Global change effects on grass-shrub interactions in an arid ecosystem

297,494    36 07/01/05

Joseph E Fargione PhD 2004 505-277-8119 fargione@unm.edu
Scott L Collins PhD 1981 505-277-6303 scollins@sevilleta.unm.edu
William T Pockman PhD 1996 505-277-2724 pockman@unm.edu
Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 04-23. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution’s expenditure of any funds under the award, in accordance with the institution’s conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix C of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☑

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix D of the Grant Proposal Guide.

Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, “Disclosure of Lobbying Activities,” in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE

NAME Rosa Gonzalez

SIGNATURE Electronic Signature

DATE Jan 10 2005 5:46PM

TELEPHONE NUMBER 505-277-7575

ELECTRONIC MAIL ADDRESS rosag@unm.edu

FAX NUMBER 505-277-4185

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.
GLOBAL CHANGE EFFECTS ON GRASS-SHRUB INTERACTIONS IN AN ARID ECOSYSTEM.

Humans are causing significant global environmental changes, including climate change, nitrogen (N) deposition, and invasion of woody species into grasslands. Although each of these factors has major impacts on plant community composition, it is not known how these factors will interact to affect ecosystem dynamics in the future. Furthermore, although arid and semi-arid systems cover approximately a third of the earth’s surface, few experimental warming studies have been conducted in these systems. We propose a multi-factorial global change field experiment in an arid grassland community at the ecotone between shortgrass prairie and desert grassland, which is undergoing shrub encroachment. Specifically, our experiment will simulate predicted future environmental conditions with increased nighttime temperatures, N deposition, and El Niño frequency (which increases winter precipitation by 50% at our field site). These are all ongoing changes both globally and locally that may influence community composition. Our study includes three dominant species, all of which are near their range margins and may be particularly responsive to the effects of climate change. We hypothesize that warmer summer temperatures and increased evaporation will favor growth of the desert grass black grama (Bouteloua eriopoda), but that increased winter precipitation and/or available nitrogen will favor the growth of the shortgrass prairie grass blue grama (Bouteloua gracilis). Furthermore, we hypothesize that growth and survival of introduced seeds and seedlings of the shrub creosote (Larrea tridentata) will be favored by increased winter precipitation, N addition, and warmer temperatures. Thus, the direct effects of these factors favor different species. Because it is unknown how these factors will interact, the net outcome of these perturbations is not easily predicted. We will measure treatment effects on limiting resources (soil moisture, nitrogen mineralization), species growth (photosynthetic rates, creosote shoot elongation), and species abundance (aboveground biomass harvests of grasses and allometric biomass estimates of shrubs) to determine the interactive effects of three key global change drivers on plant community dynamics in an aridland ecosystem.

Intellectual Merit: Interactions among global change drivers are the largest source of uncertainty in global change research. Our study will determine how N deposition and winter precipitation interact with warming to alter community composition at an ecotone. In addition, our study is novel in several important ways. First, we apply a recently developed low-disturbance approach to imposing nighttime warming, more accurately mimicking warming patterns than most previous studies. Second, no manipulative studies of global change have focused on plants at their range margins, which are predicted to be more responsive to changes in climate; our study site occurs at the range margins of three dominant species. Third, the effects of global change in arid and semi-arid lands are relatively poorly studied; our study site would be the hottest, driest site of a warming experiment to date, expanding knowledge of the effects of warming in arid systems.

Broader Impact: Our study addresses several issues with important policy and economic consequences. Specifically, our study will predict the effect of climate change on two dominant and economically important forage grasses and their susceptibility to shrub invasion. The invasion of creosote into shrublands is associated with a decrease in forage value, and increases in carbon sequestration and nitrogen leaching, with implications for ranching, climate change feedbacks, and water quality. UNM is a minority-serving institution and we will endeavor to include members of underrepresented groups in our research via an ongoing UMEB Program associated with the Sevilleta LTER. Finally, this research will expand the research experience and enhance the career opportunities for an early-career scientist, PI Fargione.
# TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

<table>
<thead>
<tr>
<th>Total No. of Pages</th>
<th>Page No.* (Optional)*</th>
</tr>
</thead>
</table>

**Cover Sheet for Proposal to the National Science Foundation**

- **Project Summary** (not to exceed 1 page) 
  - 1 page

- **Table of Contents** 
  - 1 page

- **Project Description** (Including Results from Prior NSF Support) (not to exceed 15 pages) *(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)* 
  - 15 pages

- **References Cited** 
  - 5 pages

- **Biographical Sketches** (Not to exceed 2 pages each) 
  - 6 pages

- **Budget** (Plus up to 3 pages of budget justification) 
  - 7 pages

- **Current and Pending Support** 
  - 4 pages

- **Facilities, Equipment and Other Resources** 
  - 2 pages

- **Special Information/Supplementary Documentation** 
  - 0 pages

- **Appendix** *(List below.)* *(Include only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)* 
  - 0 pages

**Appendix Items:**

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.*
Introduction

Climate change, nitrogen (N) deposition, and invasion of woody species into grasslands are three major global changes influenced by humans. Interactions among such global change drivers are the largest source of uncertainty in global change research (Sala et al. 2001). Globally, average temperatures have increased by 0.6 °C and N fixation has more than doubled since pre-industrial times (Vitousek et al. 1997, Houghton et al. 2001). Also, there is clear evidence that regional climate is becoming more variable including the possibility of more intense, longer lasting heat waves (Houghton et al. 2001, Karl and Trenberth 2003, Meehl and Tebald 2004) and that warming and N deposition have already impacted plant communities decreasing diversity and impacting species phenology and ranges (Kochy and Wilson 2001, Peñuelas and Filella 2001, Walther et al. 2002, Parmesan and Yohe 2003, Stevens et al. 2004). As temperatures and N deposition continue to increase they are expected to have a dramatic impact on plant communities over the course of the next century (Sala et al. 2000). Although much work has been conducted on the effects of these changes individually, our work will address the interactions among these drivers and the response of shrub and grassland community composition at an aridland ecotone.

It is a major goal of ecology to be able to predict the responses of species and communities to environmental changes, including increased N deposition, warming and altered precipitation regimes (Sala et al. 2000). Functional traits offer a quantitative approach to predicting species responses to various drivers of environmental change, and can provide a mechanistic link between ecological pattern and process (Smith et al. 1997a, Cornelissen et al. 2003). Traits of individuals reflect evolutionarily derived strategies of resource capture and interactions among species, both of which influence community structure and ecosystem processes (Suding et al. 2003). For example, it has been found that species with higher tissue N concentrations respond more positively to N deposition (Diekmann and Falkengren-Gerup 2002). Species phenology (i.e. a species ability to grow during the cool winter/spring season) may predict species responses to winter precipitation and species responses to a warmer and extended winter/spring growing season. Or, species responses to warming may be predicted by their sensitivity to freezing stress. Thus, an important aspect of generalizing results from global change experiments, such as the one we propose, will be to quantify trait-based species responses to multiple environmental drivers (e.g. tissue N, phenology, temperature dependence of plant water balance).

Desertification, the conversion of grassland to shrubland, is a global phenomenon (Van Auken 2000). Changes in environmental drivers will likely alter grassland vegetation dynamics by accelerating the expansion of woody species into grassland. Shrub invasion, particularly by mesquite (Prosopis spp.) and creosote (Larrea tridentata), has been increasing in semi-arid grasslands in the American southwest during the past century (Gardner 1951, Buffington and

Figure 1 (a) Black grama and blue grama co-dominate at the Deep Well study site (b) Creosote dominates the area 4 km to the south. Black Butte is to the north.
Herbel 1965, Archer 1994, Schlesinger et al. 1990, Cross and Schlesinger 1999, Asner et al. 2003, Goslee et al. 2003). Creosote, for example, has invaded and now dominates 19 million ha of former grassland (Van Auken 2000; Fig 1). Once creosote is established, the majority of other species are excluded, and interspaces between creosote individuals experience soil erosion and decreases in infiltration and soil fertility, largely preventing the establishment of new individuals of any species (Bhark and Small 2003, Whitford et al. 2001). Although there is little or no establishment of young creosote plants in mature creosote stands (Sheps 1973, Boyd and Brum 1983, Bowers et al. 1995), creosote adults experience extremely low mortality, with 84 out of 85 individuals surviving over 100 years based on repeat photography (Bowers et al. 1995). Consequently, there is no record of land reverting to grassland once creosote has become established. Creosote germination is very sensitive to precipitation (Bowers et al 2004, McGee and Marshall 1993) and establishment increases at disturbed sites (Whitford et al 2001). Additionally, studies of adult creosote have shown that the species is frequently responsive to increased precipitation and N fertilization (e.g. Sharifi et al. 1988, Fisher et al. 1988, Ettershank et al. 1978) and is limited by freezing temperatures (Wells and Shields 1964, Beatley 1974, Pockman and Sperry 1997). Thus, environmental variables such as warming, increased precipitation, and N deposition are critical for understanding the invasion and establishment of creosote in grassland.

The overarching goal of our proposed research is to determine how the interaction of nighttime warming, winter precipitation, and N deposition affects the relative abundance of grassland plant species and the extent of shrub establishment in grassland. Our study site, at the Sevilleta LTER in central New Mexico (Fig. 1), occurs at a vegetation transition zone dominated by two C₄ perennial grasses, *Bouteloua gracilis* (blue grama) and *B. eriopoda* (black grama), and a long-lived C₃ shrub, *Larrea tridentata* (creosote). We propose a multi-factorial field experiment to determine the direct and interactive effects of increased nighttime temperatures, N deposition, and winter precipitation, on grassland community composition and the growth of experimentally introduced creosote seeds and seedlings. Our treatments are designed to mimic expected conditions in the latter half of this century. Although warming is expected to favor southern species (black grama, creosote), N deposition and increased winter precipitation may favor northern species (blue grama). How these contrary forces will interact to determine community composition is unknown, and is the focus of this proposal. After the intensive measurements during this 3 year project, the Sevilleta LTER will maintain this experiment with less intensive sampling to detect longer term responses to our treatments. Thus, our field experiment will look at both the short and long term effects of climate change, and specifically how short-term effects on resource availability and plant growth may drive long-term shifts in community composition (Shaver et al. 2000, Snyder et al. 2004). Specifically we will test the following hypotheses (summarized in Figure 2), which we develop and justify in detail in subsequent sections:

1. **Responses to increased nighttime temperature**

![Figure 2](conceptual_diagram.png)
H1.1. Nighttime warming will favor species with phenology that utilizes the extended winter/spring growing season.
H1.2. Nighttime warming will decrease freezing-induced mortality of creosote seedlings.
H1.3. Nighttime warming will increase soil evaporation and favor summer growth of the desert grass black grama over blue grama.

2. Responses to increased winter precipitation
H2.1. Winter precipitation will favor species with phenology that utilizes the winter/spring growing season. In particular, blue grama will be favored over black grama.
H2.2. Winter precipitation will increase the success of creosote invasion.

3. Responses to increased N deposition
H3.1. N addition will favor species with higher tissue N.
H3.2. N addition will increase the success of creosote invasion.
H3.3. N addition will favor blue grama over black grama.

4. Interactions among environmental drivers
Although our initial hypotheses focus on main effects of each global change variable, our experiment is designed to determine how multiple global change factors will interact to affect species abundances and community dynamics. Sala et al. (2000) proposed that the interaction of global change drivers could be additive, synergistic, or antagonistic. Additive interactions occur when the effects of multiple variables can be predicted by adding together responses from individual treatments (e.g., Zaveleta et al. 2003a). Synergistic implies greater than additive effects, whereas antagonistic indicates less than additive effects (e.g., Shaw et al. 2002). For example, if winter precipitation increases blue grama biomass by 5% and N addition increases blue grama biomass by 10%, then additive interactions would lead to a 15% increase in biomass whereas synergistic interactions would result in a >15% and antagonistic interactions a < 15% change in biomass. Thus, all four possible two-way and three-way interactions among drivers in this experiment can all be tested against the following alternative hypotheses:

H4.1 Treatment effects on community responses (i.e. grama relative abundance and creosote survival and growth) will be additive.
H4.2 Treatment effects on community responses will be synergistic.
H4.3. Treatment effects on community responses will be antagonistic.

In addition, we provide a specific hypothesis for the three-way interaction. We focus on this interaction because all three variables are expected to change in concert, and because high uncertainty and page limitations do not provide the basis or space for listing hypotheses for all two-way interactions.

H4.4. Nighttime warming, winter precipitation, and N addition will positively interact to favor the invasion of creosote into grasslands because creosote establishment may simultaneously be limited by freezing stress, winter soil moisture, and N limitation.

Overview of global trends and experimental treatments
By the end of this century, global mean temperatures are expected to increase by 1.4 – 5.8 °C, inorganic N deposition is expected to increase by 20 – 60 kg ha⁻¹ yr⁻¹, and most models predict that El Niño events will increase or stay at the current elevated level (Sala et al. 2000, Houghton et al. 2001). Regional predictions of the Southwest are for increases of 1-4 °C warming, 40 kg ha⁻¹ of N deposition and increased winter precipitation due to El Niño. These trends are apparent at our field site at the Sevilleta LTER, located 80 kilometers south of Albuquerque, New Mexico. We have planned our treatments to mimic expected global changes – we propose to add 20 kg ha⁻¹ yr⁻¹ of N and 50 mm of precipitation from Oct-May, and we will increase mean daily
minimum temperature ~ 1 °C by experimentally elevating nighttime temperatures throughout the year. The magnitudes of these treatments represent plausible scenarios for the latter half of this century. We base our treatments on documented past trends in these factors, mimicking both the seasonality and event size of El Niño precipitation patterns, and the nighttime bias in warming patterns. Below we discuss these trends and predicted species responses in more detail. We begin by addressing the effects of each individual global change and conclude by discussing possible interactions among these variables. The interactions among these variables are not well understood, and characterizing these interactions will be one of the primary benefits of this project.

**Warming Trends and Effects**

Global climate models predict an increase in 1.4 – 5.8 °C by the end of the century. Regional climate models predict a 1 – 4 °C increase in average winter and summer temperatures at the Sevilleta (SRAG 2000, Han and Roads 2004, Leung et al. 2004). However, warming is not occurring evenly throughout the day. Rather, global nighttime temperatures have increased twice as fast as daytime temperatures over the last 50 years, and this trend is expected to continue (Houghton et al. 2001). The increase in nighttime temperature is also apparent in our region over the past century (Fig 3).

Nighttime warming can have important consequences for plant communities. For example, increasing average annual nighttime temperature since 1970 in shortgrass prairie has been correlated with a decrease in dominant species and an increase in invasive forbs (Alward et al. 1999). Yet most field studies have focused on daytime warming. Open top chambers, in particular have little, if any, nighttime warming effect (see reviews in Arft et al. 1999, Shaver et al. 2000 and Rustad et al. 2001). Studies using heat lamps may increase nighttime temperatures more than daytime temperatures if they are left on at the same power throughout the night (as they are at the Jasper Ridge Global Change Experiment; E. Cleland, personal communication). However, lack of electrical supply limits the use of heat lamps in remote settings such as ours.

Recently a novel warming technique was developed that mimics predicted changes in nighttime temperatures and requires minimal power (Beier et al. 2004; see also an unpublished thesis, Alward 1999). This technique uses aluminum fabric to reflect infrared radiation and increase nighttime temperatures by covering the vegetation at night and uncovering it during the day (Beier et al. 2004). This method was applied at four study sites across Europe, and caused an increase in mean daily minimum temperatures of 0.5-1.2 °C. The differences in soil temperature between treatment and control plots were maintained throughout the day, and the difference in air temperatures was partially maintained throughout the day. Thus, although the increase in air temperatures was greatest at night, the heat retained in soils effects daytime temperatures as well.
The treatment effects varied among sites in a predictable way. Because the treatment works by trapping heat radiating from the soil, conditions favoring rapid nighttime heat loss in control plots, such as absence of clouds, rapid temperature decreases, and low humidity, lead to larger treatment effects. Our arid site experiences large temperature fluctuations, low cloud cover, and low humidity, making our site particularly amenable to this type of warming treatment. Our preliminary data show an increase in minimum air temperatures of 1 °C (Fig 4). The cross-site study using this technique found site-specific increases in aboveground plant biomass up to 15% (Peñuelas et al. 2004), litter decomposition up to 22% (Emmett et al. 2004), soil respiration up to 19% (Emmett et al. 2004), and N loss up to 74% (Schmidt et al. 2004), demonstrating that this level of warming has important ecological effects.

Although arid and semi-arid lands cover approximately one third of the earth’s surface (Dregne 1970), few studies have examined the effects of warming in arid systems. These systems, which are already hot and dry, may be particularly susceptible to the effects of climate change. Much of the work on warming has focused on high latitudes (Arft et al. 1999), and other attempts to broaden the range of experimental sites have not included desert grassland (Rustad et al. 2001, Peñuelas et al. 2004). Thus, our proposal for a multi-factor climate change experiment, including warming, would expand the envelope of the types of climates studied (Fig 5). Arid systems may be particularly sensitive to warming for several reasons. First, species are already stressed by high temperatures and low moisture availability, leading to possible threshold effects that could favor desertification of these grasslands. Second, the dominant species in our system is black grama, a C₄ grasses that make little use of the winter/spring growing season. A small increase in temperature, especially nighttime minimums, could increase the spring growing season for some subdominant species by weeks or months. This could result in dramatic shifts in community composition by favoring species adapted to winter/spring growth, such as the evergreen C₃ shrubs including creosote.

**Warmer temperatures should benefit C₃ shrub encroachment, in our system by creosote.** Creosote is adapted to extremely hot and dry conditions, and whose distribution is limited by freezing temperatures (Wells and Shields 1964, Beatley 1974, Pockman and Sperry 1997). Our field site is near the northern boundary of creosote bush where winter low temperatures can drop below the freezing tolerance of creosote. Thus creosote bush should be able to increase its northern range boundary and increase

**Figure 4** (a) Preliminary data collected December 7th and 8th using (b) nighttime warming prototype with three thermocouples under the warming treatment and two control thermocouples

**Figure 5** Our experiment would expand the envelope from previous climate studies (data for previous field studies based on Rustand et al. 2001, Beier et al. 2004). The Sevilleta (SEV) is hotter than the Patagonian steppe (P), drier than Spanish shrubland (S), and hotter and drier than Colorado shortgrass steppe (C).
its abundance at our field site with warming temperatures. It has been shown that freezing causes xylem embolism in creosote (Martinez-Vilalta and Pockman 2002), that freezing nighttime temperatures inhibit creosote photosynthesis the following day (Naumburg et al. 2004), and that record minimum temperatures correspond closely with the northern range limit of creosote (Pockman and Sperry 1997). At our field site, extensive freezing-induced embolism for most of the winter suggest that creosote may strongly benefit from increased minimum temperatures (Martinez-Vilalta and Pockman 2002).

Warmer temperatures are expected to favor the most drought tolerant C_4 grasses.

In our system, we expect that black grama, a common dominant in Chihuahuan desert grasslands, will be favored over blue grama.

H1.1. **Nighttime warming will favor species with phenology that utilizes the extended winter/spring growing season.** To test this hypothesis we will measure whether the relative abundances of species with earlier phenology respond more positively to the nighttime warming treatment. Phenological changes in cover will be visually estimated monthly (Mar-Oct) in a permanently located quadrat in each plot. Relative abundance will be based on annual aboveground biomass harvests.

H1.2. **Nighttime warming will decrease freezing-induced mortality of creosote seedlings.** To test this hypothesis, we will measure whether the frequency of extreme freezing temperatures and the mortality of creosote seedlings decreases under the nighttime warming treatment.

H1.3. **Nighttime warming will increase soil evaporation and favor summer growth of the desert grass black grama over blue grama.** To test this hypothesis, we will measure whether the abundances of black grama increase and blue grama decrease under the nighttime temperature treatment. Relative abundance will be based on annual aboveground biomass harvests measured in the summer and seasonal changes in cover will be visually estimated monthly (Mar-Oct) in a permanently located quadrat in each plot.

**Precipitation Trends**

Global patterns of precipitation are also expected to change, with some regions experiencing increased precipitation, other areas experiencing decreased precipitation, and an overall increase in the frequency of extreme events (Houghton et al. 2001). Regional climate models predict a slight decrease to a slight increase in average annual precipitation at the Sevilleta (SRAG 2000, Han and Roads 2004, Leung et al. 2004). Although it is unclear how average annual precipitation will change, there is reason to expect a shift towards increased winter precipitation at the Sevilleta. In the southwest, El Niño events usually result in wetter winters (Sheppard et al. 2002), and El Niño events over the past 20 to 30 years became more frequent, persistent, and intense compared to the previous 100 years (Houghton et al. 2001). The majority of studies predict that future climate will resemble a more El Niño-like state (reviewed in Houghton et al. 2001). Thus, climate in the southwestern US in 50-100 years will likely experience greater winter precipitation.

At the Sevilleta, El Niño events cause, on average, an additional 50 mm of winter precipitation. Based on climate records from 1914, El Niño primarily increases rainfall in October and February-May (Fig 6). In addition, El Niños typically increase precipitation by increasing rainfall events of a variety of sizes (Fig 6). Our additions will mimic this pattern by adding, each winter, 50 mm of water in events of 18, 12, and 5 mm. Water will be added during the times of year when El Niños most increase rainfall (Fig 6). Because our design is dependent upon maintaining treatment differences throughout the range of climate variation that may occur during the study, we will still add 50 mm of winter precipitation in El Niño years and/or years
with above average winter precipitation. This will turn a small El Niño event into a medium El Niño event, or a large El Niño event into a very large El Niño event, and is consistent with increasing the frequency and magnitude of El Niño events.

Increased winter precipitation will favor the establishment of C$_3$ shrubs. Thus we expect that creosote will be favored by winter precipitation for several reasons. First, the highest growth rates for the C$_3$ shrub creosote are in the spring (Reynolds et al. 1999), whereas the highest growth rates for the C$_4$ grama grasses are during the summer (Archer 1994). Second, winter precipitation is more likely to infiltrate soils because cooler temperatures lead to reduced evaporation and reduced transpiration of warm-season grasses. Thus, winter precipitation contributes more to soil moisture at depth, which favors deeper rooted shrubs (Sala et al. 1989, Brown and Archer 1990, Smith et al. 1997b). Consistent with this hypothesis, Paruelo and Lauenroth (1996) showed in a cross-site comparison that shrub abundance increased with increasing proportion of winter rainfall. However, using the same data, Ogle and Reynolds (2004) showed that shrub abundance was correlated with decreased summer precipitation, but was uncorrelated with winter precipitation. In total, the evidence for the benefit of winter rainfall to shrubs is equivocal and requires further study.

Increased winter precipitation will favor the C$_4$ grass species with phenology favoring early season growth. Thus, we expect that blue grama will be favored over black grama by winter precipitation. Although both species are warm season C$_4$ grasses, blue grama begins growth earlier in the season relative to black grama when there is sufficient spring soil moisture (Buxbaum 2003). Thus, blue grama will be better able to take advantage of increased winter precipitation, and should be favored by our winter precipitation treatment.

H2.1. Winter precipitation will favor species with phenology that utilizes the winter/spring growing season. To test this hypothesis we will measure whether the relative abundances of species with earlier phenology respond more positively to the winter precipitation treatment. Phenology will be measured in a permanent percent cover plot. Relative abundance will be based on annual aboveground biomass harvests. Phenological changes in cover will be visually estimated monthly (Mar-Oct) in a permanently located quadrat in each plot. Relative abundance will be based on annual aboveground biomass harvests.

H2.2. Winter precipitation will increase the success of creosote invasion. To test this hypothesis, we will measure whether creosote survival and growth increases under the winter

![Figure 6](image-url)

N Deposition Trends
Globally, the rate of N fixation has more than doubled over “natural” levels (Vitousek et al. 1997). Much N deposition occurs in rainfall, and the sites of highest deposition are mesic to wet sites downwind of large human populations in developed countries (Holland et al. 1999). However, N deposition is dramatically increasing in arid and semi-arid areas of the world, driven by increasing population and industrialized agriculture in these areas (Holland et al. 1999). In the temperate regions of the northern hemisphere, arid shrubland and C₄ grasslands have average rates of total inorganic N deposition of 3 and 5 kg N ha⁻¹ yr⁻¹ respectively, with some areas experiencing up to 13 kg N ha⁻¹ yr⁻¹ (Holland et al. 1999). These rates represent 6 fold and 9 fold increases over pre-industrial levels of N deposition in shrublands and C₄ grasslands respectively. Although few studies predict future rates of N deposition, Sala et al. (2000) expect an increase of 40 kg ha⁻¹ yr⁻¹ in deserts and savannas and 60 kg ha⁻¹ yr⁻¹ in grasslands. At the Sevilleta, rates of N deposition have significantly increased since 1989 (Fig 7). However, at the observed rate, N deposition at the Sevilleta will only have increased by 4.3 kg ha⁻¹ yr⁻¹ in 2001. However, as population growth and industrial agriculture increase, N deposition may increase more quickly than it has. We propose to add 20 kg ha⁻¹ yr⁻¹. Although we cannot know what the actual rate of N deposition will be in the latter half of this century this rate is a compromise between existing trends and expert predictions. This rate has induced plant growth responses at our site (see below).

N addition will favor C₃ over C₄ species. In our system, creosote will exhibit the greatest response to N addition. The growth responses of creosote to N are variable, ranging from no response (Sharifi et al. 1988) to a 100% increase (Fisher et al. 1988), and may only respond to N when water was also added (Sharifi et al. 1988), or only when N was added at high levels (i.e. 100 kg/ha; Ettershank et al. 1978). It is unclear how creosote responds when competing with grasses. Woody invasion is positively correlated with N deposition in the northern Great Plains (Kochy and Wilson 2001), suggesting that woody species in competition with grasses can benefit from N addition. However it is unclear if this effect also occurs in arid systems, where water limitation may reduce competition for N.

Among the C₄ grasses, N addition will favor the grasses with higher leaf nitrogen concentration. Blue grama has been shown to be much more responsive to nitrogen additions at this site compared to black grama (Fig 8), consistent with the relative responses of these species in independent fertilization studies (Stephens and Whitford 1993, Kipple and Retzer 1959). In addition, species with higher tissue N are more likely to increase in response to N deposition (Diekmann and Falkengren-Grerup 2002) and blue grama has higher tissue N than black grama at our site (Buxbaum 2003).
H3.1. **N addition will favor species with higher tissue N.** To test this hypothesis we will measure whether the relative abundances of species with higher tissue N respond more positively to the N addition treatment. We will also be able to test whether photosynthetic pathway affects this relationship because we will measure tissue N of both C_3 and C_4 species. Relative abundance will be based on annual aboveground biomass harvests.

H3.2. **N addition will increase the success of creosote invasion.** To test this hypothesis we will measure whether the growth and survival of creosote increases in response to the N addition treatment.

H3.3. **N addition will favor blue grama over black grama.** To test this hypothesis we will measure whether the relative abundance of black grama increases and the relative abundance of blue grama decreases under the N addition treatment. Relative abundance will be based on annual aboveground biomass harvests.

**Interactions Among Global Change Drivers**

Our single-factor hypotheses suggest that the likely effect of our global change manipulations on creosote will be greater seedling establishment, increased seedling growth and decreased mortality under each treatment. Likewise, these single factor hypotheses suggest that our each factor will favor either blue grama (water addition and N addition) or black grama (warming). While these single factor responses are important, the changes in community vegetation structure and function that occur with global change will almost certainly be determined by the interactions among responses to multiple factors. Our experimental design will allow us to assess these interactions. However, previous studies provide little basis for generating well supported specific hypotheses regarding the outcome of these interactions for either creosote or grama grasses. Based on our single-factor hypotheses, we predict that multiple factors will facilitate the invasion and growth of shrubs. However, there is considerable uncertainty associated with such predictions because the interaction among factors could be additive, synergistic or antagonistic. If interactions are additive then the effect of any combination of treatments can be predicted simply by adding the effects observed in individual treatments. Alternatively, multiple global changes may be greater than additive (synergistic) or less than additive (antagonistic) (Sala et al. 2000).

The interactions between water and N treatments, perhaps the best studied pairwise interaction, are complex because soil moisture increases supply (mineralization; Fisher and Whitford 1995) and loss (leaching and denitrification; Peterjohn and Schlesinger 1991). If N addition increases plant growth, and thus transpiration, it could decrease soil moisture. Alternatively, N addition might have no effect on soil moisture if plant growth is primarily limited by water, or it could increase soil moisture if greater plant tissue N concentrations increases water use efficiency. In addition, although dry soils inhibit mineralization they also inhibit plant uptake, such that inorganic N accumulates during dry periods, resulting in a pulse of available N when soils are re-wetted (Fisher and Whitford 1995). Consequently, water and N are often co-limiting, both directly because dry soils inhibit plant uptake via diffusion and indirectly because dry soils may limit N mineralization (Hooper and Johnson 1999, Asner et al. 2001, Austin and Sala 2002, Austin et al 2004). For example, creosote plants increased their uptake of a labeled N addition by 3.5 fold after a 30 mm water addition compared to un-watered control plants (Bassirirad et al. 1999). In total, we expect net primary productivity to be co-limited by water and nitrogen, such that there is a positive interaction from the addition of both limiting resources. However, it is less clear how species-level responses will be affected by interactions among water and N.
Winter precipitation is expected to increase N supply and decrease N pool size. Precipitation will increase microbial activity such as mineralization, increasing N supply. Precipitation will also increase microbial activity such as immobilization and increases plant uptake, which will decrease N pool size. Rainfall events can also reduce N pool size via leaching losses or increased denitrification (Peterjohn and Schlesinger 1991).

Fewer studies have measured the interaction between warming and N, warming and precipitation or the interaction among all three factors. One notable exception is the Jasper Ridge Global Change Experiment. They report that NPP (above and belowground) responds additively to warming and N, but less than additively to warming and precipitation (Shaw et al. 2002), whereas species richness responded additively to warming, nitrogen and precipitation (Zaveleta et al. 2003a). Warmer temperatures may increase or decrease photosynthetic rates, depending on water availability (Hamerlynck et al. 2000). This may dry soils, offsetting some of the benefits of precipitation and leading to an antagonistic interaction between warming and precipitation. Surprisingly, Zaveleta et al (2003b) found that warming caused the annual plants in their systems to senesce earlier, reducing transpiration and resulting in a net increase in soil moisture at the end of the growing season. Warming is expected to increase N mineralization and to increase N pool size. Microbial activity, including N mineralization, generally increases with temperature (although, alternatively, warming may decrease microbial activity, including mineralization, if warming decreases soil moisture). If warming decreases soil moisture it will slow plant N uptake and increase N pool sizes.

H4.1 Treatment effects on community responses (i.e. grama relative abundance and creosote survival and growth) will be additive. This hypothesis is supported if the interaction terms (e.g. winter precipitation * N addition) in an ANOVA model are not significantly different from zero, and rejected if the interaction terms are significantly different from zero.

H4.2 Treatment effects on community responses will be synergistic. This hypothesis is supported if the interaction terms (e.g. winter precipitation * N addition) in an ANOVA model are significantly greater than zero. Such a response is expected if species are co-limited by water, N, and/or freezing.

H4.3. Treatment effects on community responses will be antagonistic. This hypothesis is supported if the interaction terms (e.g. winter precipitation * N addition) in an ANOVA model are significantly less than zero. Such a response would occur if a single factor cancels or dampens the effect of other factors. For example, warming and water addition may both independently increase creosote growth, but in combination warming may eliminate the benefit of water addition by increasing evaporation.

H4.4. Nighttime warming, winter precipitation, and N addition will positively interact to favor the invasion of creosote into grasslands because creosote establishment may simultaneously be limited by winter soil moisture, freezing stress, and N limitation. We will test whether the effect of warming, precipitation, and N addition in combination have a greater benefit to creosote survival and growth than would be predicted by the individual effects of these factors on creosote. Statistically, this hypothesis predicts that, in an ANOVA, the three way interaction term will be significantly positive.

It will be possible to test a large number of

![Figure 9 Black grama and blue grama relative cover at Deep Well since 1989.](image)
additional hypotheses using the infrastructure of our experiment. Once funded, we plan to solicit collaborations that utilize this infrastructure to measure responses in other variables that may be affected by global changes, including organisms such as soil crusts, mycorrhizae, microbes, and herbivores, and processes such as decomposition and denitrification.

**Site background.** The Sevilleta is an ideal location to study the effects of shrub invasion because the northern range limit of creosote passes through the Sevilleta, locating it on the front lines of any future range expansion by creosote. Within the Sevilleta, we chose for our study an area adjacent the Deep Well meteorological station, established by the Sevilleta LTER in 1989. The site is currently co-dominated by blue grama and black grama, but only 4 km north of a large area dominated by creosote (Fig 1). At Deep Well, black grama has been increasing in relative abundance since 1989, and blue and black grama combined now comprise 80% of the total plant cover at this site (Fig 9). In addition to these two dominants, several other species are common, which will allow us to measure tissue N and phenology on a variety of species and life forms (Table 1).

The SNWR contains extensive semi-arid grassland dominated by C4 perennial grasses (*Bouteloua gracilis*, *B. eriopoda*, *Sporobolus* spp., *Hilaria jamesii*, *Muhlenbergia* spp.) located on relatively level topography along the western edge of the Los Piños Mountains. Total vegetation cover (live plus litter) averages 60% with 40% bare soil. Mean annual temperature from 1989-2002 at the Deep Well meteorological station, a grassland site on the SNWR, was 13.2°C, with a mean monthly temperature of 1.6°C in January and 25.1°C in July. This site receives approximately 250 mm of precipitation annually, about 60% of it is delivered in isolated, short duration showers during the summer monsoon season (July – September); the remainder arrives with winter frontal systems. However, the relative contribution of summer monsoon and winter rains varies considerably from year to year.

Total soil N and C pools in these grasslands are small (20 and 200 g m⁻², respectively) and N mineralization rates are low relative to mesic systems (Zak et al. 1994, Keift et al. 1998). Total potential mineralizable N ranges

<table>
<thead>
<tr>
<th>Common name</th>
<th>Latin name</th>
<th>Life from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black grama</td>
<td><em>Bouteloua eriopoda</em></td>
<td>Grass</td>
</tr>
<tr>
<td>Blue grama</td>
<td><em>Bouteloua gracilis</em></td>
<td>Grass</td>
</tr>
<tr>
<td>Galleta grass</td>
<td><em>Pleuraphis jamesii</em></td>
<td>Grass</td>
</tr>
<tr>
<td>Sand dropseed</td>
<td><em>Sporobolus cryptandrus</em></td>
<td>Grass</td>
</tr>
<tr>
<td>Purple threeawn</td>
<td><em>Aristida purpurea</em></td>
<td>Grass</td>
</tr>
<tr>
<td>broom snakeweed</td>
<td><em>Gutierrezia sarothrae</em></td>
<td>Sub-shrub</td>
</tr>
<tr>
<td>Wright's globemallow</td>
<td><em>Sphaeralcea wrightii</em></td>
<td>Forb</td>
</tr>
<tr>
<td>Lacy tansyaster</td>
<td><em>Machaeranthera pinnatifida</em></td>
<td>Forb</td>
</tr>
</tbody>
</table>

**Table 1** Eight common species for which we will measure species traits.

**Figure 10** Plot layout. Warming, water additions, and N additions will be made to the entire 3 x 3.5 meter plot, but measurements will be restricted to the center 2 x 2.5 meters.
from 1.6 to 4.0 g m$^{-2}$ y$^{-1}$ (White et al. 2004). Atmospheric N deposition averages 0.2 g m$^{-2}$ y$^{-1}$. Aboveground net primary production (ANPP) averages 110 g m$^{-2}$ y$^{-1}$. Copious information about the Sevilleta (e.g. soil maps, vegetation maps, meteorological records, past and current research projects, research database) is available through the Sevilleta LTER website (http://sev.lternet.edu).

**Detailed Methods**

**Plots:** Our measurements will be made on 3 x 3.5 m experimental plots. To protect the integrity of the plots over the course of our experiments, all measurements and sensor installation will be performed from scaffold planks that allow us to access the entire plot without disturbing the plot surface or vegetation. This is critical in our arid system because walking even twice in the same area can have a lasting effect. The use of scaffold planks has been demonstrated to successfully protect the plots in an extensive rainfall manipulation experiment (27, 10 x 15m plots) at the Sevilleta. No measurements are made in a 50 cm strip around the edge, which ensures that measurements will reflect the full effect of the warming treatment (Fig, 10, Beier et al. 2004).

**Treatments:** We use proven methods to increase temperature, winter precipitation, and available nitrogen. The magnitudes of the treatments we impose reflect the environmental conditions expected in this region during the latter half of this century. Our experimental design consists of three fully crossed factors (warming, increased winter precipitation and N addition) in a complete randomized design, for a total of eight treatment combinations. We will use five replicates of each treatment combination, for a total of 40 plots. The plots will be located in a grassland community co-dominated by blue grama and black grama, adjacent to the Deep Well meteorological station, which has collected precipitation, irradiance, soil moisture, and N deposition data since 1989.

**Warming:** Our nighttime warming treatment will be imposed using lightweight aluminum fabric shelters (mounted on rollers similar to a window shade) that are drawn across the warming plots each night, reflecting outgoing longwave radiation. This approach has been previously used with success and provides a simple alternative to the use of infrared heat lamps (Beier et al. 2004). The dataloggers controlling shelter movements are programmed to retract the shelters on nights when wind speeds exceed a threshold value (to prevent damage to shelters) and when rain or snow is detected by a leaf wetness sensor (to prevent an unintended rainout effect).

To determine the effectiveness of the warming treatment, air and soil temperature will be measured in each plot with copper constantan thermocouples connected to dataloggers (Campbell Scientific, Logan UT). One plot will be extensively measured in order to determine the spatial pattern of warming due to the warming treatment. In the extensively measured plot, we will use 11 moveable thermocouples to collect data on spatial patterns of air temperature, and 8 thermocouples to collect data on soil temperature profile at 0, 2, 5, and 10 cm depths under both grass and bare soil. The data collected from this plot will allow us to model the spatial patterns of warming across the experiment. In all other plots, we will make six temperature measurements in an undisturbed central portion of the plot (Fig 10). Temperature will be measured 10 cm above the soil surface, at the soil surface, and 5 cm below the soil surface for grass canopy and bare soil cover types.

**Water addition:** Our water addition treatment will be maintained by adding high quality (low salt) water produced by a reverse osmosis system from Albuquerque tap water, trucked to the research site in 32,000 L batches and stored on-site in tanks. Water will be applied to plots using an overhead irrigation system designed and tested by Jim Elliott (M.S.) for an ongoing water manipulation project (Pockman PI). Elliott will be employed part-time and will take
responsibility for developing and implementing the treatments.

To assess the effect of the water addition treatment, we will measure soil moisture will also be measured extensively in one plot, at depths of 2, 5, 10, 15 and 30 cm under both grass and bare soil using ECH2O soil moisture probes (Decagon, Logan UT). ECH2O probes measure dielectric permittivity which is correlated with volumetric water content. Probes are 10 cm long by 2 cm wide, and will be installed with the 10 cm axis of the probe horizontal to the surface, and the 2 cm axis vertical to the surface. This will measure soil moisture at a specific depth and prevent puddling of water on top of the probe. The data collected from this plot will allow us to model the vertical patterns of soil moisture in other plots. In all other plots, four soil moisture measurements will be made in each plot at two depths (5 and 15 cm) under both grass and bare soil using the same type of probes. All soil moisture probes will be measured continuously by dataloggers.

Temperature and soil moisture measurements will be collected with dataloggers, with data uploaded in real time to the Sevilleta LTER’s NSF-funded wireless network. These measurements represent a substantial investment in equipment (~$30,000), and although we would welcome the ability to make additional measurements to more rigorously document the vertical and horizontal variation in temperature and moisture, we felt the scientific benefit could not justify requesting the additional funds necessary to make additional air and soil temperature measurements per plot.

For comparison with our measurements of soil moisture, we will measure predawn leaf water potential of blue and black grama and creosote in spring and summer of each year. Leaves of each species will be harvested before dawn and immediately placed in a plastic bag with a damp paper towel to prevent water loss that would alter the water status of the tissue. Leaves will be stored in a cooler and measured using a Scholander pressure chamber (Turner et al, 1987). The resulting measurements will provide a measure of plant water status that should reflect the integrated effect of our treatments on each species. This sampling will consume a significant fraction of the total leaf area of selected seedlings. Because this could affect the survival of these seedlings, we will remove sampled seedlings from the plot after sampling. To assess whether night-time transpiration is altering predawn water potential (Donovan et al, 2001), we will make spot measurements of transpiration by each species around the time of water potential sampling using a LiCor LI-6400 portable gas exchange system.

**Nitrogen addition:** We will add 20 kg ha\(^{-1}\) yr\(^{-1}\) of N, equivalent to 2 g N m\(^{-2}\) yr\(^{-1}\). Ammonium and nitrate contribute approximately equally to N deposition at our field site (57% ammonium and 43% nitrate), so we will add N in the form of ammonium nitrate (50% ammonium and 50% nitrate). N deposition at our site occurs during both the summer and the winter growing seasons, with 50% of the N deposition at our site occurring during the summer (July-Sep), and the other half of N deposition throughout the year. In order to mimic this increased availability of N during both growing seasons, N will be applied in two pulses of equal magnitude, one at the beginning of each growing season (i.e. early July and late February). We selected this amount both because it is a plausible rate of N deposition in many arid systems by the end of this century and because preliminary results suggest that it is sufficient to induce a vegetation response in at least some species (Fig 8). Although the most common application rate for N fertilization studies is 10 g m\(^{-2}\), this rate is an order of magnitude higher than the highest observed rates of N deposition in northern temperate C4 grassland and arid shrubland (Holland et al. 1999) and such rates are not expected to occur in arid systems in this century (Sala et al. 2000).

Soil N will be measured using resin bags and inorganic N extractions. Resin bags 5 cm in
length will be placed under grass and under bare soil, from 0-5 cm. Resin bags will be collected
twice a year, once sampling the summer growing season (June-Oct), and one sampling the rest of
the year (Oct-June). Inorganic N will be extracted with 1 molar KCl extractions during each
growing season. Previous sampling of inorganic soil N at the Sevilleta has shown strong
temporal variation associated with precipitation, antecedent soil moisture, and antecedent
primary productivity (e.g. White et al 2004). In order to capture differences among treatments,
we will sample after the large October rainfall treatment, and after the large March rainfall
treatment. Intensive soil N sampling in the summer and spring growing seasons in first year of
the experiment will determine the optimal times for additional sampling to capture variation
among treatments.

Herbaceous biomass: Biomass of herbaceous species will be measured by harvesting two 1 x 0.1
m strips each year (red to yellow section of Fig 10) at peak standing biomass (usually Sept in our
system). We have allocated enough area for biomass such that we can harvest a new area each
year for 10 years. The plant tissue harvested from each strip will be sorted by species, dried and
weighed. Each species will be sub-sampled for measurement of tissue N of eight common
species (Table 1).

Phenology: We will also measure species phenology monthly from March through October of
each growing season. At each measurement date, we will estimate percent cover using standard
methods.

Creosote seed germination and seedling survival: To assess the effect of our treatments on the
ability of creosote to establish among grassland vegetation, we will measure the germination of
seeds placed in our experimental plots as well as the survival of greenhouse-germinated
seedlings planted in a small sub-plot. Creosote seed will be added at a rate estimated to produce
200 germinated seeds per 1.2 x 0.25 m subplot. Seed will be collected from multiple maternal
plants in a population near the 5 Points area at the Sevilleta and each seed germination plot will
receive equal numbers of seeds from each maternal line. Fresh seed will be used because it has
significantly higher germination success (McGee and Marshall 1993). In the creosote seed
addition subplots we will measure germination success weekly over the first fall, mortality
monthly over the first year, and growth of all surviving of individuals bi-annually (at peak
biomass for each growing season).

In the second year, nine individual seedlings will be transplanted into each plot, for a
total of 360 creosote seedlings in the entire experiment (Fig 10). We will grow seedlings in
the greenhouse using techniques successfully used to grow large numbers of seedlings by Will
Pockman’s graduate student Juliana Medeiros. Creosote size and growth of all individuals will
be measured twice each year, in the spring and fall. To measure creosote biomass non-
destructively, we will develop allometric relationships between seedling volume and green and
woody biomass using additional greenhouse-grown seedlings. We have used these methods with
success for adult creosote in the past. These relationships will be combined with measurements
of percent cover (at peak biomass for each of the spring and summer growing seasons) in a
permanent percent cover subplot in the creosote seedling subplot.

Broader Impacts: Arid ecosystems, which cover approximately 33% of the terrestrial
environment, are considered to be very sensitive to increased interannual climate variability,
atmospheric N deposition and precipitation intensity and amount. However, the effects of these
impacts on species interactions and changes in species composition are uncertain. Our long-term
nighttime warming, winter precipitation, and N deposition experiment is unique in that it will
address the individual and interactive affects of key environmental drivers on an arid land
ecosystem at the interface of grassland and shrubland community-types. Our experimental work will allow us to evaluate several hypotheses in the context of multiple global change phenomena. The product will be a better understanding of how precipitation patterns, N deposition and warming will accelerate or delay the currently on-going transition of arid grassland to shrubland vegetation. This biotic transition has significant consequences on both ecological (e.g., carbon storage; Huenneke et al. 2002, Jackson et al. 2002) and economic (e.g., grazing) systems in arid environments. Specifically, shrub invasion has important effects on nutrient cycling and hydrology, and may exhibit positive feedbacks, making the process difficult to reverse (Schlesinger et al. 1990, Van Auken 2000, Peters et al. 2004). In our system creosote invasion increases carbon sequestration (Jackson et al. 2002), increases resource heterogeneity (Schlesinger et al. 1996), increases runoff and nutrient losses (Schlesinger et al. 2000), and decreases forage value (de Soyza et al. 1998).

The University of New Mexico is a Hispanic-serving institution, and individuals from groups under-represented in science will be recruited at all levels throughout the project funding period. The work will enhance and expand the research experience of a young scientist (PI Fargione) and provide opportunities for several undergraduate researchers. To enhance participation by underrepresented groups, we will recruit undergraduate students from our ongoing Undergraduate Mentorships in Environmental Biology (UMEB) Program associated with the Sevilleta LTER. Many UNM ecology classes take field trips to the Sevilleta and our research and research infrastructure can be used in the context of class projects and REU programs. To maximize our informal educational programs, we will frequently participate in educational activities organized by staff at the Sevilleta National Wildlife Refuge. The SNWR headquarters includes a small visitor’s center, conference room and teaching laboratory. As part of our activities we will also hold several brown bag lunches with Refuge staff and volunteers to discuss this project and the value and importance of ecological research, in general. These events are open to the public and will be announced in the visitor’s center. The Refuge staff and volunteers are an important conduit of information to the general public. To help broaden undergraduate training in ecology, we will develop and contribute education modules for ESA’s Teaching Issues and Experiments in Ecology (TIEE http://tiee.ecoed.net/). PI Fargione has contributed to a module to TIEE based on his research at the Cedar Creek LTER site.

Results from prior support.

PI Collins, Co-PI Pockman. DEB-021744 - Sevilleta LTER: Long-term ecological research in a biome transition zone. The Sevilleta Long-term Ecological Research Project is located about 80 kilometers south of Albuquerque, New Mexico, in and around the Sevilleta National Wildlife Refuge (SNWR). The Refuge, managed by the Department of Interior U.S. Fish and Wildlife Service, and its surroundings are situated at the intersection of several major biotic zones: Chihuahuan Desert grassland and shrubland, Great Plains grassland, Piñon-Juniper woodland, Colorado Plateau shrubsteppe, and riparian vegetation along the middle Rio Grande Valley. The Sevilleta LTER Program, managed by the Department of Biology, University of New Mexico, became part of NSF’s LTER Program in 1988. The overarching goal of the Sevilleta LTER Program is to understand how abiotic pulses and constraints affect dynamics and stability in arid land ecosystems. Long-term research at the Sevilleta includes multiple rainfall manipulation experiments (Pockman, PI) and fertilization experiments, studies of soil nitrogen dynamics and climatic variability, vegetation dynamics, patterns and controls on net primary production, and consumer population dynamics. A complete list of Sevilleta LTER publications can be found at (http://sev.lternet.edu).
References Cited


