we are testing. Thus, within each plot, we can control the amount and duration of soil moisture in the rooting zone, the frequency of soil moisture events at the surface, or both.

To completely control soil moisture, each plot is covered by a 3x3m complete rain-out shelter (n=20) made of polycarbonate Suntuf[©] panels. Gutters divert ambient rainfall away from the plots and aluminum flashing is buried to 10 cm depth along the perimeter of each plot to avoid run-on of ambient rainfall. Each plot contains soil moisture and temperature probes, and Vaisala CO_2 sensors (Allen *et al*. 2007, Thomey *et al*. 2011, Vargas *et al*. 2012). With this experimental design we can directly measure soil CO_2 production at depth, respiration, and N_2O production in response to surface and/or subsurface soil moisture to test how rainfall pulses affect ecosystem processes, and more explicitly incorporate microbial processes, N and C dynamics and soil CO_2 into the TDND model. Additionally, because this infrastructure is simple and portable, we can conduct different experiments over time by simply moving the shelters, relocating the PVC tubes, and reinstalling the soil moisture

probes to new locations as needed to prevent confounding the results of one experiment (surface pulses) with another (prolonged soil moisture pulse with added glucose to determine if soil C limits soil respiration). The landscape is homogeneous and the experiments will be established in blocks to account for the potential spatial heterogeneity among replications and treatments.

All of the methodology proposed is currently in use at SEV including extracellular enzyme assays for C, N and P (Stursova *et al*. 2006), N_2O production with and without acetylene block (Stursova *et al*. 2006, Crenshaw *et al*. 2008), translocation between grass and crust samples using ^{15}N-NO_3 or ^{15}N, ^{13}C-glutamate (Green *et al*. 2008), soil CO_2 production and efflux measured at 30-min intervals with *in situ* Vaisala CO_2 sensors (Vargas *et al*. 2010, 2012), ANPP (Muldavin et al. 2008), and NEE using a custom made 1 m diameter canopy chamber plumbed to a portable closed-system infrared gas analyzer (LI-6400).

SMaD-Ecotone. SMaD-Ecotone will address water and N competition between grasses and shrubs in the grass-shrub ecotone at SEV. As noted above, precipitation events add pulses of water (Loik et al. 2004), surface hydrology affects its distribution (Bhark & Small 2003) and high potential evapotranspiration depletes it. Without accessible groundwater, dry soil conditions prevail and even dominate in some years. Horizontal redistribution caused by micro-topography and differential infiltration results in variation of soil moisture by depth and cover type (Pockman & Small 2010). Such redistribution may vary seasonally, with intense summer convective storms producing greater spatial variability in soil moisture than synoptic winter rain/snow storms. The functional response of co-occurring plants to a rain event varies widely, depending on phenology and the correspondence between available water, microbes and active fine roots of each species (Fernandez 2006). **The goal of SMaD-Ecotone is to determine how patterns of available water drive plant responses and why shrubs invest in roots in soil that is only rarely wet by growing season rainfall.** Addressing this goal is key for predicting plant interactions and species responses to climate change-induced shifts in precipitation seasonality, amount and variability. Specifically, SMaD-Ecotone will determine how patterns of soil moisture interact with plant traits to influence plant C and water relations at the grass-shrub ecotone at SEV.

The physiological traits that determine the response of co-occurring grasses and shrubs to rainfall are the basis of most conceptual models of herbaceous and woody species interactions in arid ecosystems. Yet most models focus on ecosystem function and plant species interactions rather than factors that control individual plant function. Walter's (1971) widely applied (e.g. Soriano & Sala 1984) two-layer model described a shallow layer dominated by herbaceous plant uptake and a deeper-layer dominated by roots of woody plants. However, in arid ecosystems many storms do not increase moisture in deep soil, suggesting that while the two-layer model describes rooting depth, shrubs gain C in response to rain events that wet the upper layer of soil. While grass root systems are restricted to the upper soil layers, root systems of shrubs often span wet surface soil following rain and drier deeper soil not reached by infiltration (Schenk & Jackson 2002). Hydraulic redistribution (Prieto *et al.* 2012) may drive flow between wet and dry portions of the root system, keeping fine roots alive and potentially facilitating nutrient uptake from dry soil (McCulley *et al.* 2004). Thus, although plant functional responses to precipitation and vertically structured patterns of soil moisture are well studied, the lack of manipulative studies of soil moisture with depth limits quantitative linkages between plant functional types and pulse dynamics as presented in our TDND model.

In the grassland-shrubland ecotone at SEV, a 15 mm event wet only the upper 30 cm of the soil profile. Infiltration from this relatively large storm (most are <2 mm) encompassed most of the root systems of grasses but left the lower half of shrub root systems in dry soil (Pockman & Small 2010). Grasses at SEV exhibit large increases in gas exchange in response to storms that wet the upper 30 cm of the soil (Pockman & Small 2010), and grasses can respond to events as small as 5 mm (Thomey *et al*. 2011). Shrubs also respond to individual rainfall events, but they exhibit smaller

increases in water potential, stomatal conductance and Anet than co-occurring grasses. Differences in the proportion of the root volume affected by rain are probably responsible: moisture increases throughout the root volume of shallowly rooted grasses but in only a fraction of the root volume of deeper-rooted shrubs. *SMaD-Ecotone will test three hypotheses describing the interaction of roots with soil moisture to understand their contribution to plant function as climate fluctuates.*

Over the next six years, we will test the following three hypotheses: 1) *Shrubs only achieve maximum water status, gas exchange and growth when most of the root volume is at high water potential.* Although this is somewhat obvious, it is important to empirically confirm the simplest case of this hypothesis before exploring shrub responses to different soil moisture patterns (e.g., Sponseller *et al*. 2012) and evaluating the behavior of grasses with deep soil moisture. A corollary hypothesis is that *deep water has a greater impact early in the growing season than during the summer when the high root length density of C_4 grasses allows them to effectively compete with shrubs for water.* 2) *When shrub root systems span deep dry soil and surface soil is wet by recent precipitation, hydraulic redistribution stores water in deep soil and facilitates nutrient uptake throughout the root volume*. 3) *The rate of recovery and the magnitude of the response of shrubs relative to grasses are increased by small increases in water potentials at depth, even when these increases are not accompanied by a large change in volumetric water content.* During severe drought, the entire soil profile is at low water potential but deep soil may mitigate the physiological impacts on shrubs even when the volume of available water is small.

To test these hypotheses, we will use modified versions of the SMaD-Rs infrastructure. Again 3x3m plots will be covered by polycarbonate to exclude precipitation from a target shrub and
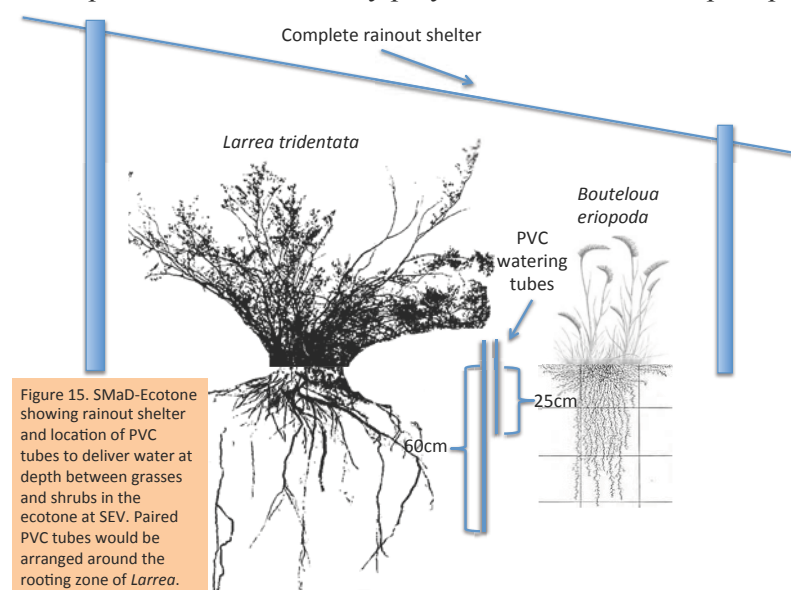

Figure 15. SMaD-Ecotone showing rainout shelter and location of PVC tubes to deliver water at depth between grasses and shrubs in the ecotone at SEV. Paired PVC tubes would be arranged around the rooting zone of *Larrea*.

adjacent grasses, enabling us to control the water these plants receive (Fig 15). Gutters divert ambient rainfall and flashing buried to 10 cm depth prevents run-on of ambient rainfall. PVC tubes buried to depths of 20 cm (where grass and shrub roots overlap) and 50 cm (below grass roots), combined with surface application of water, provide control over the pattern of soil moisture. Plots will be instrumented with automated soil psychrometers, stem heat balance sensors will measure shrub sap flow (Cavanaugh *et al.* 2011), and we will assess the state and growth of root tips and fungal hyphae across species and treatments using automated, wireless minirhizotrons developed by Mike Allen at UC-Riverside. We will measure predawn and midday water potential and Anet of target plants in each plot. Plant hydraulic conductance will be measured as appropriate for root or stem segments. Treatments (n=7) include water at surface, deep, and both depths, with the same amount of water applied in each treatment in both spring and summer to differentiate the importance of spring vs summer moisture on grass and shrub growth. Pulse sizes will vary during the season and we will assess relative uptake of deep and shallow water using isotopically labeled water for surface (D_2O) and deep ($H_2^{18}O$) applications for a small and large event.

To assess the role of deep roots in nutrient uptake in the absence of deep water, plots will be labeled with ^{15}N-ammonium at depth by augering small diameter holes between PVC watering tubes.

Labeled nutrient will be deposited at 50 cm under plant canopies between grasses and shrubs. One group of shelters will receive only surface water while the other group will receive an equivalent volume of water split between surface and deep positions. Soil psychrometer data will be used to measure differences in water potential and record diurnal fluctuations associated with hydraulic redistribution. Leaf tissue will be sampled three times during the growing season to assess uptake of label in grasses and shrubs.

To test the role of deep roots during drought, shelters will be assigned to one of three treatments: ambient deep soil (no water addition at depth), +1 MPa and +2 MPa with the latter two treatments produced by adding small quantities of water at depth to raise deep soil water potential during drought. The goal is to increase deep soil water potential enough to facilitate its proposed effect on sustaining shallow roots without providing large volumes of water for plant activity (in the dry portion of moisture release curves small amounts of water cause large changes in water potential).

B. Regional Soil Monolith Study (ReSMoS). Because processes in aridlands are strongly tied to precipitation pulses (Schwinning & Sala 2004, Collins *et al.* 2008a), aridland ecosystems are expected to be highly responsive to future climate variability. This variability includes warmer temperatures and more variable climate extremes in both wet and dry years. **The goal of ReSMoS is to determine the impacts of climate warming and increased interannual variability in precipitation on microbial populations and ecosystem processes (Rs, Nmin, NPP) in arid grasslands.** To do so, we will move replicate soil monoliths along a latitudinal gradient extending

Figure 16. Regional soil monolith study (ReSMoS) showing study sites, core extraction and an intact grassland core now in shrubland to simulate the effects of shrub encroachment on grass ecophysiology and soil processes. Monoliths are 30 cm diameter by 40 cm deep.

MAT=8.8C MAP=310mm SGS
MAT=11.8C MAP=356mm Kiowa
MAT=13.5C SEV MAP=250mm
MAT=14.7C MAP=232mm JOR
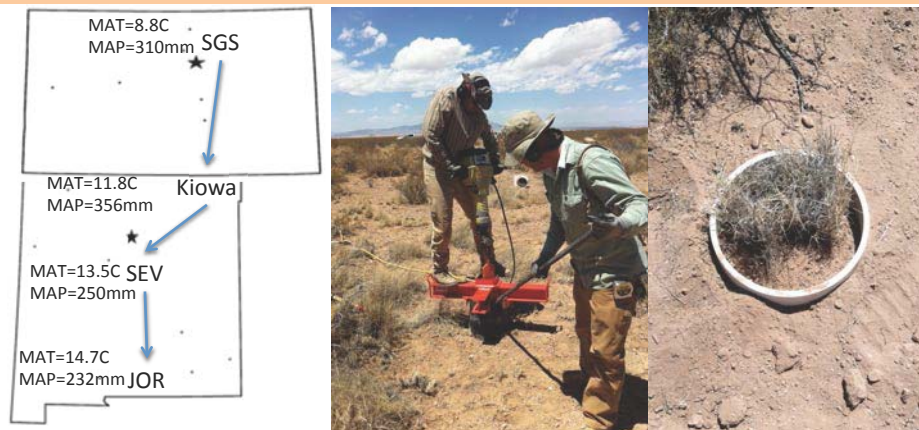
from northeastern Colorado (SGS) to southern New Mexico (JOR LTER)(Fig 16). Each of these 20 monoliths will contain an intact clump of *B. gracilis* from Colorado (SGS LTER) to the Kiowa Grassland in northeastern NM, 20 *B. gracilis* monoliths from Kiowa to SEV, and 20 *B. gracilis* monoliths from SEV to JOR. In doing so, the monoliths will naturally experience warmer and in most cases drier climates. We will also extract and reinstall "reference" monoliths at all sites to assess the effects of extracting and installing the monoliths on ecosystem processes. A subset of the monoliths at each site (n=10) will be subjected to increased interannual climatic variability. Treatments will include ambient conditions and interannual extremes via artificially imposed drought-irrigation-drought cycles during the growing season. Droughts will be -50% of ambient using passive rainout shelters (Yahdjian & Sala 2002) and irrigation will be +50% of ambient by collecting and diverting precipitation onto treatment plots. Within each experimental treatment we will measure aboveground NPP of *B. gracilis* using non-destructive allometric methods (Muldavin *et al.* 2008), soil C content, Rs (weekly using a LiCor 6400 and soil collars at SEV only), soil microbial communities (annually), and growing season available NO_3 and NH_4 using ion exchange resins. We will test the following hypotheses: *climate warming will (1) initially increase but ultimately reduce Rs, Nmin, and NPP, and (2) increase abundance of Pleosporales. (3) Responses to interannual variability will be asymmetric, that is, the*

decrease of process rates (e.g., Rs) under drought will be greater than the increase under elevated moisture availability. With this long-term experiment we can also assess legacy effects of soil moisture availability from one year to the next.

Soil monoliths have been successfully used to simulate climate change along an elevational gradient in Arizona (Blankenship *et al*. 2010), across the Great Plains (JM Blair, KNZ, Pers. Comm.) and in growth chamber experiments (Verberg *et al*. 2005, Arnone *et al*. 2008). Also, we have tested the method at SEV by moving grassland monoliths into creosote-dominated areas to simulate shrub encroachment (Fig 16). The monoliths in combination with rainfall manipulations provide an inexpensive yet effective mechanism for simulating climate change and variability, and measuring key ecosystem responses including NPP, Rs, soil microbial community composition and structure, and soil N availability. In summary, this experiment will allow us to assess the impacts of a warmer and more variable climate across a latitudinal gradient from desert grasslands to shortgrass steppe.

D2b. ITA3: Biotic responses and feedbacks.
I. Monitoring studies.
Producers. On 3 Feb 2011 temperatures at the SEV fell to -29C, roughly a 25-50 year T_{min} based on a nearby temperature record from 1943-2008. Widespread chlorosis of *L. tridentata* was visible within days of this abiotic pulse event, followed within weeks by widespread canopy dieback.

Figure 17. Percent of individuals of *Larrea tridentata* out of 200 at three sites with >75% canopy mortality (orange) in response to a severe cold event in February 2011.
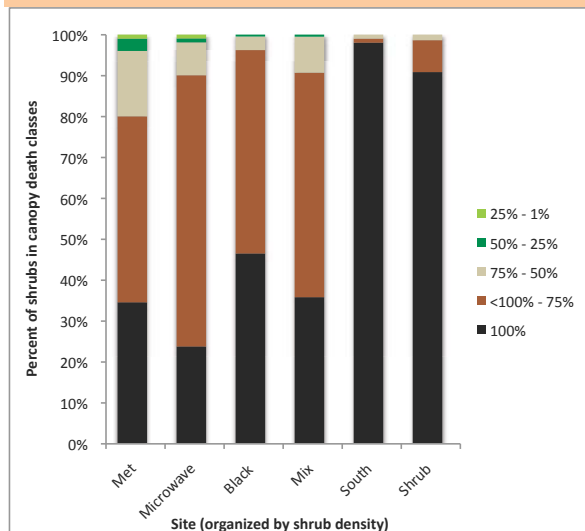
Preliminary measurements showed some sites with complete and many with partial canopy dieback (Fig 17). The observed outcomes are consistent with predictions from laboratory studies of *L. tridentata* freezing responses (Pockman & Sperry 1997, Martinez-Vilalta & Pockman 2002, Medieros & Pockman 2010). **The goal of this study is to use this natural "external driver" event to determine the relationship between observed damage and freezing recovery of *L. tridentata* at SEV and JRN.** Specifically, we will test the hypothesis that *the extent of resprouting after freezing will mitigate the immediate consequence of the extreme freeze, with variation in resprouting performance related to the freezing tolerance variables and environmental conditions during the recovery period.* Resprouting is a key physiological response to link the immediate result of extreme freezing to survival and population dynamics. We will follow marked individuals from six measured populations to assess the long-term outcomes of plants exhibiting a range of damage following the severe freeze. We expect that variation in the timing and extent of re-sprouting will correlate with the extent of damage caused by low temperatures and by conditions following the freeze. At SEV, there were only trace amounts of precipitation from February through August 2011. Thus, we used an existing irrigation system to compare watered plants and adjacent plants subjected to ambient precipitation to assess the impact of soil moisture on the extent of resprouting and on whole plant mortality. We hypothesize that *plants receiving supplemental water during spring 2011 will exhibit improved resprouting and lower mortality than adjacent individuals subjected to prolonged spring and summer drought*. Finally, we will establish plots of marked individuals to be used for repeated simulated canopy mortality. Treatments will include canopy removal at 1-, 2- or 4-year intervals to assess the limitations of energy reserves required to support resprouting. We expect that repeated cycles of dieback and resprouting require the accumulation of energy reserves that need

a period of growth to accumulate. We will then couple these monitoring plots with lab-based, short term experiments/measurements of leaf cell osmotic potential on sprouting branches and xylem conduit diameter of living and dead branches to develop a mechanistic understanding of creosote mortality in response to extreme freezing events.

II. Manipulative experiments.

Consumers. Vertebrate and invertebrate consumers can have an important influence on vegetation dynamics in arid and semi-arid ecosystems (e.g., Brown *et al*. 1979, Guo *et al*. 1995, Ryerson & Parmenter 2001). While most plant species interact with both consumer guilds over the course of their life cycle, the interactive effects of vertebrate and invertebrate consumers on shared host plants are largely unknown (Warner & Cushman 2002, Maron & Crone 2006). This is particularly true of long-lived perennial plants, for which the frequency and intensity of interactions with different consumer guilds can vary over ontogeny (Boege & Marquis 2005, Miller & Rudolf 2011). Quantifying the impacts of consumers that attack different plant stages requires an understanding of how those stages contribute to population dynamics. **The goal of our plant-herbivore work is to evaluate the independent and interactive effects of vertebrate and invertebrate consumer guilds on plant abundance, distribution, and population dynamics.** We take a demographic approach to our studies of plant-herbivore interactions by quantifying the influence of different consumer guilds on individual-level vital rates at different points in the plant life cycle. We will use demographic models to scale up from individual-level data to population dynamics (e.g., Miller *et al*. 2009). A major component of the TDND model that we are beginning to address is the linkage between plant growth (NPP), consumer abundances, and feedbacks between consumers and producers (Fig 2). Long-term data on plant demography and the impacts of consumers allows the construction of more realistic models that can accommodate stochastic variation in demographic rates, identify key abiotic drivers, and provide inferences about population-dynamic responses to environmental change.

Our plant-consumer work focuses on *Opuntia imbricata*, a dominant cactus species that occurs throughout the grassland and high-elevation areas of SEV, where it serves as a resource for a variety of vertebrate consumers and specialist insect herbivores. This is a model system for plant-consumer studies because it occurs in a diversity of habitats, providing an opportunity to examine whether and how landscape context modifies the impacts of consumers. Previous work demonstrated the effects of competition (Miller 2008), host-plant quality (Miller 2007a), ant-plant defensive mutualism (Miller 2007b), and spatio-temporal climate variability (Miller *et al*. 2006) on *O. imbricata* and its herbivores. Currently, insecticide experiments are being used to quantify the influence of insect herbivory on plant demography and population dynamics across the grassland-mountain gradient (e.g., Miller *et al*. 2008, 2009) at SEV. Results to date identify subtle but chronic reductions in demographic performance due to insect herbivory as a key driver of variation in plant density across the gradient, a result that highlights the importance of arthropod consumers in the spatial distribution of a dominant plant species.

Our proposed work will focus on the population-level effects of vertebrate herbivory and its interaction with insect herbivory on *O. imbricata*. We hypothesize that this interaction will be manifested at the population and not individual level, since attack by vertebrates and invertebrates occurs at different points in the plant's life cycle. Insect herbivory is concentrated in later plant life stages, while rodents are frequent consumers of cactus seeds, seedlings, and small vegetative plants. To quantify the effects of rodent herbivores on plant population dynamics, we will establish seed addition plots (0.25m x 0.25m) in each of three elevation zones (low [1670 m], mid [1720 m], high [1790 m]) along four established transects that span the grassland to piñon-juniper gradient. Forty plots will be established in each elevation zone on each transect (N = 480 plots); 20 plots will be assigned to rodent exclusion (caged with hardware cloth) and 20 will serve as controls (covered with sham cages). Each of the 20 plots in each treatment will be assigned a level of seed addition, ranging

from 0 (control) to 300 seeds (3x mean ambient seed rain). This design will allow us to estimate the density-dependent seedling recruitment function and the influence of habitat and vertebrate consumers on the shape of this function. Seeds will be added in fall, when natural seed dispersal occurs, and recruits will be counted, tagged, and re-censused each subsequent fall. New seed addition plots will be established each year, allowing us to quantify the influence of abiotic pulses (monsoon precipitation) on germination and recruitment. We will incorporate experimental results from early life stages into existing stochastic demographic models that span the remainder of the life cycle (Miller et al. 2009). These methods will allow us to ask if and how vertebrate consumers modify the population-level effects of insect herbivory (population growth rate and equilibrium density), and if the demographic effects of both consumer guilds vary across the environmental gradient.

Over the next six years we will test the following four hypotheses. (1) *Vertebrate herbivores have, on average, weaker population-level impacts than invertebrate herbivores*. This hypothesis, which runs counter to previous theory (e.g., Crawley 1990), is based on the relatively low sensitivity of population growth to early life-cycle demographic transitions, as is common for long-lived perennials (Silvertown et al. 1993). (2) *Demographic impacts of vertebrate herbivores are more variable than impacts of invertebrate herbivores*. Since vertebrate herbivory is concentrated in early life stages dependent upon the timing and magnitude of monsoon precipitation, stochastic abiotic

Figure 18. Seed addition experiments show strong differences in seedling recruitment across elevation zones. These differences are entirely due to rodents, which have stronger effects at higher elevations.
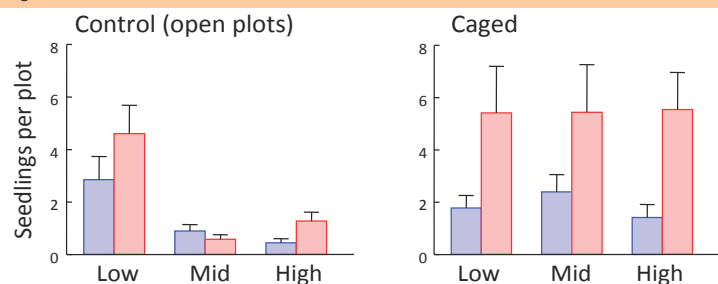
pulses should mediate its population-level impacts. (3) *Vertebrate and invertebrate herbivores have interactive effects on* O. imbricata *population dynamics*. Because each consumer guild alters the sensitivity structure of the plant population (Caswell 2001), their joint impact should be greater than expected from the sum of their independent impacts. (4) *The main and interactive effects of vertebrate and invertebrate herbivores vary across the grassland to piñon-juniper gradient*. Previous work has documented variation in insect and rodent activity across the gradient (Miller et al. 2009; Fig 18), setting the stage for complex patterns of consumer impacts across the landscape.

III. Modeling – shrub encroachment.
A. Species interactions. We will use simulation modeling to examine alternative hypotheses related to 1) differential invasion by *L. tridentata* seedlings in *B. eriopoda* vs *B. gracilis* patches, 2) the establishment and dominance of *B. eriopoda* compared with *B. gracilis* and *L. tridentata* in different vegetation patches and soil types, and 3) the spatial extent of individual patches dominated by *B. eriopoda* or *B. gracilis*, in addition to their overall density and spatial distribution, that are expected to be important to past and future invasion dynamics by *L. tridentata* at the landscape scale. **Our overarching hypothesis is that pulses in precipitation across a range of temporal and spatial scales have strong and differential effects on recruitment, growth, and mortality by different species at the plant to patch scale with consequences for long-term patterns in dominance and composition across landscapes.** This is a cross-site project with JOR LTER. We will use the SOILWAT model to examine the importance of daily to weekly precipitation pulses for recruitment by the three dominant species in different vegetation patch and soil types. SOILWAT is a multi-soil

layer, daily time-step model that simulates daily soil-water dynamics in response to precipitation inputs, temperature, and soil properties (Minnick & Coffin 1999, Peters 2000, Peters *et al*. 2010). Sub-daily pulses of precipitation, such as high intensity-short duration rainfall events, will be incorporated into the model and calibrated using met station data. We will use ECOTONE developed for grassland and shrubland at SEV (Peters 2002a, Peters *et al*. 2009) to examine the importance of spatial patterns in *B. gracilis* and *B. eriopoda*-dominated areas to past invasion dynamics by *L. tridentata*, and to predict future landscape dynamics under alternative climatic scenarios. ECOTONE is an individual plant-based, gap dynamics model that simulates the recruitment, growth, and mortality of individual plants on small plots (1-5 m^2) at an annual time step (Peters & Herrick 2001, Peters 2002a). ECOTONE is being modified to include dynamics of patches of variable size, species composition, and spatial arrangement. Because ECOTONE is linked to SOILWAT, we can simulate effects of rainfall pulses within a year on recruitment, and among years on growth and mortality. We will investigate the relative importance of these different plant processes and scales of rainfall pulses to vegetation dynamics under alternative climate change scenarios including changes in the amount, intensity and duration of precipitation pulses across sub-daily to decadal time scales.

B. Microclimate. Near-ground air temperature in the shrubland is up to 2°C warmer than in the grassland at night during winter at SEV (He *et al*. 2010). The larger bare soil fraction (70%) and lower vegetation cover in shrubland than in grassland (40%; Kurc & Small 2004) alters surface energy balance and results in higher winter nighttime temperatures (He *et al*. 2010). Because of the sensitivity of *L. tridentata* to minimum temperature (Pockman & Sperry 1997; Medeiros & Pockman 2011; Fig 17), such temperature differences could be crucial to the survival of *L. tridentata* and may facilitate further expansion of shrubs into grassland. To test this hypothesis, we will use numerical models to extrapolate temperature change induced by shrub encroachment at a regional scale and over longer time periods. Using an existing detailed vegetation map, along with known land-atmosphere dynamics between grassland and shrubland and known temperature tolerances of *L. tridentata* adults and juveniles (Pockman & Sperry 1997, Medeiros & Pockman 2011), we will model the geographic region in which the winter minimum temperature potentially allows for the survival of *L. tridentata*. In addition, different vegetation cover scenarios will be simulated to determine the possible extent of shrub encroachment regionally if facilitated only by known vegetation-microclimate feedbacks.

To do so, we will use the state-of-art Weather Research and Forecasting (WRF) model (Skamarock *et al*. 2008) coupled with the NOAA Land Surface Model (LSM) (Mahrt & Ek 1984, Chen & Dudhia 2001, Ek *et al*. 2003), which we have used to successfully simulate the cause, existence and temporal evolution of the nighttime temperature differences between shrubland and grassland (He *et al*. 2011). The configuration will contain an outermost domain covering a large area in the southwestern US with four nested grids to ensure the fine horizontal resolution (333m × 333m) in the innermost domain, which centers on the SNWR and covers the encroachment front of *L. tridentata*. Accurate vegetation distributions in SNWR from high-resolution imagery will be used and important modifications to the model and vegetation parameters will be made based on prior 2D simulations (He *et al*. 2011). The numerical model will be run on a yearly time step, and using temperature soundings recorded in grassland and shrubland in winters of 2008-2009 and 2011-2012. Through these simulations, we can determine the effects of vegetation cover types on boundary layer and near-ground temperatures for the SNWR region over relatively long time periods.

**E. Cross-site Activities.** SEV researchers are involved in cross-site and synthesis efforts, such as PDTNet (Suding et al. 2005, Cleland et al. 2011, Gough et al. 2012) and SHRUBnet (Knapp et al. 2008b, Ratacjzak et al. 2012). Our proposed ReSMoS study is explicitly cross-site, including JOR LTER. Also, SEV is part of a newly funded (NSF Macrosystems Biology) multisite (LTER and non-

LTER) collaboration called EDGE (Extreme Drought in Grasslands Experiment). Through long-term manipulative experiments and modeling, this project will determine the relative contribution of ecosystem attributes vs. environmental context in grassland response to extreme climatic events.

F. Intellectual Merit: Integration and synthesis. The goal of our integrated research program is to understand how key abiotic drivers and constraints (climate, water, and soils) regulate ecosystem processes and resource availability to affect the dynamics, stability, interactions, and feedbacks of producers and consumers in this aridland ecosystem. Abiotic drivers affect biogeochemical pools and cycles, mediated by soil microbes, as well as water input, storage, use, and loss. Biotic and ecosystem responses to these abiotic drivers include microbial community composition, patterns and controls on NPP and the distribution, abundance, diversity, and dynamics of plant and animal populations and communities. We integrate these approaches through our Threshold-Delay Nutrient Dynamics (Fig. 2) model that explicitly includes interactions among microbial and plant functional types. Together our long-term observational and experimental studies allow us to determine **the degree to which community dynamics and ecosystem processes are coupled periodically through precipitation events that trigger pulses of biological activity by different microbial and plant functional types and consumer populations, depending on the size, frequency, intensity, and seasonality of rainfall.**

Although we present much of our research as a series of independent projects addressing explicit goals and hypotheses, we also develop synthetic understanding by combining information across studies. For example, we have used data from the drought plots, WENNDEx, MRME, vegetation transects, NFert,

Figure 19. Summary of interactions among the dominant species, aboveground net primary production (ANPP) and environmental drivers derived from long-term vegetation monitoring and several manipulative experiments at SEV.
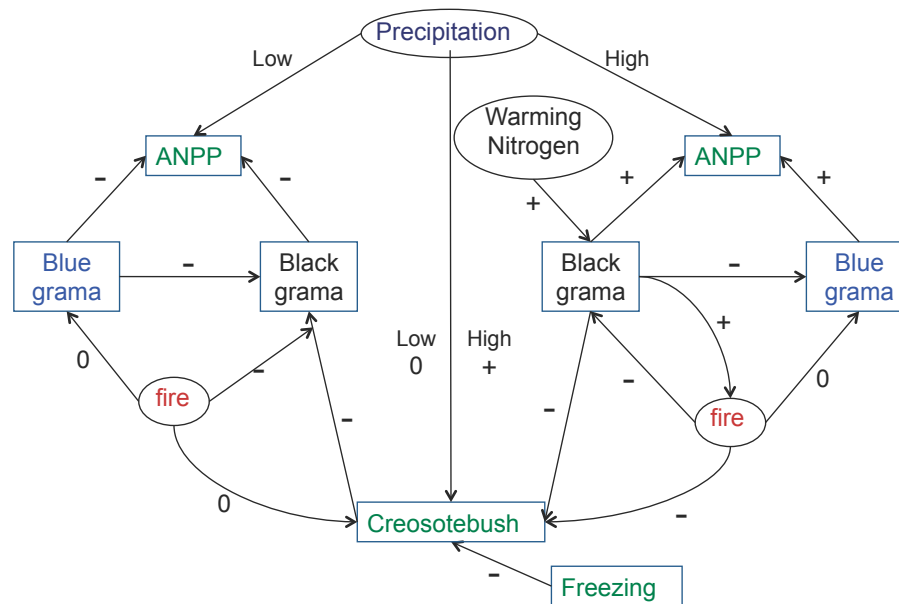
ECOTONE, and NPP studies to develop a comprehensive understanding of factors affecting abundance and interactions among dominant species at SEV (Collins *et al*. *unpubl*. Fig 19). Our studies on consumer interactions rely on high-resolution weather data, population abundances of consumers, plant species composition (line-intercept transects) and NPP measurements. Treatments in MRME, WENNDEx, NutNet and NFert create an N fertilization gradient of 0, 2, 5 and 10 gN m^{-2}yr^{-1}. Finally, after several years of above and belowground NPP measurements, soil respiration measurements (MRME, WENNDEx) and NEE data from grass and shrub flux towers (SEON), we are beginning to integrate interannual responses of Rs, total NPP and NEE to better understand regional C fluxes. In addition, to site level syntheses, data from a variety of long-term experiments have been and continue to be used in cross-site syntheses (e.g., Collins et al. 2008b, Breshears *et al*. 2009, Cleland *et al*. 2011, Gough *et al*. 2012, Ratajczak *et al*. 2012). Thus, SEV encompasses a set of well-defined, but highly related

projects that allow us to test specific hypotheses about aridland ecosystems, assess mechanisms, as well as integrate our data to address general ecological theory.

Our on-going and proposed research activities reflect core components of our TDND framework, integrate the five LTER core areas, and address recommendations by site visit teams. Specifically, SEV research focuses on organic matter dynamics and turnover, C and N cycles, patterns and controls of NPP, disturbances (fire, drought), and dynamics of key species and communities. New research will provide a more detailed mechanistic understanding of climatic and soil moisture controls on microbial communities, soil N availability, soil respiration, and species interactions, including a better understanding of herbivore feedbacks on plant species distribution, and plant community composition and dynamics. We monitor and analyze climate variables locally and throughout the northern Chihuahuan Desert to provide a context for our experimental and observational work. This information feeds directly into our analyses of pulse dynamics, nutrient availability and fluxes of C, N, water and energy across scales as described in our TDND model. We assess microbial responses to precipitation pulses and N availability, microbial contributions to decomposition, C cycling, and nutrient availability, plant-microbe interactions, and plant-consumer interactions. Finally, seasonal responses integrate individual pulse events through changes in community composition over time, which varies seasonally and serves as the primary resource for key consumers and trophic relationships.

Overall, LTERV is a logical progression of research ideas generated from previous research and in response to advice from our past site visits. New research will yield a more detailed long-term perspective on producer, consumer and microbial communities and processes regulating soil C and N dynamics. Our new experiments (SMaD, ReSMoS) coupled with our on-going studies and modeling efforts, will generate detailed understanding of microbial responses to climate change and climate variability, and a mechanistic understanding of controls on soil respiration and shrub expansion. Our new study of creosote response to a rare extreme freezing event represents an ideal opportunity to determine the impacts of a dramatic change in abundance of a regionally dominant species. Expanding our prairie dog restoration experiment will generate important understanding of how a keystone consumer affects plant and soil communities. Finally, our new experimental study of plant-herbivore interactions will generate insight into the mechanisms controlling the distribution and abundance of a characteristic species in this aridland ecosystem. Together these studies lead us toward our long-term integrative goal: ***to understand how abiotic pulses and constraints affect species interactions, community structure, and ecosystem processes in aridland ecosystems***.

G. Education and Outreach
G1. BEMP. The Sevilleta schoolyard LTER Program – the Bosque Ecosystem Monitoring Program (BEMP) – has been at the vanguard of both collecting and providing useful, necessary information on the Middle Rio Grande riparian ecosystem and involving students in this data collection effort, educating them through regular scientific monitoring of a greatly altered ecosystem. Since 1997, BEMP has brought K-12 students and their teachers into the field to collect data on structural and functional change within the middle Rio Grande and its riverside forest, or "bosque." At BEMP sites along a 240 km stretch of the Rio Grande, including a site at the SNWR and 24 other similarly organized sites, students gather field data and take samples back to the lab for processing. All data and findings are placed on-line (http://www.bosqueschool.org/BEMP.aspx) and published in reports produced by UNM BEMP staff and then used by local, state, tribal, and federal governmental agencies to create models and make land management decisions. The data have continually been requested and used by the Middle Rio Grande Conservancy District, US Army Corps of Engineers, US Bureau of Reclamation, US Fish and Wildlife Service, NM Interstate Stream Commission, and the Association of New Mexico Soil and Water Conservation Districts. As students collect field data

and process samples they increase their understanding of science and complex riparian ecosystems. BEMP started with three sites in 1997 and the 25th site was completed in 2008. A 26th site is currently being installed at the Mesilla Valley Bosque State Park in Las Cruces, near the JOR LTER. Local schools will monitor this site with help from an intern at NMSU in partnership with the Scientifically Connected Communities Director and Science Field Specialist at New Mexico State University.

Continued funding will allow BEMP to directly serve, support, and expose over 5000 students and their teachers (approximately 120) each year who participate in BEMP classroom and field-based data collection activities including teacher training, class participation support, transportation to the field sites, outreach to the classrooms, and training of high school summer interns. The BEMP outreach educator visits schools interested in BEMP and makes presentations about BEMP, data collection, and the Middle Rio Grande riparian ecosystem. The outreach educator also conducts tours of BEMP sites, hosts field collections, and regularly goes out with classes for their monthly field collection. After a field visit, the outreach educator does follow-up visits and plants activities so that the students can help process the field collections (e.g., leaf litter labs and arthropod labs) and then graph and analyze their data, allowing the students to better understand what they were monitoring and how sites differ from each other or how specific sites differ over time.

BEMP involves a rich and diverse blend of Hispanic, Native American, and Anglo cultures. BEMP schools are located in inner-city, suburban and urban-rural interface areas. BEMP students span all ages and economic groups, from private college preparatory schools to alternative high schools in disadvantaged areas. Currently, BEMP schools with monthly field monitoring include high school classes that have strictly Spanish speaking students, three Native American pueblos, and hundreds of other Hispanic and Native American students that participate once or twice a year. High school interns work with BEMP staff in the field, lab, and help with community outreach. This allows students to increase their exposure to science, education, and stewardship while adding to their resumes. In addition, BEMP trains and uses university interns for field and lab assistance during work-intensive months when fewer students are available. Involving K-12 and university students in scientific monitoring, lab work and analyses and data interpretation greatly enhances their education in the fields of science, math, etc. In addition, these students become aware of both local and global issues in the environment and are more likely to be effective stewards of this and other ecosystems.

G2. SEV REU Program. Our REU Site Program (PIs: Collins and McFadden) at SEV allows 10-11 undergraduate students each year to conduct independent research under the guidance of UNM faculty in the Departments of Biology and Earth and Planetary Sciences, and staff at the US Fish and Wildlife Service. Additionally, our summer program includes 2-3 undergraduate fine arts majors as part of the Arts and Ecology program in the UNM College of Fine Arts. All students participate in the weekly seminar series, journal club, annual symposium, professional development workshops, ethics training, and fieldtrips. Natural science students conduct independent research while art students work on presentation pieces, and all present results of their work at the annual symposium. In addition, art students accompany natural science students in the field, and art students offer training in their specialty to the natural science students. The program includes faculty in ecology, geosciences, meteorology and fine arts. Working at SEV fosters interactions among students, faculty, and graduate students. Students have numerous opportunities to share ideas and explore issues within and across disciplines. A goal is to increase the number of students, particularly underrepresented minorities, pursuing careers in biogeosciences (Table 1). The program provides exposure to a large, multidisciplinary research program and creative activities, and inspires students to continue into professional careers, and to prepare for the rigors of graduate school, professional careers, and responsible citizenship. The program exemplifies the integration of research and education.

G3. Sevilleta Visitors Center and Seminar Series. The Sevilleta National Wildlife Refuge is currently developing a new visitors center to educate the public about the role of National Wildlife Refuges, the SNWR and its environment, and the role of research in understanding and managing these ecosystems. SEV LTER scientists are actively involved with the development of educational materials

TABLE 1	2008	2009	2010	2012	3-year total
TOTAL PARTICIPANTS	10	11	11	11	43
Male	3 (30%)	3 (27%)	4 (36%)	4 (36%)	14 (33%)
Females	7 (70%)	8 (72%)	7 (63%)	7 (63%)	29 (67%)
Freshman	0	0	1 (9%)	1 (9%)	2 (5 %)
Sophomore	3 (30%)	6 (54%)	7 (63%)	2 (18%)	18 (42%)
Junior	7 (70%)	5 (45%)	3 (27%)	5 (45%)	20 (46%)
Senior	0 (0%)	0 (0%)	0 (0%)	3 (27%)	3 (7%)
Small Colleges	3 (30%)	4 (36%)	3 (27%)	4 (36%)	14 (33%)
Large Universities	7 (70%)	7 (63%)	8 (72%)	7 (63%)	29 (67%)
African-American	0	2 (18%)	1 (9%)	1 (9%)	4 (9%)
Hispanic	2 (20%)	6 (54%)	6 (54%)	4 (36%)	18 (42%)
Native American	0 (0%)	0 (0%)	1 (9%)	2 (18%)	3 (7 %)
Pacific Islander	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Asian	1 (10%)	1 (9%)	1 (9%)	2 (18%)	5 (12%)
Caucasian	7 (70%)	2 (18%)	2 (18%)	2 (18%)	13 (30%)

for the new visitors center including specific exhibits about our LTER research. As part of this enhanced outreach program, the SNWR is offering more frequent public tours and a monthly seminar series for the public. Sevilleta faculty, graduate students and staff frequently provide tours of the refuge and are active, regular participants in the seminar series.

G4. ESA SEEDS. The Sevilleta LTER Program has a long and active history with the ESA SEEDS Program. Our SEEDS Campus Chapter was established in 2005 (PI Collins is the Advisor). The Sevilleta LTER hosted the Annual SEEDS Workshop in November 2005. Collins was a participant in the 2006 SEEDS Leadership Workshop at Arizona State University. In 2007-8, Collins mentored a SEEDS Fellow at the Sevilleta. In 2008, Sevilleta hosted the SEEDS Leadership workshop. In 2010 PI Collins helped to establish a SEEDS Chapter at Arizona State University and recruited one of the Chapter co-Chairs to be an REU student at SEV. Thus the Sevilleta LTER has a strong and lasting relationship with ESA SEEDS beyond recruiting REU students. As part of this partnership, we will continue to work closely with ESA's SEEDS Program, hosting workshops and field trips, participating in regional SEEDS activities and providing research opportunities for SEEDS students.

G5. UNM Biology – Junior Scientist Outreach Program. As a new outreach activity, SEV will participate in the Junior Scientist Outreach Program (JSOP) that has been coordinated by the UNM Department of Biology since 2010. The JSOP initiative is aimed at making science fun, interesting, and accessible to 4th and 5th grade underrepresented children from the mostly Hispanic and generally low-income South Valley neighborhoods of Albuquerque. The bilingual camp is free of cost and sponsored by UNM Biology Department, Sandia National Laboratories, and the Westside Community Center, and staffed by undergraduate student volunteers (22 in 2011) drawn from the Biology Undergraduate Society – BUGS. Each year, the JSOP engages students (42 in 2011) in hands-on activities, with each day's activities coordinated by a research scientist from UNM or Sandia National Lab. Beginning in 2012, SEV staff and faculty will lead JSOP field trips each year, by featuring different aspects of SEV research over time.

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*indicates Sevilleta publication
_indicates current or former graduate student author

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Facilities and Equipment

Laboratory facilities used by the LTER Program exist both on the UNM campus in Albuquerque and at the Sevilleta Field Station (SFS). On campus, the LTER operates both organic and inorganic chemical analysis laboratories ("clean" labs), as well as a sample processing lab for soil and plant samples. The LTER Program has a full wet chemistry lab for processing soil, water, and gas samples, including a Buck Scientific Model 610 gas chromatograph, a Perkin-Elmer AA, a Technicon Model 306 autoanalyzer, a Dionex DX-100 ion chromatograph, a Shimadzu TOC-5050A total organic carbon analyzer, and a Theromoquest NC-2100 C and N analyzer. The Sevilleta also maintains a GIS lab for image processing and analysis.

The Sevilleta Education and Research Facility **(**SERF) at the Sevilleta Field Station was completed in 2008. It contains approximately 20,000 square feet and houses four laboratories for research and training in areas ranging from molecular ecology and evolution to animal and plant physiological ecology and systematics. The building contains a large conference room (capacity 80-100), a second room that doubles as a dining and conference room, a suite of three rooms for specimen handling and collections, and support rooms.

In addition to SERF, the Field Station has the following existing resources: (1) A 3000 square-foot facility that once served as our major laboratory building, but which has been renovated to increase housing. This building also has a 1220 square-foot conference room. (2) A 2,100 square-foot classroom and library with collections of books and journals on ecology, geology, climatology, and soils. The classroom portion of this building was created by recent renovations that resulted in the visitor computer-pods being moved from this building to office space in SERF. (3) A 1,500 square-foot laboratory is used for plant studies and as a staging area for construction and configuration of small equipment items employed in field studies. This laboratory has deionized and ultra-pure water, including a 100-gallon storage tank for purified water. It is also equipped with a wide variety of power-tools and construction equipment. (4) A 1,200 square-foot storage building houses research equipment, supplies and tools.

The Sevilleta Field Station has a long-term commitment to providing state-of-the-art computing resources for visiting researchers and educators by means of broadband internet connectivity, provision of wireless coverage and wireless data transmission over significant portions of the Sevilleta National Wildlife Refuge (SNWR) and Station facilities, as well as on-site server and desktop computing. The Field Station will be connected to Lambda Rail and will provide 100 mbps data transmission starting in summer 2012.

Sevilleta's network infrastructure extends beyond the SFS facilities by way of a wireless network that covers extensive portions of the Sevilleta NWR and beyond. There are now two 25+ km wireless backhaul links from the field station to the crest of the Los Piños Mountains along the eastern border of the Refuge. At the Los Piños repeater sites, 2.4 GHz 802.11b/g access point radios serve to cover the entire McKenzie Flats region of the Refuge on the west side of the mountains and the valley on the east side. Two additional repeater sites located on the Refuge serve areas, such as the Rio Grande bosque, that do not have line-of-sight to the Los Piños. The existing refuge wireless network serves thirty individual research sites ranging from meteorological stations, flux towers (SEON) and wildlife monitoring webcams to MRME and WENNDEx manipulative experiments. These sites, powered by solar panels and batteries, possess 2.4 GHz 802.11b/g client radios and serial-to-ethernet converters connected to Campbell data loggers. Some sites also have webcams for real-time monitoring of weather, wildlife or scientific infrastructure. This network continues to grow and was recently expanded to include flux towers 30 and 50 km east of the refuge, near the towns of Mountainair and Willard.

The field station utility infrastructure was recently upgraded substantially in conjunction with the construction of SERF. Upgrades included new electrical lines with three-phase underground feed, construction of a 50,000 gallon water storage tank fed by a dedicated deep well, and a new septic system and drain field. All laboratories are now provided with purified water for research. All residences are equipped with reverse-osmosis units with delivery at kitchen sinks for drinking and cooking. A reverse-osmosis system is being installed in the SERF building in the spring of 2012.

The Sevilleta Field Station has eight comfortable three bedroom, two bathroom houses, two five bedroom, two bath houses, and additional sleeping and dining quarters in the original lab building which was converted to dormitory space. Each house and the former lab are equipped with full kitchens (pots, pans, dishes, cutlery, etc), dining and living areas.

Both the UNM campus and Field Station have extensive computer capabilities for data analysis and storage. The Sevilleta LAN on campus consists of approximately 150 Windows, Linux, Macintosh, and Solaris servers and clients. SEV servers host email, web, database, license, file, anti-virus, domain, backup, dial-up, and firewall services. The LAN is connected to the internet via the UNM campus Gigabit backbone.

SEV has three 802.11b/g wireless networks. The first serves the primary SEV offices on the UNM main campus. The second serves the entire Field Station. The third, a field-based wireless network, consists of a sixteen mile wireless backbone link from the Field Research Station to the top of the Los Piños mountains on the east side of the Sevilleta National Wildlife Refuge. Two access point radios on the mountaintop communicate with client radios at field research sites in order to facilitate real-time wireless transmission of data from these sites back to the SRFS.

UNM fully supports the LTER project with the availability of the following administrative positions: Project Manager, Climate Czar, and Information Manager to ensure the program meets its staffing needs. These professional positions are available on an as needed basis to provide consultation, assistance, analysis, maintenance, guidance and professional expertise. In addition, UNM provides administrative support and office capacity for SEV staff both on the UNM campus and at the Sevilleta Field Station. The CERIA building on campus houses all LTER personnel except Lab Manager John Craig (Biology Annex) and PI Collins (Castetter Hall). Wet and dry labs are located in the Biology Annex adjacent to Castetter Hall. The Field Station has office and laboratory space for SEV researchers in SERF. The Field Station also has a library with many current journal subscriptions, and common areas for formal and informal interactions. The Field Station and SEV LTER share administrative services when appropriate.

The Sevilleta Field Research Station provides the following for the LTER project: residence space for field crew members and senior staff during field sampling campaigns; 4X4 vehicles for access to field study sites; storage space for equipment and supplies used in the project; access to computers and databases related to the project; and other miscellaneous equipment as needed. The US Fish and Wildlife Service (FWS) and UNM share shop facilities (including tools for wood- and metal-work projects) in support of field research operations. FWS personnel also maintain roads on the Sevilleta refuge, and provide maintenance of cattle fences and law enforcement security.

IV. DATA MANAGEMENT PLAN:

The Sevilleta LTER Information Management System (SIMS) aims to support LTER science at both the site and network levels. At the site level, the goal of SIMS is to provide high quality, well-documented, easily discoverable and accessible data and other information products from the SEV web site. At the network level, the goal is to harvest rich metadata and data into the LTER Network Information System (NIS). SIMS currently meets all standards described in the LTER Network's Review Criteria for Information Management Systems (LTER 2009b). During LTERIV, SIMS streamlined data management workflows for several core long-term research projects, developed strategies to process and archive sensor data, and implemented a new metadata management system. As the needs of LTER scientists and the LTER NIS evolve, SIMS will continue to adopt new technologies and standards that improve the quality of SEV data and metadata, and the efficiency of data collection, processing and contribution to the NIS. During LTERV, SIMS will emphasize support for streaming sensor data, production of NIS-ready EML, and implementation of an enterprise-level geodatabase.

Information Management System Design

Scope: At the core of SIMS are long- and short-term datasets collected by SEV scientists and graduate students. SIMS data are frequently downloaded from the SEV web site by a variety of users, usually by individuals in academia but also by members of government or private research programs and K-12 teachers or students (Table 1). Other information, including a comprehensive GIS, proposals, annual reports, presentations, publications and an extensive photo archive are also available online (http://sev.lternet.edu/). SIMS adheres to the LTER Network Data Policy and makes core data and metadata publicly accessible within two years of collection, and in many cases much sooner. SIMS has produced rich metadata since project inception, and has generated structured Ecological Metadata Language (EML) since 2004, when EML became an LTER standard. SIMS contributes Level 5 EML (containing identification, discovery, access, integration, and attribute information) to the LTER Network Office (LNO) centralized metadatabase (Metacat).

Data Policy: The SEV Data Access Policy is consistent with the LTER Network's Data Policy and uses the same Type 1 and Type 2 terminology. With few exceptions, SIMS data are Type 1, freely accessible from the web site within a maximum of two years of collection. Data collected by graduate students are considered Type 2, and access is restricted until the student publishes or permits the data to be made public.

Metadata: SEV believes strongly in participating in cooperative efforts to build tools that can be used at multiple sites, both because of the economy of scale and because it increases the consistency of products such as EML. Since 2010, SIMS has undergone a significant change in metadata management through collaboration with IMs from NTL, LUQ, PIE, ARC, VCR, MCM, NWT and JRN in the development of the Drupal Ecological Information Management System (DEIMS) (San Gil *et al.* 2010). Drupal, an open source content management system, was used to develop a web-based EML editor. This new editor is more user friendly than previous SIMS tools. SIMS metadata, which were either in text files or an MS Access database, have been migrated to the MySQL database that is part of DEIMS. By pooling IM supplement funds, the DEIMS group hired a PHP programmer to write a script that generates EML 2.1 from the metadata in the DEIMS database. The script also dynamically generates an EML harvest list that facilitates ingestion of site EML into the LNO Metacat. Having all metadata in a relational database is a major advance for SIMS, as is having an automated tool to generate EML 2.1 and the EML harvest list. SIMS is well positioned to contribute EML to the LTER Network's Provenance Aware Synthesis Tracking Architecture

(PASTA), the framework being developed for harvesting and archiving all LTER site data and metadata into the NIS.

Use of DEIMS has greatly improved the efficiency of SEV metadata management and the quality of EML being supplied to NIS. During metadata migration into DEIMS, SIMS team members had the opportunity to update units so that they conform to the LTER Standard Unit Registry (Kortz *et al.* 2009). Datasets were also inspected at this time to ensure agreement between the names and the order of attributes found in metadata and data, a requirement for generating EML for the NIS.

IT Resources: SIMS hardware is comprised of three Oracle Sun Fire X4140 servers that support science and information management. One server supports web services and MySQL database while a second server handles email functions and runs scripts that backup SIMS servers via a Dell PowerVault 124T Tape Autoloader. The third server handles SIMS authentication via LDAP and will soon be replacing a 12-year old Sun Microsystems E450 as the primary file server. A new and powerful Dell Precision T7500 Windows-based GIS server was purchased with IM supplement funds in 2011. This server will provide enterprise-level geodatabase services based on ArcGIS 10 for Server technology and greatly increase storage capacity for spatial datasets. A wireless network at the Sevilleta NWR transmits sensor data to a server at the Sevilleta Field Station, from which it is harvested to campus via a 10 Mbps connection.

SIMS data protection occurs at multiple levels. First, SIMS servers reside behind a SonicWALL Pro 3060 Firewall. Second, storage space on all SIMS servers is backed by RAID 5 in order to provide data redundancy in the event of hard drive failures. Third, data are incrementally backed up to tape on a daily basis and full backups are performed once a week. The most recent set of full backups is stored offsite. Backups are kept for three months before being rotated out. Quarterly backups for the past year and a permanent annual backup are stored in a fireproof vault. Approximately 1 TB of redundant, backed-up storage space is available to SIMS users.

Human resources: The SIMS team consists of a 1 FTE Information Manager, a 0.5 FTE systems administrator, a 0.5 FTE GIS analyst, and part-time help from four 1.0 FTE Field Crew Members. In addition to providing oversight for day-to-day data management, the IM ensures that SIMS is developing or adopting the tools and standards needed to produce data products compliant with LTER NIS requirements. The systems administrator provides software and hardware support to all SEV staff and numerous graduate students and scientists, and maintains security and functionality of the SIMS database, web, and email servers. The Field Crew are responsible for data entry and QA/QC of long-term core datasets as well as metadata updates. Through IM supplements we have hired student programmers for part-time assistance over the last six years. The programmers generated code to support QA/QC of core datasets and production of EML. The GIS analyst manages all SIMS spatial data and assists researchers with spatial analyses. To guard against knowledge loss in case of personnel turnover, SIMS maintains frequently updated wiki pages that describe how critical system administration and IM tasks are accomplished.

Data Processing and Archiving
Core data: Core SEV datasets are those that are collected by SEV staff, and are generally long-term in nature. The SEV IM works very closely with SEV's research scientists to ensure that datasets are well-documented, high quality, and available in accordance with LTER Network Data Policy. Many of the core datasets are collected on hand-held computers and archived using Perl programs that efficiently QA/QC the data and upload them to a MySQL database. The Perl programs check the accuracy of species codes, detect missing data, and confirm the reasonableness of measurements. The core datasets are at the heart of many SEV analyses, and making them accessible online is a high

priority. A new version of each dataset is generated every year as data are added. The most recent versions of SEV datasets are available from the SEV web site as comma-delimited text files, and older versions are archived in the file system. Data management procedures are documented on wiki pages, which are actively maintained by all members of the IM team.

Environmental sensors are used to collect data from SEV research projects MRME and WENNDEx. These high-volume, high-frequency data are transmitted wirelessly to a server at the Sevilleta Field Station every few hours. Until the wildfire that interrupted these studies, the data were automatically ingested in to a MySQL database, range-checked, merged with plot and treatment information, and then archived as comma-delimited text files for download from the web site. More sophisticated software is now being implemented to manage data streams from the newly designed and installed sensor arrays in these long-term experiments (see *Future Projects*).

Non-Core Data: In order to obtain non-core datasets, the SEV IM remains aware of students and scientists working at the Sevilleta NWR so that they can be apprised of the LTER data sharing policy and procedures for submitting data and metadata. For example, each year 8-10 graduate students receive Summer Fellowships to work at SEV. These students sign a written agreement to submit their data to SIMS, and they do not receive stipends until they have created metadata describing their research. An MS Word metadata template is supplied to all researchers, and they are requested to submit data in spreadsheet or ASCII format. Email prompts are sent to all LTER researchers until data and metadata are received. QA/QC of non-core datasets is the responsibility of the researcher, but the SEV IM consults with researchers to ensure that data submissions are appropriately described, structured and formatted. Incentives for scientists to contribute data include the promise of safe, long-term storage and submission to the NIS to increase visibility and reuse. The process of obtaining non-core datasets will be formalized in LTERV with the implementation of the Project Database (see *Future Projects*).

Web Site: Considerable effort over the last two years has gone toward migrating the SEV web site to a new Drupal format that improves discovery of, and access to, SEV data products. Design of the new web site follows the LTER Website Design and Content Guidelines (LTER 2009a). The Drupal web site is much easier to manage than the previous site. Tasks that were programming-intensive, such as building queries for content, are now readily accomplished within the Drupal GUI. Drupal has a module for managing publications that simplified this process at SEV and also offers an improved query interface. Because the back-end of the web site is a database, it is easy to cross-link content to display, for instance, individual projects and their related personnel, datasets, and publications. Importantly, the DEIMS EML editor is integrated into the web site, and the SEV web site is becoming the portal for SEV information management.

SIMS will exploit other Drupal features to enhance the user experience as the web site evolves. Drupal uses taxonomies to link content together to improve navigation to related information, and SEV taxonomies will be defined. The LTER Controlled Vocabulary (Porter 2010) has already been imported into the Drupal taxonomy framework, and datasets will soon be tagged with these standard keywords. This will make SEV data easier to find both on the SEV web site and the centralized NIS, which has a tool for querying data based on terms in the LTER Controlled Vocabulary. The SEV web site also takes advantage of the Data Access Server (DAS), a service created by NIS developers to capture information about a user before they download data. Use of this centralized system means one less custom function for SIMS personnel to maintain.

Network Level IM Activities:
SEV IM and LTER Co-PI Kristin Vanderbilt has been involved in network level IM activities and has also participated in IM outreach efforts. She served on the Network Information Management

System Advisory Committee (NISAC) from 2006 to 2010 and has participated in working groups on the LTER Controlled Vocabulary and DEIMS, as well as the Metadata Management Suite Tiger Team in support of NIS development. She also served as the chair of the International LTER (ILTER) Information Management Committee from 2006-2010. She has co-taught information management workshops for diverse audiences in the US and internationally, and as a member of the DataONE Community Education and Engagement Working Group is developing information management education modules. She has also participated in workshops to advance the development of an IMS for the ILTER (Vanderbilt *et al.* 2010), and build tools to facilitate synthetic science (Lin *et al.* 2011). She has served on three LTER site review teams in recent years.

SIMS regularly contributes to the following LTER Network databases: 1) PersonnelDB, 2) LTER Data Portal, 3) SiteDB, and 4) All-Site Bibliography. SEV contributes data from ten meteorological stations to ClimDB on a weekly basis.

Future Projects:

Management of Sensor Data: SIMS will adopt new methods for managing the high volume, high frequency sensor data that is being collected at SEV. QA/QC of these data has consisted of range-checking, but more sophisticated quality assurance can now be done using the GCE Data Toolbox for Matlab (Sheldon 2008), which SIMS is implementing. This software also facilitates visualization and analysis of streaming sensor data, and will be used directly by SEV scientists for this purpose. The SEV IM received funding through an IM supplement to participate in a workshop at GCE in early 2012 to learn to use this tool. Additionally, DataTurbine, an open source real-time streaming data management tool (Fountain *et al.* 2009), is being implemented to facilitate visualization of the data to improve response time to malfunctioning instruments in the field. Finally, per discussions at the October 2011 SensorNIS workshop, factors such as sensor relocation, calibration, and deployment events need to be tracked in sensor metadata. The SEV IM will collaborate with the SensorNIS group to articulate how best to capture sensor metadata.
Milestone: Implementation of tools for sensor data management by mid-2012.
Deliverable: Well documented, quality assured sensor data.

Generate NIS-ready EML: DEIMS currently produces schema-valid EML 2.1, but the content of the EML from SEV does not conform entirely to the new version of EML Best Practices for LTER Sites (LTER 2011). SEV will continue to collaborate with the DEIMS working group to improve the EML-generating script so that it meets Best Practices criteria. DEIMS will also incorporate the LTER Unit Dictionary into the metadata editor so that DEIMS-generated metadata conform to this standard. In addition, SEV EML will be assessed for quality using the newly developed EML Congruence Checker. "Dataset congruence" refers to agreement between a data entity and its EML metadata, and reflects the degree to which EML-described data can be automatically loaded and used by a workflow program such as Kepler. SEV metadata that conform to Best Practices and pass the tests in the congruency checker will yield metadata ready to be ingested into PASTA, which will be in production in 2014.
Milestone: System for generating EML that conforms to LTER Best Practices and meets congruency requirements by 2014.
Deliverable: EML ready to be used by the PASTA architecture.

GIS: In keeping with recommendations from the 2009 SEV Site Review Team, SEV is investing in technician time, hardware and software to further manage and develop our valuable spatial data catalog. A new Windows Server (Dell T7500) supports ArcGIS 10 Server technology, allowing SEV to efficiently bring existing remote sensing and vector datasets to GIS IM standards both in terms of data integrity (QA/QC) and EML-ready FGDC metadata to be harvested into NIS. Furthermore, SEV

can now develop and deploy an enterprise-level geodatabase and GIS web services to be made available to the public via the SEV web site and to the SEV LTER community over the Local Area Network. Such a centralized geodatabase makes it possible for SEV to maintain integrity of spatial data while providing multi-user access and editing. SEV GIS data, which are now only accessible as downloadable .zip files, will be migrated into the geodatabase. As site science (i.e., SEON) directs the acquisition of new remote sensing datasets, SEV GIS can now provide storage and archival services to accommodate exceptionally large datasets such as LIDAR DEM and Rapid Eye high resolution satellite imagery. Finally, SEV will continue to participate at the network level to develop GIS web services and NIS-ready spatial datasets.
Milestone: Deployment of ArcGIS 10 Server geodatabase and expansion of GIS archive – ongoing.
Deliverable: Readily accessible archive of well-documented SEV GIS and remote sensing data.

Project Database: The 2009 SEV Site Review Team suggested that SEV needs to develop a formal process for adding new projects to SIMS so that all PIs can be aware of new research and project tracking can be enhanced. SIMS will develop a protocol for adding new research projects to the database, and for tracking project status, personnel, and products. This will help ensure that project reports and data are submitted in a timely manner, and that the SEV IM can be involved in designing data management protocols for projects, when needed. A web-based user interface will be developed to allow easy entry of project information into the SIMS DEIMS framework.
Milestone: Development of a system for adding project information to SIMS and for tracking project status by 2015.
Deliverable: Web-based tool for tracking all SEV LTER projects and related information.

Archive Model Information: In LTERV, SEV researchers will be utilizing simulation models. SIMS will need to support management, documentation, and archiving of model code and related data. SIMS will adopt existing protocols for this task, or will work with other LTER IMs to define methods for managing such information.
Milestone: SIMS strategy for managing model code and model inputs and outputs by 2017.
Deliverable: Publication of SEV model information on the SEV web site.

Table 1. Number of unique data access sessions on the SEV web site per category of user from 2004 to 2011. More than one dataset may have been downloaded per session. About 30% of users in the "University Research" category indicated they needed data for a class project.

Type of Institution	Year							
	2004	2005	2006	2007	2008	2009	2010	2011
Education (K-12)	50	29	9	3	6	4	10	2
University Research	127	135	108	141	112	143	140	146
Government Research	23	15	7	8	6	14	6	10
Other Research	15	11	4	9	7	3	1	1
Other	18	8	5	5	6	5	10	9
Total	233	198	133	137	137	169	167	168

Postdoc Mentoring Plan:

N/A

TITLE	SEV_ID	PI	Long-Term?	Grad Student?
[Sevilleta LTER Meteorology Data, 1988-2011](#)	001	Moore	LT	
[Precipitation Chemistry](#)	002	Moore	LT	
[Lightning Strike Data for New Mexico, 1986-1999](#)	003	Moore	LT	
[Plant Line-Intercept Transects](#)	004	Collins	LT	
[Pinon Branch Demography Study: 1989-1993](#)	006	Marshall		
[Plant Water Potentials/Plant Physiology](#)	007	Wisdom		
[Small Mammal Mark-Recapture Population Dynamics at Core Research Sites](#)	008	Friggens	LT	
[Reptile Populations](#)	009	Snell		
[Plant Litter Decomposition](#)	012	White	LT	
[Rodent Parasites](#)	013	Duszynski	LT	
[Burn Exclosure Rodent Population Study (1991-1993)](#)	015	Parmenter		
[Bird Community Assessment](#)	017	Parmenter		
[Litter Fall Collection Data](#)	022	Parmenter		
[Rabbit Survey](#)	023	Parmenter	LT	
[Creosote Plant Dimension Study: 1989-2008](#)	024	Moore	LT	
[Pinon-Juniper Plant Dimension Study: 1989-1999](#)	025	Gosz		
[Creosote Branch Demography Study:1989-1993](#)	026	Marshall		
[Grass Demography Study: 1989-1993](#)	027	Moore		
[Juniper Branch Demography Study: 1989-1993](#)	028	Marshall		
[Ground Arthropods](#)	029	Lightfoot	LT	
[Sierra Ladrones Study Basin (SLSB) Sediment Micro Climate](#)	047	Molles		
[Plant Phenology Transects: 1991-1995](#)	048	Evans		
[Coyote Scat Survey](#)	049	Parmenter	LT	
[Master Plant Species Information Database](#)	051	Lowrey		
[Temporal Dynamics of Soil Carbon and Nitrogen Resources at Five-Points Grassland-Creosote Ecotone](#)	052	White		
[Ocotillo Plant Dimensions](#)	054	Gosz		
[East-West C3-C4 Grassland Biomass Fertilizer Plots](#)	055	Gosz		
[Soil Surface Dynamics](#)	065	White	LT	
[Time Domain Reflectometry (1996-2005)](#)	078	Gosz	LT	
[Bowen Ratio Evapotranspiration Data 1996-1999](#)	079	Gosz		
[Water Balance Modeling Project: Vegetation Plots Data (1995-1998)](#)	081	Milne		
[Deep Well Burn Line-Intercept Vegetation Transects](#)	084	Moore	LT	
[Small Mammal Exclosure Study (SMES) Ant Data](#)	088	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Rabbit Feces Data](#)	091	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Termite Mud Casing Data](#)	092	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Cryptogamic Crust Data](#)	094	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Vegetation Line Intercept](#)	095	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Leaf Litter Study](#)	096	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Vegetation Data](#)	097	Lightfoot	LT	
[Small Mammal Exclosure Study (SMES) Surface Soil Disturbance](#)	099	Lightfoot	LT	
[Long-Term Core Site Grasshopper Dynamics](#)	106	Lightfoot	LT	
[Multi-temporal TM-NDVI Vectors at Rodent Webs](#)	107	Parmenter		
[Desertification/Bureau of Land Managment (BLM) Transects](#)	109	Parmenter	LT	

Coyote Population Densities	112	Parmenter	LT	
Core Site Net Primary Productivity (NPP) Study	129	Muldavin	LT	
Long-term Dynamics in Soil Field Available Nitrogen and Potentially Mineralizable Nitrogen in a Desert Grassland	134	White	LT	
Pollinator Monitoring Study	135	Wetherill	LT	GS
Core Site Phenology Study	137	Wetherill	LT	
Effects of Kangaroo Rats on Plant Species Dominance	144	Peters		
Ecological Effects of Prescribed Fire in Desert Grassland	146	White		
Rainfall Manipulation Study Vegetation Data	147	Pockman	LT	
2003 Prescribed Burn Effect on Grasses and Shrubs - Grass Recovery Study	148	Muldavin	LT	
Phosphorus Fractions in Grassland and Shrubland Soils	149	Cross		GS
Snakeweed Patch Soils Data	150	Moore	LT	
Snakeweed Patch Vegetation Transect Data	151	Moore	LT	
Soil Nutrient Distributions in Grassland and Shrublands	152	Cross		GS
15N Tracer Study in Grassland and Shrubland: 1989-2002	153	Cross		GS
Hydraulic Constraints on Two Life History Stages of Larrea tridentata	154	Medeiros		GS
Fertilizer Net Primary Productivity (NPP) Study	155	Collins	LT	
Burn Net Primary Productivity (NPP) Study	156	Collins	LT	
Net Primary Productivity (NPP) Weight Data	157	Collins	LT	
Ocotillo Plant Demography, 2003	158	Redfern		GS
Livestock Exclosure Nutrient Study	159	Zeglin		GS
Allometric Ant Foraging Data 2003	160	Moses		GS
2003 Prescribed Burn Effect on Grasses and Shrubs -- Shrub Recovery Study	164	Pendleton		
2003 Prescribed Burn Effect on Grasses and Shrubs - Fuel Load Study	165	Muldavin	LT	
2003 Prescribed Burn Effect on Grasses and Shrubs -- Species Composition Study	166	Muldavin	LT	
Recovery of Vegetation Following Disturbance: Plant Removal Study.	168	Peters	LT	
Pino Gate Prairie Dog Study: Landscape Plot Lizard Data	173	Davidson		GS
Root Ingrowth Donuts	175	Collins	LT	
Warming Net Primary Productivity (NPP) Study	176	Collins	LT	
Pino Gate Prairie Dog Study: Mound-Scale Lizard Data	177	Davidson		GS
Livestock Exclosure Study: Plant Species Composition	178	Collins	LT	
Rio Grande Water Chemistry Data	180	Van Horn		GS
Warming Experiment Temperature Data	181	Collins	LT	
Seasonal Biomass and Seasonal and Annual NPP for Core Research Sites	182	Muldavin	LT	
Warming Experiment Soil Moisture Data	183	Collins	LT	
Livestock Exclosure Study: Aboveground Standing Crop	184	Collins		
Seasonal Biomass and Seasonal and Annual NPP for Burn Study Sites	185	Collins	LT	
Seasonal Biomass and Seasonal and Annual NPP for Fertilizer Study Site	186	Collins	LT	
ANPP Quadrat Sampling Data for Pinon-Juniper Site: 1999-2001	187	Collins		
Monsoon Rainfall Manipulation Experiment (MRME) Net Primary Productivity (NPP) Study	188	Collins	LT	

[Pinon-Juniper Dendrometer, Height, and Crown Area Measurements at Cerro Montosa](#)	189	Muldavin	LT	
[Rio Grande Sonde Data](#)	190	Van Horn		GS
[Monsoon Rainfall Manipulation Experiment (MRME) Meteorology Data](#)	191	Collins	LT	
[Pino Gate Prairie Dog Study: Landscape Plot Vegetation Data](#)	193	Davidson		GS
[Pino Gate Prairie Dog Study: Mound-Scale Vegetation Data](#)	194	Davidson		GS
[Pino Gate Prairie Dog Study: Landscape Plot Ground-Dwelling Arthropod Data](#)	195	Davidson		GS
[Pino Gate Prairie Dog Study: Mound Scale Ground-Dwelling Arthropod Data](#)	196	Davidson		GS
[Pino Gate Prairie Dog Study: Landscape Plot Grasshopper Data](#)	197	Davidson		GS
[Pino Gate Prairie Dog Study: Mound-Scale Grasshopper Data](#)	198	Davidson		GS
[Discontinued Plant Line-Intercept Transects](#)	200	Gosz	LT	
[Point-Quarter Distance and Dimension Measurements to Calculate Shrub Density and Estimate Shrub ANPP](#)	201	Muldavin	LT	
[Point-Quarter Harvested Plant Weight Measurements to Estimate Shrub ANPP](#)	202	Muldavin	LT	
[Larrea Seedling Monitoring Study](#)	203	Moore	LT	
[Tree Mast Production](#)	204	Moore	LT	
[Seasonal Biomass and Seasonal and Annual NPP for the Warming Study](#)	205	Collins	LT	
[Seasonal Biomass and Seasonal and Annual NPP for the Monsoon Study](#)	206	Collins	LT	
[Pinon-Juniper Overstory Density, Cover and Biomass Data at Cerro Montosa](#)	207	Muldavin	LT	
[Effects of Herbivores on Seed Banks](#)	209	Koontz		GS
[The Burden of Reproduction in Lizards: Changes in Respiratory Physiology Associated with Reduced Lung Volume](#)	211	Gilman		GS
[Gunnison's Prairie Dog Reintroduction Study: Vegetation Cover Data](#)	212	Friggens	LT	
[Gunnison's Prairie Dog Reintroduction Study: Vegetation Standing Crop Data](#)	213	Friggens	LT	
[Ground-Truthing Satellite Imagery with Phenological Observations: Visual Observations](#)	214	Vanderbilt		
[Monsoon Rainfall Manipulation Experiment (MRME) Soil Moisture Data](#)	223	Collins	LT	
[Monsoon Rainfall Manipulation Experiment (MRME) Carbon Dioxide Data](#)	224	Collins	LT	
[Monsoon Rainfall Manipulation Experiment (MRME) Soil Temperature Data](#)	225	Collins	LT	
[Population Ecology of Banner-Tailed Kangaroo Rats (Dipodomys spectabilis)](#)	228	Edelman		GS
[Effects of Multiple Resource Additions on Community and Ecosystem Processes: NutNet ANPP Quadrat Sampling](#)	231	Collins	LT	
[Snakeweed Patch Vegetation Quad Data](#)	233	Moore	LT	
[Hobo Precipitation Data](#)	234	Moore	LT	

V. SITE MANAGEMENT.

An initial objective of the LTER Network was that long-term, site-based research with a stable funding base would be managed to accommodate and plan for changes in leadership and personnel (Hobbie *et al*. 2003). We have in place a management structure to organize our site-based activities, accommodate change, and meet our obligations to NSF and the LTER Network. Our system is flexible to foster and encourage scientific creativity among participants. We strive to retain key LTER personnel while at the same time adding new participants (see below). All of this occurs within a relatively broad but clearly articulated conceptual framework that guides our research program. SEV has successfully weathered adversity and dealt with change. A group of UNM faculty led by Jim Gosz developed the original proposal to establish the SEV LTER. When Gosz became State Project Director for EPSCoR, Cliff Dahm served as interim PI while UNM conducted a national search for a senior ecologist to serve as LTER PI. In March 2003 Collins was hired by UNM as a Professor of Biology and PI of SEV. Collins will remain PI through LTERV at which time leadership will likely change. A number of current UNM faculty members (e.g., Pockman, Sinsabaugh, Dahm, Litvak, Wolf) are all capable and willing to serve as PI. In addition, UNM will be hiring 3-4 ecologists (including a senior hire) over the next two years and it is likely that one of these new hires could provide intellectual leadership as well. Thus, we feel that we currently have a strong leadership team in place, as well as an extensive group of highly qualified faculty to assume leadership and guide our program in the future.

During LTERV, Collins will serve as the PI-of-record and primary LTER point-of-contact at the local (UNM) and Network (Collins is currently Chair of the LTER Science Council and Executive Board, and he led the LTER Network Planning Process from 2004-2007 [Collins *et al*. 2011]) levels. Collins is responsible for day-to-day administrative decisions, budgets, annual reports to NSF and FWS, supplement requests, and overall project management, integration and cheer-leading. Essentially, Collins deals with the day-to-day issues so that SEV scientists can concentrate on research. Collins is assisted by Project Manager Mike Friggens and Field Station Manager Jennifer Johnson. Friggens has administrative, data management, coordination and research duties. Jennifer Johnson serves as the main liaison between the SEV LTER and the SNWR Research Coordinator, Jon Erz. Whenever new experiments are planned or proposed, we immediately communicate with Erz both the scientific justification and the details of experimental protocols. Erz is also involved in site selection and permit approval processes for the SNWR. Finally, Collins is assisted by Rina Ouellette who maintains research budgets, creates reports, processes purchase orders and reimbursements, coordinates the hiring process, and keeps the books for the Sevilleta Field Research Station.

Co-PI's Dahm, Pockman and Litvak represent key habitat and conceptual emphases. They are responsible for scientific coordination and intellectual leadership in the riparian, grassland-shrubland, and woodland components of the SEV LTER, respectively. Co-PI Vanderbilt is our Information Manager with leadership responsibility for data management protocols and keeping the SEV LTER compliant with Network-level IM goals and objectives. Vanderbilt also plays a leadership role in the LTER Network having served on both NISAC and IM-Exec, and now serving as Co-Chair of the US membership in ILTER.

The SEV LTER Executive Committee is made up of lead PIs, senior scientists and staff members (see below). Currently, this group consists of Pockman, Litvak, Dahm, Vanderbilt, Sinsabaugh, Muldavin, Wolf, Natvig (who is also Sevilleta Field Research Station Director) and Moore (Staff representative), and this group serves as an advisory council and decision-making body for larger issues regarding personnel (current and new), equipment purchases,

new experiments, terminating research projects, supplements, etc. These interactions occur regularly during the academic year.

As part of our overall management plan, SEV has discontinued the following five projects for the following reasons. First, we ceased our annual sampling of the Small Mammal Exclosure Study, because no vegetation changes have occurred after 14 years, and the grassland plots were burned in the 2009 wildfire. We will maintain the exclosures and continue to sample these plots at 5-year intervals. Second, we stopped the cattle grazing experiment because the landowners cut the exclosure fences, and the land is slated for development. Third, we stopped sampling the line intercept transects installed in 1995 across a burned-unburned grassland boundary because we have other data sets measuring fire effects, including several of our long-term experiments that burned in 2009. Fourth, we have terminated our annual drought and rainfall addition experiment across the grassland to shrubland boundary. That 10-yr project, started in 2001, was originally designed for five years of treatment (Báez *et al*. *in revision*) followed by five years of recovery. The grassland plots burned in 2009. Finally, we stopped our pitfall trapping of ground-dwelling arthropods. Analysis of these data showed high variability and little useful information.

For LTERV we have recruited nine new members to serve as senior scientists. These individuals were chosen based on their knowledge and research history at SEV along with their expertise. New members include: Amy Powell (Sandia National Labs), Sujith Ravi (Postdoc U Arizona), Morgan Ernest (Assoc Prof, Utah State), Ethan White (Asst Prof, Utah State), Rodrigo Vargas (Asst Prof, U Delaware), Jose Herrera (Prof, Truman State), Andrea Porras-Alfaro (Asst Prof, Western Illinois), Tom Miller (Asst Prof, Rice U), Laura Turnbull (Junior Research Fellow, U Durham). Ravi and Turnbull are ecohydrologists who study the causes and consequences of shrub encroachment. Community ecologists Ernest and White will enhance our consumer research group with particular focus on small mammals. Vargas is a specialist in soil respiration. Herrera, Powell and Porras-Alfaro will enhance our expertise in belowground systems, metagenomics, microbial ecology and plant-microbe interactions. Miller studies plant-herbivore interactions, an area of need noted at our 2009 Site Review.

A challenge for all LTER sites is communication and information sharing, especially among individuals at other institutions. SEV uses a number of mechanisms to promote communication among participants. For day-to-day operations, SEV staff meet with Collins monthly to review on-going activities and set short-term priorities. An all-SEV LTER meeting is held on campus each month during the academic year for information sharing, updates, scientific presentations and discussions. Finally, we hold an annual SEV LTER Research Symposium and Pep Rally to share research results and ideas, and stimulate communication among LTER participants. The symposium includes posters and oral presentations and is held at the SNWR so that FWS staff can take part, as well. This symposium is attended by SEV LTER scientists and representatives from state and federal agencies. In 2008 SEV hosted a regional all-Scientists meeting (SEV, JOR, CAP, NWT, SGS) to promote cross-site communication and integration. We propose to host regional All-Scientist meetings once every three years to maintain regional integration. This 3-yr cycle allows sites to have a site-specific meeting in one year, a regional meeting in the next year, and attend the LTER All Scientists meeting in the third year. To keep as many personnel informed as possible, we use email lists to share relevant information (funding opportunities, successes, proposals submitted, meeting announcements, minutes of EB and SC meeting, newsletters, etc). Also, PI Collins sends out pdfs and summaries of all SEV publications every 2-3 months to the SEV listserv to increase awareness of SEV research activities and products. Finally, in keeping with our management philosophy, "take what you do seriously

but don't take yourself seriously," we have many research discussions through informal interactions in offices, hallways, restrooms, parties, parking lots, and local bars.

Because much of our research occurs at SNWR, we do not control access to our site. When contacted, we facilitate interactions between potential new investigators and FWS staff. An important mechanism we use to increase the diversity of SEV research and researchers is our Summer Fellowship program. Summer stipends are open to UNM and non-UNM graduate students and are awarded competitively based on a research proposal relevant to the overall goals of the SEV LTER. This program is coordinated by Field Crew boss Amaris Swann. Most summer students help to mentor REU students and they are required present results from their work at the annual SEV Research Symposium. To increase the number of students supported over time, students can receive support for no more than two summer sessions.

Currently, the Sevilleta LTER does not have an external advisory committee but we will establish one by fall 2012 so that committee members can attend our annual Research Symposium held in January. This Committee will be made up of a member from a regional LTER site, an FWS staff member, and an information manager. Our external advisory committee will meet every other year to advise us on scientific progress, overall integration, and serve as a sounding board for our mid-term site review, which would be scheduled for the summer 2015. We will share with them the panel summary and reviews of this proposal, annual reports and other relevant information.
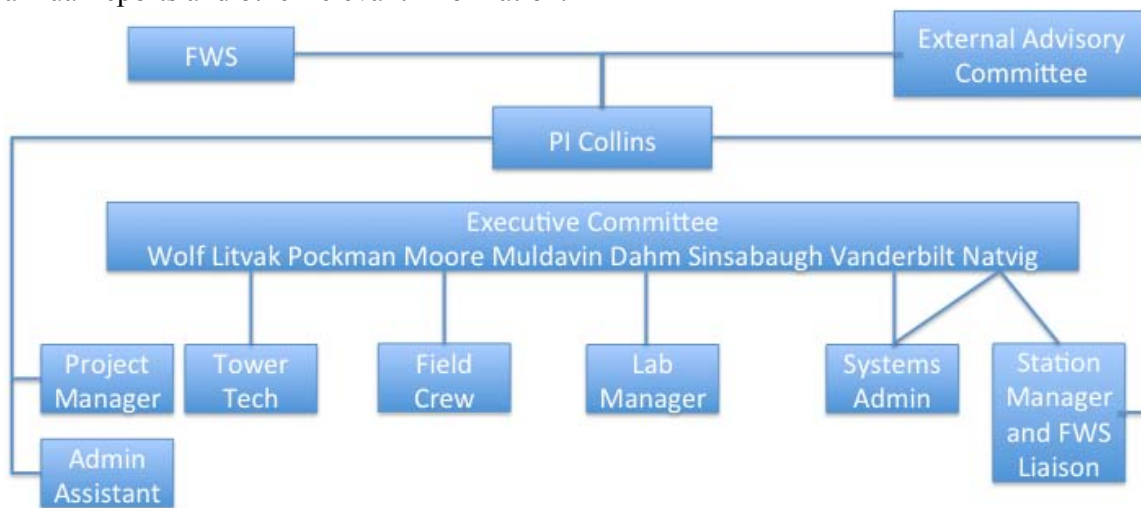
Key research team members:

Climate	Water Fluxes	Biogeochem. & Soils	Microbial	Producers	Consumers
Dahm	Collins	Allen	Allen	Collins	Brantley
Gutzler	Dahm	Collins	Herrera	Ford	Cook
Litvak	D'Odorico	Dahm	Natvig	Lowery	Friggens
Moore	Turnbull	Wainwright	Porras-Alfaro	Muldavin	Lightfoot
D'Odorico	Litvak	Litvak	Powell	Peters	Wolf
Wainsright	Pockman	McFadden	Sinsabaugh	Pendleton, B	Ernest
	Ravi	Meyer		Pendleton, R	White
	Small	Sinsabaugh		Vanderbilt	Miller
	Parsons	Vargas		McDowell	Parmenter
	Small	Ravi			Finch