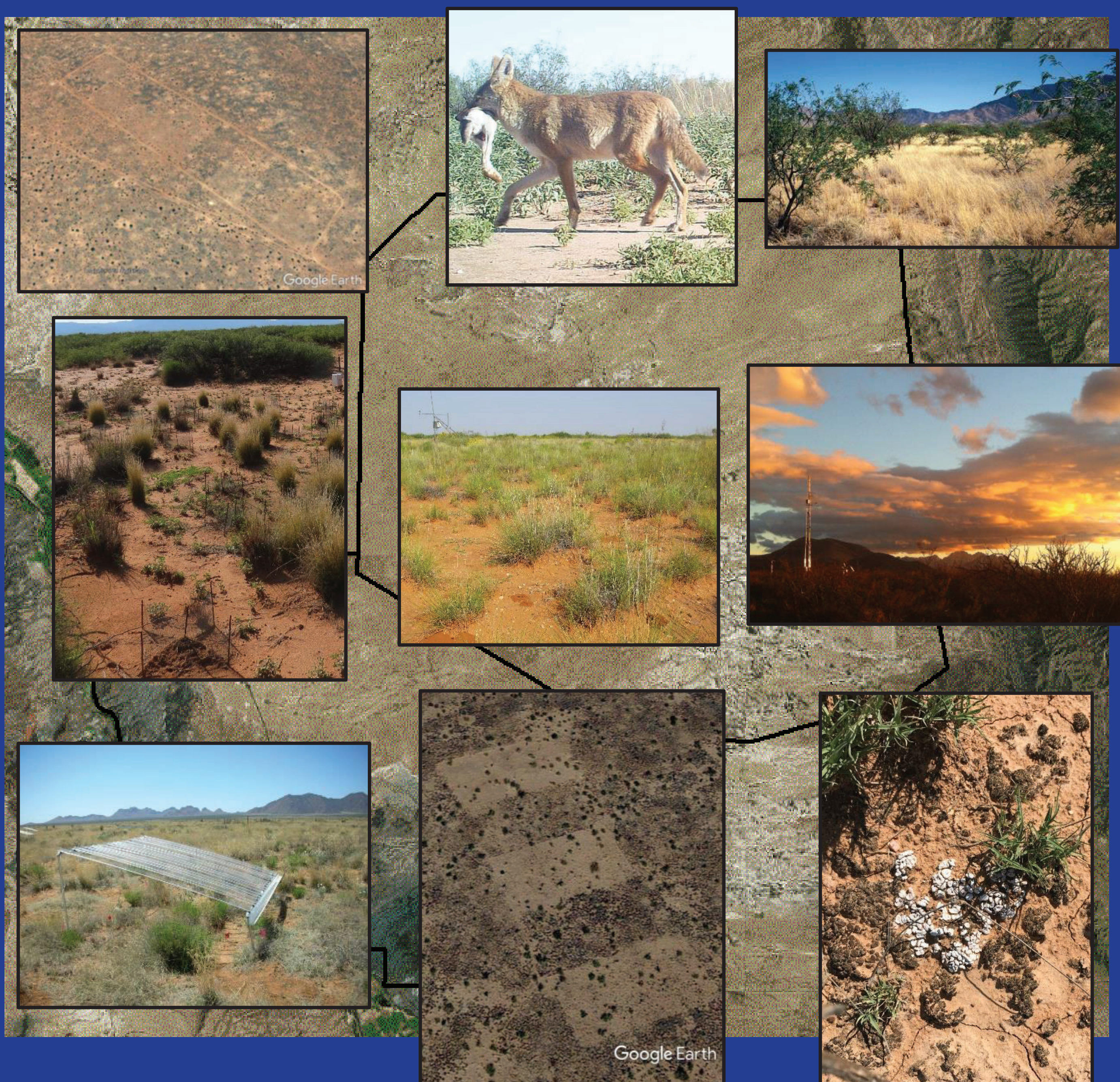
LTER: Long – Term Research at the Jornada Basin (LTER VII)



NSF Proposal 2018-2024

LTER: Long –Term Research at the Jornada Basin (LTER VII)

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By:
New Mexico State University
Las Cruces, NM 88003

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TITLE OF PROPOSED PROJECT: LTER: Long - Term Research at the Jornada Basin (LTER VII)

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
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THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
- ☐ BEGINNING INVESTIGATOR
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PROJECT SUMMARY

Overview:

Chihuahuan Desert landscapes exemplify the ecological conditions, vulnerability, and management challenges in arid and semi-arid regions around the world. The goal of the Jornada Basin Long Term Ecological Research program (JRN LTER) is to understand and quantify the key factors and processes controlling ecosystem dynamics in Chihuahuan Desert landscapes. In collaboration with the Jornada Experimental Range (USDA ARS), studies initiated in 1915 have been incorporated into the JRN LTER program. Previous research focused on desertification, a state change from perennial grasslands to woody plant/bare ground dominance that occurs globally. More recently, JRN research has explored the role of spatial interactions (wind and water connectivity) in driving multiple types of transitions, including grassland recovery, non-native plant invasion, and changes in dominant shrub species. These transitions have profound implications for the processes reflected in the 5 core LTER research themes (primary production, trophic interactions, carbon and nutrient cycles, and susceptibility to wind and water disturbance). In LTER-VII we introduce the "trigger-feedback-heterogeneity" framework for understanding the dynamics of state-change in dryland landscapes subject to varying anthropogenic and natural presses, including climate change. The overall goal of Jornada LTER-VII (2018-2024) is to develop robust principles governing dryland state changes and apply them across spatially heterogeneous landscapes to forecast future states in response to changing climate and land use.

Intellectual Merit:

In LTER-VII, we will explore how spatial heterogeneity of dryland ecosystems evolves over time in response to disturbance triggers, positive feedbacks, and their interactions with the eco-geomorphic template. We will address the critical need for integration of long-term observations into an evolving conceptual and predictive framework for drylands. We propose to expand our landscape linkages framework (Peters et al. 2006; 2012) to fill this critical need, and to contribute to emerging ecological theory on: (a) alternative states and resilience, (b) ecosystem sensitivity to global change, and (c) cross-scale interactions. Our recent observations indicate the need to conceptually and computationally integrate data and knowledge into a Data Science Integrated System (DSIS) of drylands that will allow Jornada results to be translated to other locations in the Chihuahuan Desert and to drylands globally. Our research will result in five major products: (1) new understanding of state changes, in particular in drylands, that lead to theory development, testable hypotheses, and new experiments; (2) accessible data, derived data products, and visualization tools applicable at multiple scales; (3) explanatory and predictive relationships among drivers, patterns, and processes that can be used to (4) predict dynamics of alternative states at new locations or future conditions with assessments of their impacts on ecosystem services; and (5) provide training, outreach and information transfer to broader audience locally, nationally and internationally.

Broader Impacts:

Training opportunities will be provided for a large number of graduate and undergraduate students, including year-long and summer internships, REU and graduate fellowships, awarded to students from collaborating institutions (including NMSU, U. Texas, El Paso, U. Arizona, Arizona State U.) all of which are Hispanic-serving institutions). JRN LTER research supports a highly successful K-12 and teacher-training program: more than 90,000 students, teachers, and other adults were involved in educational outreach programs during LTER VI. The majority of participants are from underserved populations from southern New Mexico and west Texas: ca. 80% are classified as economically disadvantaged, and 75% are Hispanic. These programs will continue to include inquiry-based science education curricula, field trips, schoolyard ecology activities, teacher workshops, and public education events. Interactions with resource management practitioners will occur via workshops, seminars, and service by LTER scientists on various boards of directors. The JRN LTER annual research symposium is attended by > 100 scientists, educators, and land managers. Internet- and mobile-phone (App)-based systems will be employed to share knowledge and information, and collaboration with the USDA Southwest Climate Hub will disseminate climate adaptation information produced via LTER research.

LTER: Long –Term Research at the Jornada Basin

I. INTELLECTUAL MERIT

1. Project Overview

Many arid and semiarid ecosystems ("drylands") of the world have experienced dramatic changes in vegetation structure and ecosystem function over the past several centuries. These changes, typically interpreted as "desertification", are often manifested as broad-scale conversion of perennial grasslands to landscapes dominated by unpalatable, xerophytic shrubs, and are often accompanied by soil erosion and loss of biological resources, including aboveground production and biodiversity (Barger et al. 2011, Archer et al. 2017). Because drylands occupy >40% of the Earth's land surface, these state changes have important long-term consequences for the provisioning of goods and services to the > 1 billion people who are directly linked to these landscapes (Reynolds and Stafford Smith 2002, Boone et al. 2018).

Established paradigms for understanding this prominent and potentially devastating state change in drylands emphasize that: (1) shrub-dominated states are very stable under current climatic conditions as a result of positive feedbacks between woody plants, soil water and nutrients, such that grass recovery is rare and restoration is difficult (Schlesinger et al. 1990, van de Koppel et al. 1997); (2) different shrub species or functional groups invade and eventually dominate on different soil types (Wierenga et al. 1987, McAuliffe 1994, Wondzell et al. 1996); (3) expansion of woody plants is governed by broad-scale drivers, primarily climate, fire, and livestock overgrazing, and mediated by soil properties interacting with local plant-scale processes (Geist and Lambin 2004, Asner et al. 2004, Reynolds et al. 2007, Cowie et al. 2011); (4) destabilization of biological and physical soil crusts increases vulnerability of desert soils to wind and water erosion, with crust recovery following disturbance depending on weather, soil and crust biophysical properties (Belnap and Gillette 1998, Belnap and Eldridge 2003, Jimenez Aguilar et al. 2009, Herrick et al. 2010b); and (5) global warming reinforces and accelerates the trend of shrub encroachment and desertification in the American Southwest and globally (Seager et al. 2007; Schlaepfer et al. 2017).

Recent studies by the Jornada LTER and others are challenging these paradigms by demonstrating that: (1) multiple alternative states can occur, including shifts from desertified shrublands back towards native grasslands and shifts from grasslands or shrublands to novel ecosystems dominated by non-native annual or perennial grasses (Allington and Valone 2010, Archer 2010, Wilcox et al. 2010, Peters et al. 2012); (2) shrublands developing on a given grassland location can change functional group or species dominance (e.g. from deciduous to evergreen) at decadal time-scales (Gibbens et al. 2005); (3) cross-scale interactions driving spatial and temporal variation in rates and patterns of woody vs. herbaceous expansion/contraction involve factors that trigger recruitment events, alongside numerous connectivity-mediated feedbacks among drivers, transport vectors (wind, water, animals), and vegetation patches at varying scales (Bestelmeyer et al. 2011a, Ratajczak et al. 2017). The ecological responses to these interactions vary with spatial scale and context, and result in multiple scales of spatial heterogeneity in outcomes (D'Odorico et al. 2010, Turnbull et al. 2010, Browning et al. 2017); (4) cross-scale interactions between soil properties and geomorphology with patch-scale wind and water erosion prevent fine-scale biocrust recovery in locations no longer subject to livestock trampling or similar disturbance (Okin et al. in review; Pietrasiak et al. 2011; 2014); (5) climate non-stationarity interacts with the intrinsic non-linearities, feedbacks, thresholds, lags and legacies that drive plant-, patch- and landscape-scale processes in dryland ecosystems, thus making prediction of future dynamics challenging (***Sala et al. 2012***, Monger et al. 2015, ***Peters et al.*** 2012; ***2014b.*** Note: references in **bold font** throughout the proposal identify the 10 most significant publications of LTER-VI shown in Table 1***)***.

There is a critical need to integrate these recent observations into an evolving conceptual and predictive framework for drylands. We propose to expand our landscape linkages framework (***Peters et al. 2015***) to fill this critical need (Fig. 1).

Our goal is to develop robust principles governing dryland state changes and apply them across spatially heterogeneous landscapes to forecast future states in response to changing climate and land use.

The JRN LTER is uniquely poised to achieve this goal via an integrated research program that includes: (1) a history of leadership in developing theory and conceptual frameworks at the forefront of drylands science, including advances in characterizing alternative states and mechanisms of transitions via the roles of triggers, feedbacks, spatial context, and cross-scale interactions (Wooton 1908, Schlesinger et al. 1990, Archer 1994, Reynolds et al. 2004; 2007, ***Peters et al.*** 2004; 2006; ***2014b***; ***2015;*** in review, ***Bestelmeyer et al.*** 2011b; ***2013;*** in review, Peters and Okin 2017), (2) accessible legacy data quantifying trends in and constraints on drivers (climate, management history, soils), transport vectors, and ecosystem state changes from field observations, experiments, and an extensive imagery library (Buffington and Herbel 1965, Gibbens et al. 2005, Havstad et al. 2006, ***Sala et al. 2012***), (3) established expertise in understanding the role of connectivity by wind, water, and animals within and among spatial units (Peters et al. 2008, Monger et al. 2009, Okin et al. 2009, ***Schooley et al. in revision***, ***Schreiner-McGraw and Vivoni 2017***) coupled with new expertise on the role of role of biological crusts (Garcia-Pichel et al. 2013, Pietrasiak et al. 2013), (4) the development of simulation models, image acquisition and analysis tools, and methods for monitoring, assessment, and prediction of state changes (Vivoni 2012, Hanan et al. 2014, ***Peters 2014a, Okin et al. 2015***, Herrick et al. 2016), (5) experience in transferring state change concepts, information and technology to broad audiences, including K-12 students and teachers, the general public, and private and public land managers (***Herrick et al. 2013***, Peters et al. 2013b, http://www.asombro.org), ***Bestelmeyer et al. 2015***), and (6) in describing the consequences of state changes for the provisioning of ecosystem services and applying this knowledge at regional to global scales (Peters et al. 2008, Anadón et al. 2014, Archer and Prednick 2014, Sala and Maestre 2014, Petrie et al. 2018).

The Jornada Basin is broadly representative of processes affecting drylands globally. Historically, the site exhibited classical grassland-to-shrubland transitions beginning in 1858 (Buffington and Herbel 1965), which now affect virtually all areas. More recently, new alternative states are emerging, including a reversal from shrublands towards perennial grasslands (***Peters et al.*** 2012; ***2014b***), shifts between shrubland types (Gibbens et al. 2005), and non-native grass invasions (McGlone and Huenneke 2004), reflecting a variety of transition processes occurring in global drylands. The site typifies the climate, soils, vegetation, and livestock grazing history of the Chihuahuan Desert. The site's key transport vectors and variety of soils, however, are representative of many drylands. Finally, the site is a critical node in cross-site studies within the LTER Network, the National Ecological Observatory Network (NEON), and other networks where the Jornada represents: (a) a shrubland endpoint to compare with the SEV LTER where large expanses of grasslands still persist (Peters and Yao 2012), (b) a remnant subtropical desert grassland endpoint to compare with the temperate mesic grasslands at the Konza and Cedar Creek LTER sites, (c) an arid rangeland node in the emerging Long Term Agricultural Research network (LTAR) (Petrie et al. 2018), (d) a northern Chihuahuan Desert endpoint to compare with the Sonoran Desert NEON site in southern AZ (Santa Rita Experimental Range), sites in other NEON domains (www.neoninc.org), and (e) arid and semiarid sites globally (e.g., ILTER: www.ilternet.edu).

2. Research Questions and General Approach

In LTER-VII, we will explore how landscape-level spatial heterogeneity evolves in response to the cascading effects of disturbance histories, connectivity-mediated feedbacks, and their interactions with the soil-geomorphic template. We will address the critical need for integration of long-term observations into an evolving conceptual and predictive framework for drylands. We propose to expand our landscape linkages framework (Peters et al. 2006; 2015) to fill this critical need, and to contribute to emerging ecological theory on: (a) alternative states, (b) ecosystem sensitivity under global change, and (c) cross-scale interactions. Our recent activities have positioned us to conceptually and numerically integrate data and knowledge into a *Data Science Integrated System (DSIS)* that will allow Jornada results to be translated to other locations in the Chihuahuan Desert and to drylands globally. New research in LTER-VII will address important unresolved questions:

(1) How can we *integrate* and *analyze* diverse observations of flora, fauna, microbiology, soils, hydrology, and climate within and across spatial and temporal scales to improve our ability to *understand* historic and on-going state changes across spatially heterogeneous dryland landscapes?

(2) How do *pattern-process relationships* interact across a wide range of spatial and temporal scales to drive state change dynamics and regulate the conservation of ecosystem resources? Specifically, under what conditions in time and space are connectivity-mediated *feedbacks* important to state change dynamics at broad scales? Under what conditions do *broad-scale drivers and transport vectors* overwhelm fine-scale feedbacks to govern state change dynamics?

(3) How can we use *knowledge of pattern-process relationships across scales* to promote and prioritize the conservation of biological resources, avert undesirable state changes, and reinforce positive (desirable) state changes, including grassland recovery and restoration? Specifically, how can we apply our understanding of alternative states from intensively-studied locations *to under-sampled locations* across heterogeneous landscapes? How can we *predict future alternative state dynamics* across heterogeneous landscapes accounting for non-stationarity in drivers and temporal contingencies?

(4) How can we make our data *readily accessible* in a timely fashion, our tools more easily used, and our findings better understood by (and relevant to) a broad, diverse audience?

Our integrated research plan will use extensive short- and long-term datasets and multi-scale spatial analyses to quantify a suite of state change dynamics within a framework stressing: *triggers, feedbacks, and spatial heterogeneity*. In our framework, spatial heterogeneity in alternative states is the result of: (1) environmental drivers (e.g., precipitation, temperature, human activities) that trigger (2) transport vectors (wind, water, animals) interacting with (3) patch structure, spatial context, and temporal contingencies and (4) resource redistribution with feedbacks across a range of scales (5) mediated or constrained by geomorphic and topo-edaphic features (Fig. 1). We focus on climate as the predominant driver of this currently shrub-dominated landscape with low and discontinuous grass biomass. We strategically examine the role of livestock grazing through long-term studies (e.g., *ThreshEx*) in collaboration with local USDA and NMSU scientists, and the role of fire with the SEV LTER and others where grass biomass is still sufficient for fire. Our historic land use maps include locations, intensities, and frequencies by disturbance type for comparative studies (e.g., grazing, fire, shrub treatments). In LTER VI, we focused on the role of patches (cover, composition, spatial distribution) in influencing alternative states at the landscape unit scale. Our objectives in LTER VII are more challenging. We seek to:

Obj. 1 to quantify the role of multiple triggers and connectivity-mediated feedbacks interacting with patches and soil-geomorphic patterns on the rate and nature of state transitions

Obj. 2 to explain and predict multi-scale spatial heterogeneity in alternative states

Obj. 3 to apply new analytical concepts and tools developed at the Jornada to broader extents (regional to global) and examine consequences for ecosystem services through our collaborations (Fig. 2).

To accomplish these objectives, we will gather new data and enhance our Jornada Information Management System (JIMS) into a Data Science Integrated System (DSIS) (S2. Data Management Plan, Peters et al. in review). Our diverse temporal data (long-term observations, sensor data, data from investigator-led studies) will be spatially and temporally harmonized with each other and with our spatial data layers to allow the analyses required to address our questions with application to other locations.

Our research will result in five major products: (1) new understanding of state changes, in particular in drylands, that lead to theory development, testable hypotheses, and new experiments; (2) accessible data, derived data products, and visualization tools applicable at multiple scales; (3) a library of explanatory and predictive relationships among drivers, patterns, and processes that can be used to (4) predict dynamics of alternative states at new locations or under future environmental conditions, including applications at broad spatial extents with assessments of their impacts on ecosystem services; and (5) usable information transfer to a broad audience. Our approach is to test hypotheses and unravel pattern-process-driver relationships using existing short- and long-term data from a suite of accessible databases and other lines of evidence in our iterative "Data-Analysis Loop" human and machine learning framework (Fig. 3). New observations and experiments are strategically designed to complement and extend existing data, and incorporate new studies, such as those aimed at elucidating the functional role of biological soil crusts in preventing (or reversing) erosion feedbacks in drylands. This framework requires readily-accessible data. Thus, linking our Data Science Integrated System (Peters et al. in review) with our science program is a top priority (see Data Management plan for details). Our findings will contribute to ecological theory and to the development of strategies aimed at forecasting state changes (Scheffer 2009, Carpenter et al. 2011, Dakos et al. 2013). We will also contribute to advances in restoration ecology, landscape ecology, ecohydrology, novel ecosystems, global change, and Earth system science as well as continuing our contributions to the science underpinning desertification and land management. These products are particularly timely for the United Nations Decade for Deserts (2010-20) and the fight against desertification (http://unddd.unccd.int/).

3. Landscape Linkages: Developing a Unified Framework for Alternative States

Our current 'landscape linkages' framework reflects the evolution of the Jornada. LTER-I to -III (1982-2000) focused on causes and consequences of desertification governed by processes at the plant-interspace scale (e.g., Schlesinger et al. 1990, Wainwright et al. 2002). LTER-IV and -V (2000-2012) considered redistribution of resources and organisms across multiple scales with a focus on patch structure and connectivity, and how these pattern-process relationships might explain spatial variation in desertification dynamics (e.g., Peters et al. 2004; 2006, Okin et al. 2009). A conceptual framework for quantifying the redistribution of resources across a hierarchy of spatial scales was developed (Fig. 1) where we hypothesized that interactions among six elements connect levels of the hierarchy and generate complex dynamics across heterogeneous landscapes: (1) legacies of past climate, management practices, and disturbance; (2) current and future environmental drivers, (3) the soil-geomorphic template that determines how relatively static soil properties (e.g., texture, depth) and geomorphology promote or constrain effects of (1) and (2); (4) biotic properties and their spatial arrangement; and (5) horizontal and vertical transport vectors interact to drive state change by (6) redistributing resources within and between patches. Interactions and feedbacks among these elements propagate across space and over time to elicit threshold changes in patch structure and associated process rates, culminating in broad-scale state transitions (i.e. "cross-scale interactions"; Peters et al. 2004; 2006). Thresholds are crossed when a change in driver or dominant process changes the slope of a response(s) (Peters et al. 2007). Spatial variability in land-surface or driver properties, including local soil properties and adjacency to features such as seed sources, and temporal contingencies, such as legacies, control the evolution of spatial heterogeneity in a landscape (Yao et al. 2006). Our framework was applied to other types of ecosystems (*Ecosystems* 2007 Special Feature), and was extended to explain regional to continental scale dynamics that contributed to the initial design of NEON (*Frontiers in Ecology and the Environment* 2008 Special Issue).

In LTER V and VI, we tested and confirmed elements of our conceptual framework in the context of grassland to shrubland transitions. Notably, we demonstrated that state change is a function of: *(i) temporal contingencies* (legacies: Reichmann and Sala 2014, Monger et al. 2015; future climate: Gherardi

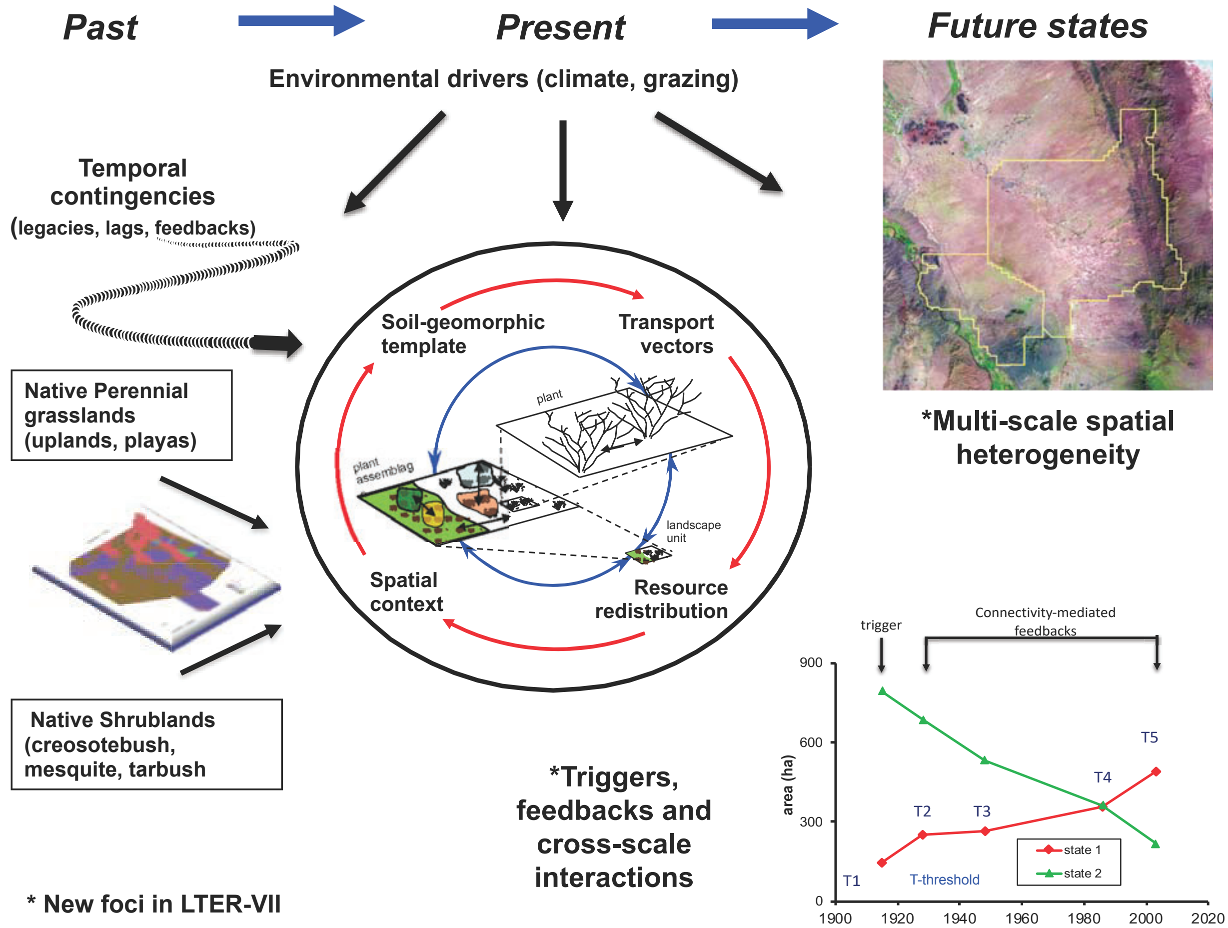

Fig. 1 Jornada framework for alternative states based on a hierarchy of interacting scales and connectivity-mediated redistribution of resources. Interactions among six key elements connect levels of the hierarchy and generate complex dynamics across heterogeneous landscapes: (1) legacies of past climate, management practices, and disturbance; (2) current and future environmental drivers, (3) a soil-geomorphic template that determines how local properties (e.g., soil texture, depth) and geomorphology promote or constrain effects of (1) and (2); (4) biotic properties and their spatial arrangement; and (5) horizontal and vertical transport vectors interact to drive state change by (6) redistributing resources within and between spatial units. Interactions and feedbacks among these elements propagate within, and in some cases across spatial scales, to elicit threshold changes in patch structure and associated process rates that culminate in broad-scale state transitions. **New studies in LTER VII** are designed to investigate: triggers of state change and connectivity-mediated feedbacks that maintain or accelerate transitions between states that lead to cross-scale interactions in time and spatial heterogeneity across the Jornada landscape.

and Sala 2015b), and *(ii) spatial context and contagion* (biotic properties of spatial units: Peters et al. 2010, redistribution of resources within and between units: ***Schreiner-McGraw and Vivoni 2017***, interacting transport vectors: Okin et al. in review), and *(iii)* the *soil -geomorphic template* (Weems and Monger 2012, Michaud et al. 2013). A major outcome was the development of concepts and metrics associated with bare soil gaps (another patch type) now used in drylands globally (e.g., Herrick et al.

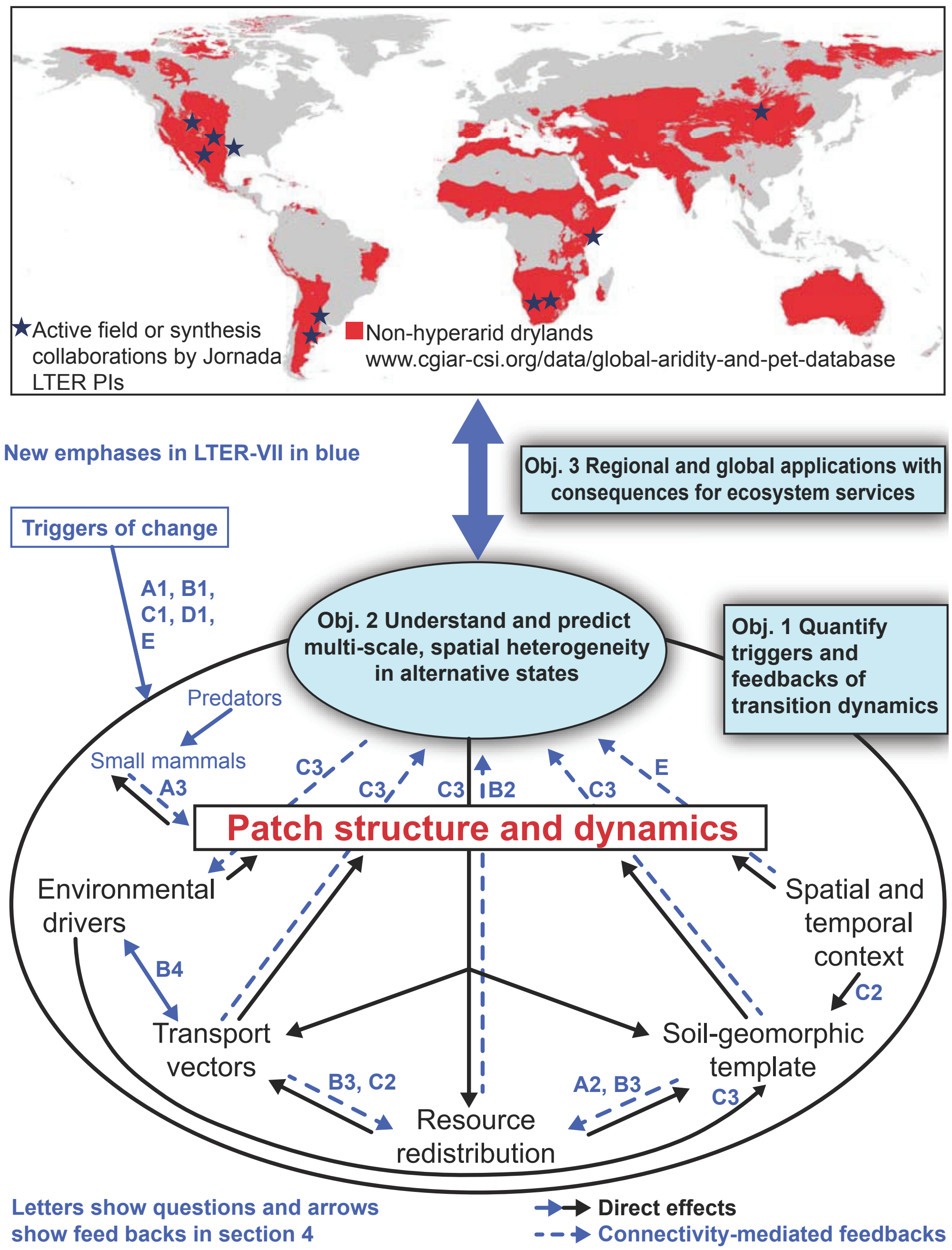

Fig. 2. Major objectives for Jornada LTER-VII are to transform our understanding of alternative states in drylands by quantifying triggers and feedbacks that lead to spatial and temporal heterogeneity in transitions at multiple scales from patch to landscape, regional and global. Key LTER-VII Research Questions and feedbacks are shown in blue text and arrows (A1. B1. etc. described in Section 4.2).

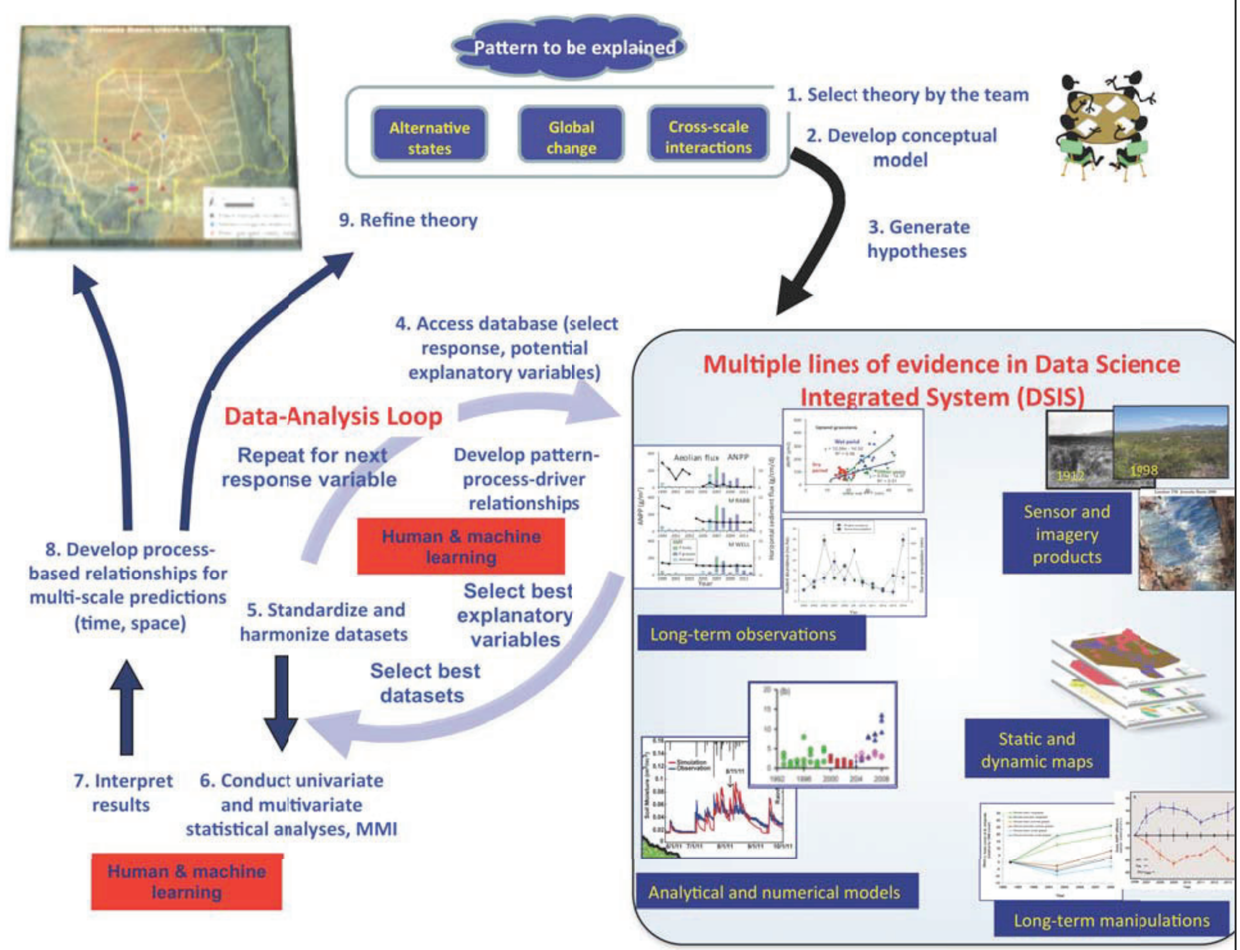

Fig. 3. Framework for data-model integration and hypothesis testing in trans-disciplinary research. An approach based on spatio-temporal modeling combined with human and machine learning to select, integrate, and analyze data and knowledge drawn from multiple lines of evidence (i.e., short- and long-term observations, experimental manipulations, analytical and numerical models, products from imagery, conceptual model reasoning, theory). Nine steps are used to investigate a pattern that needs to be explained: (1) select a theory (three examples from drylands are shown), (2) develop a conceptual model of the system, (3) generate testable hypotheses, (4) access the database of multiple lines of evidence to select a response variable and potential explanatory variables that include developing pattern-process relationships, select best explanatory variables and corresponding datasets; this step is often iterative with learning as the databases is accessed multiple times for different explanatory variables to improve the statistical relationship. Machine learning can be used to optimize this process (e.g., Peters et al. 2014a). (5) standardize and harmonize datasets and iterate for the next response variable, (6) conduct univariate and multivariate statistical analyses including multi-model inference (MMI) and machine learning procedures (e.g., MaxEnt), (7) interpret the results, (8) develop process-based relationships for the landscape predictions in time and space, and (9) refine the theory (Peters et al. in review).

2006b). These gaps control redistribution of soil, water, nutrients, seeds, and other plant material, and are key to operation of plant-soil feedbacks at multiple scales, and govern erosion-deposition processes. We now routinely measure bare soil gap size distributions in our experiments and multi-scale analyses.

In LTER VI, we also expanded our research to examine transitions: (a) from degraded shrublands towards perennial grasslands, (b) between shrublands dominated by contrasting shrub functional groups, and (c) shifts from grasslands or shrublands towards novel ecosystems. For each transition type, we quantified patterns through time and initiated mechanistic studies to explain those dynamics (e.g., ***Peters et al. 2014b***). We initially assumed a high degree of soil-geomorphic fidelity in these transitions (e.g., black grassland (*Bouteloua eriopoda* to mesquite shrubland (*Prosopis glandulosa*) transitions only occur on the sand sheet). However, we now believe that different types of transitions occur in multiple soil-geomorphic settings based on fine-scale reconstructions. Accordingly, in LTER-VII we will seek to generalize our conceptual framework to accommodate this new perspective.

Our initial transition studies in LTER VI provide qualitative support for the dynamics of our cross-scale interactions framework, first proposed in 2004 (Peters et al. 2004). Threshold-feedback processes involved in shrub encroachment also occur when grasses re-establish into degraded shrublands: perennial grass recruitment is triggered by a sequence of wet years followed by positive feedbacks allowing them to persist in subsequent dry periods (***Peters et al.*** 2012; ***2014b***). Spatial variability in soil properties and other contextual components result in spatial heterogeneity in grass recovery across a landscape (Peters et al. in review). While 'triggers' are at play in both state transitions, the nature of the triggers differs: grasses require a series of above-average precipitation years (***Peters et al. 2014b***) whereas shrub encroachment is triggered by livestock overgrazing or drought (Buffington and Herbel 1965).

Next steps in our Conceptual Framework

We are now positioned to **quantify the components of this "trigger-feedback-heterogeneity**" framework for our four transition types and to develop a comprehensive, unified framework for dryland landscapes that will be applicable beyond the Jornada and the specific vegetation-soil-geomorphic associations of the Chihuahuan Desert. Transition **triggers**, including disturbance (e.g., grazing, drought) or resource pulses (rainfall), that push systems across critical thresholds have effects at the finest spatial scales, at the level of individual plants or plant/crust patches (Scheffer et al. 2009, ***Bestelmeyer et al. 2013***) (Fig. 1). Changes at these levels initiate connectivity-mediated **feedbacks** at expanding spatial scales, involving resource redistribution from bare soil to adjacent plant patches (Schlesinger et al. 1990, Alvarez et al. 2012, Svejcar et al. 2015) or from one landform to another (Monger et al. 2015). These feedbacks create and reinforce patchiness (Rietkerk et al. 2004) and can lead to pronounced shifts in vegetation composition, soil function, and ecosystem processes at local to landscape scales (Okin et al. 2009) with potential consequences for land surface-atmosphere feedbacks (Beltrán-Przekurat et al. 2008).

Trigger-feedback effects are mediated by: (a) the soil-geomorphic template, including variations in inherent (e.g., parent material) and dynamic soil properties (e.g. surface sand, organic matter, microtopography) that change at different rates relative to vegetation transitions, and the spatial organization of landforms that govern climate and potential aeolian or hydrological connections, (b) spatial context or adjacency to land surface features (e.g., historic shrub populations that affect seed availability), and (c) temporal contingencies, including land use legacies (Fig. 2). Climate variability and land use affect rate, type, and magnitude of change within each spatial scale. Changes in patch structure (vegetated and bare) locally modify transport vectors and drivers to influence resource redistribution and connectivity across scales, and attenuate or amplify processes that propagate and culminate in broad-scale state changes. Collectively, these effects control the evolution of **spatially heterogeneous dryland** landscapes (Fig. 1).

Triggers and the magnitude of feedbacks appear to differ depending on climate, landform, and soils, such that a trigger of a given magnitude may result in stability, gradual change or rapid transition (Bestelmeyer et al. 2006, Browning et al. 2012). Complexity, contingency, lags, thresholds, feedbacks, and the interdependence of system components are major obstacles to prediction in ecosystem science.

We propose to test the proposition that an explicit accounting of triggers, feedbacks, and spatial heterogeneity in the context of patch and geomorphic structure, temporal context, and cross scale interactions will improve our predictive capabilities by resolving what heretofore have been seeming controversies, such as the singular, dominant causes of state changes, and a large pool of unexplained variance (Archer and Bowman 2002, Peters et al. 2006, Archer et al. 2017).

4. Proposed Research for LTER VII (2018-24)

The 100,000 ha Jornada Basin site, located in the northern Chihuahuan Desert (Fig. 4), is managed by the USDA Agricultural Research Service and New Mexico State University. Mean annual precipitation over the past 80 years is 24 cm; average temperatures range from 13°C in January to 36°C in June. The Jornada consists of four geomorphic units defined by soils, topography, and current vegetation that are characteristic of the Basin and Range Physiographic Province (Monger et al. 2006). Research dating to the 1920s initially focused on the basin and bajada (see Havstad et al. 2006). These locations were studied and managed separately until re-analyses of species distribution maps in LTER-VI showed historic commonalities that have been used to test specific predictions from our conceptual framework. In 1858, both the basin and the bajada were dominated by black grama grasslands with interspersed shrubs (mesquite, tarbush, creosotebush) representing contrasting functional groups (e.g. evergreen v. deciduous; N_2-fixing v. not; long- v. short-lived; drought -avoidance v. drought tolerance) (Fig. 4.1a). Livestock overgrazing in the late 1800s interacting with periodic drought reduced grass cover throughout the northern Chihuahuan Desert, and provided opportunities for shrub recruitment and growth. Mesquite proliferation was evident in the basin in 1915, whereas the bajada was tarbush-dominated by this time (Fig. 4.1b). Creosotebush then displaced tarbush on the upper bajada by 1928, with tarbush communities persisting on the lower bajada (Fig. 4.1c). By 1998, mesquite, tarbush and creosotebush shrublands characterize the basin, lower bajada and upper bajada, respectively, while tarbush and mesquite are important sub-dominants in the bajada communities (Fig. 4.1d). Although not shown at the resolution of these maps, patches of native (black

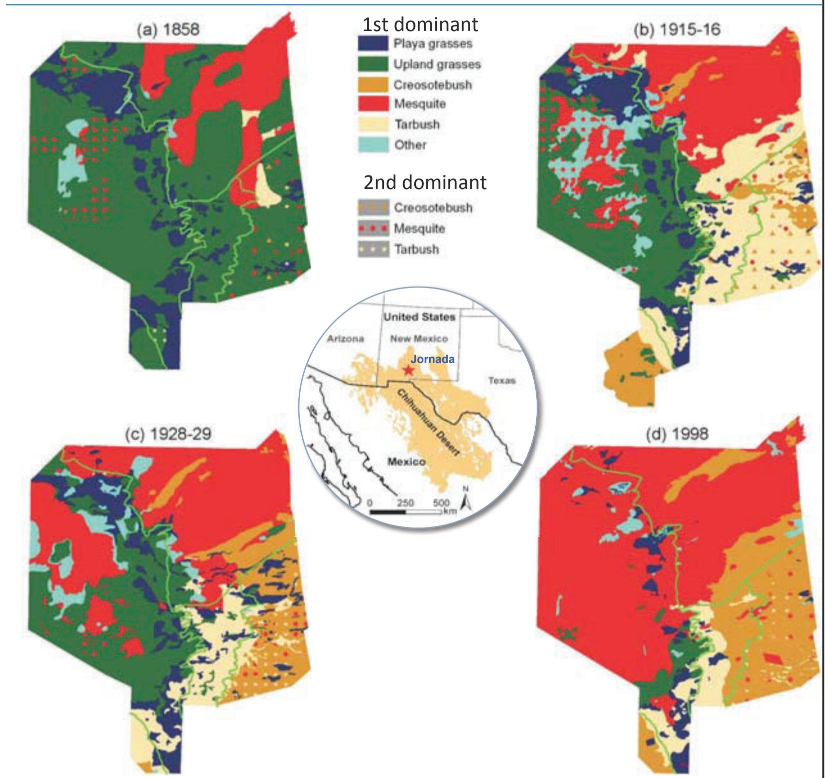

Fig. 4. Jornada vegetation maps showing first and second dominant species: (a) 1858, (b) 1915-16; (c) 1928-29, (d) 1998 (modified from Gibbens et al. 2005). Note major transitions from grasslands to shrublands and shifts between shrublands. We will create an updated species map in LTER VII using a combination of remotely-sensed data, geo-referenced species data from numerous ongoing studies, maps of environmental variables, machine learning (presence/absence) and multi-model inference (abundance) approaches.

grama, dropseeds, bush muhly) and exotic (Lehmann's lovegrass) perennial grasses are present and have increased locally since 2004, coincident with a sequence of wet years. Thus, the potential is high for shifts in species and functional group abundance under future environmental conditions.

Some of these observations are consistent with our knowledge base: patterns of mesquite expansion in the basin are well-documented (e.g., Okin and Gillette 2001), and the importance of interactions among aeolian processes, mesquite plants, and bare soil gaps in driving these dynamics has been the focus of a number of our studies (e.g., Okin et al. 2006). Similarly, the role of soils and hydrologic connectivity in maintaining tarbush on the lower bajada and creosotebush on the upper bajada has been investigated for decades (e.g., Wondzell et al. 1996, Weems and Monger 2012). **We cannot, however, account for key aspects of four critical state transitions:** 1) Grassland to shrubland transitions (G →S): the interplay between livestock overgrazing and drought as triggers of perennial grass loss leading to shrub encroachment remains a black box for aridlands globally (Archer et al. 2017). Quantifying interactions among these triggers on thresholds of grass loss required for shrub recruitment will advance our understanding of desertification mechanisms and refine emerging theory on the role of factor interactions in threshold phenomena. 2) Shrubland to grassland transitions (S → G): grass recruitment in desertified shrublands in recent years suggests climate variability (e.g., a sequence of wet years) has the potential to initiate state change reversals, but the nature of climatic events and processes necessary to trigger grass recruitment and long-term persistence are unknown. 3: Shrubland to shrubland transitions (S → S): shrub-dominated states are more dynamic than previously believed. The future of these ecosystems is unknown: will drought-avoiding mesquite give way to creosotebush, a true xerophyte? Will tarbush be lost entirely or will it expand under future climatic conditions? Will aeolian and hydrologic processes, and interactions with biotic crusts, differentially influence shrub functional groups? 4: Transitions to novel states (G/S → N): increases in non-native grasses in other deserts suggest that the future of the Chihuahuan Desert may include new species assemblages and novel ecosystems, but we are ill-equipped to predict rates, spatial patterns, and consequences of spread. **These four types of state transitions occur in drylands worldwide; the knowledge gaps associated with them will be addressed in LTER-VII.**

Our research activities are organized into four major sections to allow us to address these knowledge gaps, and test hypotheses relevant to these four transitions and their spatial distribution across dryland landscapes. Within each section, we provide results from LTER VI as the basis for new research. Section 4.1: Core long-term studies have been re-evaluated. Some will be maintained, others will be continued with restructuring aimed at freeing up resources for other activities, and others will be expanded and integrated with other studies to experimentally evaluate key elements of our conceptual framework. Section 4.2: New studies for each transition type will integrate existing short- and long-term core data with new analyses, strategic collection of new data or implementation of new manipulations. The new studies are designed to investigate **triggers** of state change and connectivity-mediated **feedbacks** that maintain or accelerate transitions between states. Section 4.3: Creation of a comprehensive database linking geospatial environmental data (land-, air- and space-based products), output from process-based numerical simulators, and data from observational and experimental studies gathered over the past century with new big data and machine learning approaches to explain spatio-temporal variations in state transitions. Our goal is to develop capabilities to predict future transitions across the **spatially heterogeneous** Jornada landscape with non-stationary drivers. Section 4.4: Extending data, analysis, and insights to regional, continental, and global scales via network participation and leadership alongside analysis of data collected in collaboration with partners, including local government agencies and international organizations. Our goal is to apply the concepts and tools developed at the JRN site to solve land management problems in global drylands, and facilitate the use of our data for identifying global scientific generalities.

4.1 Existing core long-term studies and sensor network

Core long-term studies and distributed sensors provide: a) the context for short-term and new efforts; b) data to discern trends from natural variability; c) insights needed to design new experiments; and d) comparative data for the LTER network, other research sites nationally and globally, and emerging networks such as NEON and the LTAR (Fig. 5). We have been collecting long-term data for each core area since the 1980s. Details of each study are shown in Suppl. Table A1, and core long-term study names are shown in italics below. Spatial and temporal variation in environmental drivers and transport vectors will continue to be monitored via our sensor network. The number, type, and wireless connectivity of sensors are upgraded as funding permits. Two priorities for LTER VII are the expansion of our air temperature network to capture spatial variation in extreme events (e.g., unusual freeze in 2011) and an increase in the frequency and density of soil water measurements. We also continue to recover historic information, and to add it to our map library of elevation, hydrology, soils, management practices, vegetation, and extensive image library that dates to the 1930s. We continue to work with NM State archeologists to document the location of prehistoric Jornada Mogollon encampments. Our interactive Jornada App (available on Google Play and iTunes ['Jornada Arid Land Research'] contains our base maps with options for users to obtain and add geo-tagged data acquisition, study locations, field notes, and photographs.

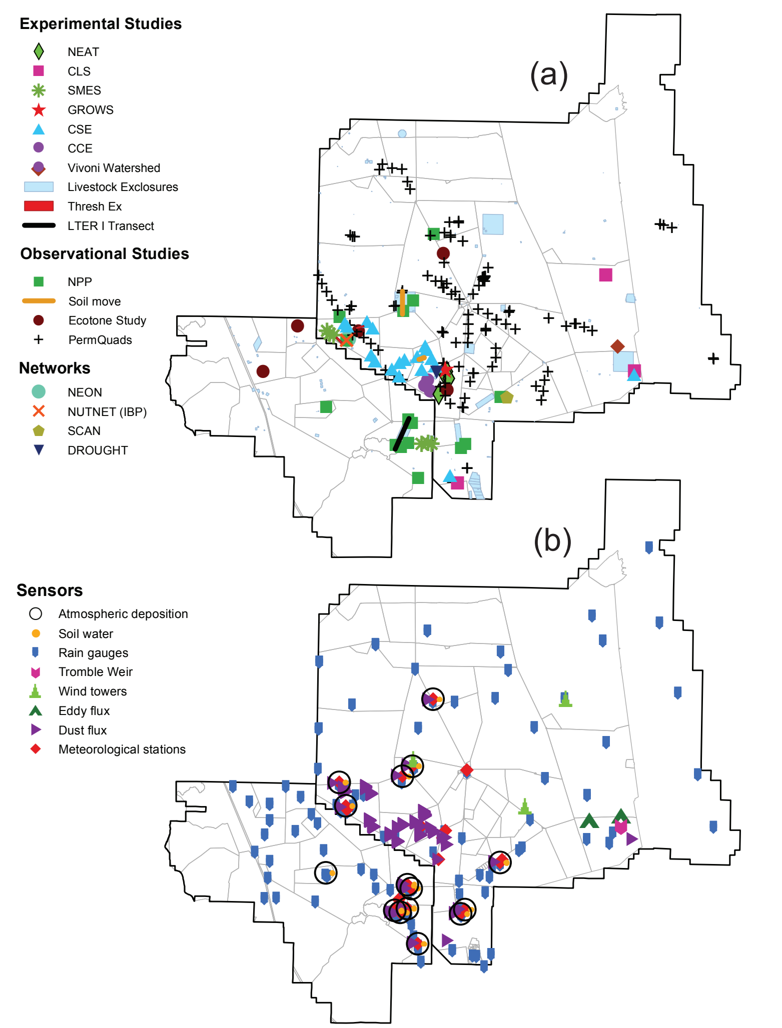

Fig. 5. Jornada research site showing locations of (a) core long-term studies and (b) sensor networks.

4.2 Integrated site-scale studies of state transition dynamics

Obj. 1 to quantify the role of multiple triggers and connectivity-mediated feedbacks interacting with patches and soil-geomorphic patterns on the rate and nature of state transitions

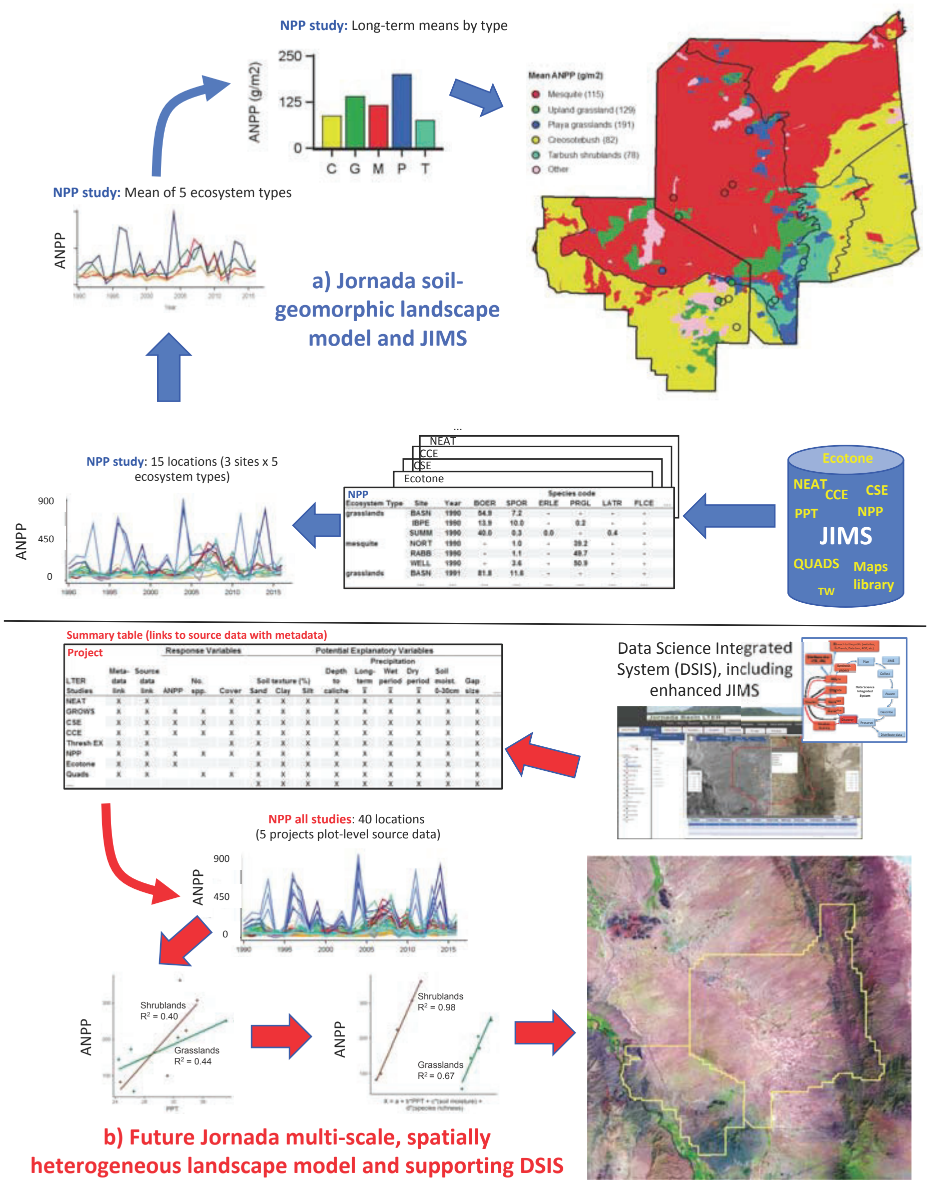

Fig. 6. Comparison of previous and future approaches: (a) Jornada I-VI model where the Jornada landscape was simplified by associating ecosystem processes (e.g. ANPP-PPT relationships) and state transitions to specific soil-geomorphic units. Our JIMS (information Management System) contains each project with associated data and metadata as searchable entities with limited ability for cross-project queries. (b) Proposed Jornada VII multi-scale spatially heterogeneous landscape model where the four transition types and their states can occur anywhere at multiple scales across the landscape. Our enhanced JIMS contained within our new DSIS (see S2. Data Management Plan) with a common database structure containing links to source data and metadata will allow queries, integration of data, and analyses across multiple projects. One example is shown as an illustration of the power of our future DSIS.

Previously, we simplified the Jornada landscape by associating ecosystem processes (e.g. ANPP-PPT relationships) and state transitions to specific geomorphic units (Fig. 6a). This disentangling approach facilitated a deep understanding of the processes and drivers governing patterns at fine to intermediate spatial and temporal scales (Havstad et al. 2006, Peters et al. 2012). While generating novel insights, this approach: (1) ignores the role of connectivity as a driver of change among geomorphic units across the landscape, (2) assumes that inferences can be reliably applied to other locations within a soil-geomorphic unit, (3) fails to address how independent, uncoordinated studies established on "representative, local areas" of interest for particular reasons can be applied across heterogeneous landscapes where large areas remain under-sampled and under-characterized (e.g., NE part of JRN; Fig. 5a), and (4) presents substantial integration challenges for data collected from short- and long-term *ad hoc* investigations with inconsistent response and explanatory variables, methods, timings and durations.

Our new approach in LTER-VII is based on an integrated landscape paradigm wherein the four transition types and their states the four transition types can occur anywhere and at multiple scales across the landscape. This approach is more comprehensive in time and space, and represents heterogeneity more realistically (Fig. 6b). Accordingly, it is a more realistic view of dryland landscapes. For example, G → S transitions have historically occurred throughout the Jornada Basin, including on the piedmont slope bajada in the 1850s (Gibbens et al. 2005), and are currently common on these landforms and soils throughout the Chihuahuan Desert (e.g., Big Bend, TX; Sevilleta LTER) and neighboring Sonoran Desert (Santa Rita NEON). Furthermore, small patches of grass recovery in shrublands indicative of early S → G transitions occur throughout the Jornada Basin (Herrick et al. 2006b). Our general approach includes a premeditated integration of multiple lines of evidence: (a) conceptual and theoretical frameworks, (b) new and existing short- and long-term data from different studies (Suppl.Table A1), (c) a suite of new and integrated cross-scale field experiments, (d) libraries of geo-referenced maps and imagery products, (e) suite of analytical tools and numerical simulators, and (f) forecasts of alternative landscapes state change dynamics in future environments. We will use our suite of numerical simulators: to generate testable hypotheses and guide experimental designs, to explore outcomes of multi-dimensional, multi-scale interactions among system components, and to backcast and forecast system conditions. Our simulators can address fine-scale vegetation and soil water dynamics (ECOTONE and SOILWAT, Peters 2002, Peters et al. 2010), wind and aeolian redistribution (WEMO, Okin 2008), and horizontal water redistribution (Vivoni et al. 2009). These simulators will be inter-linked as needed to address specific questions.

Our aim in LTER VII is to determine the interactions of drivers and processes generating the triggers and feedbacks producing state transitions, and how spatial context and temporal contingencies mediate those interactions to amplify or attenuate multi-scale spatial heterogeneity. We propose to integrate multiple lines of evidence from specific study locations and time periods in a process-based framework by accounting for spatial heterogeneity in patterns and temporal nonlinearities in processes at multiple interacting scales (Peters et al. in review). The approach will use data from multiple, spatially-distributed transition types to develop general principles to allow application to new locations and new time periods. *Working with our Data Science Team, we will elevate our Information Management System to be a Data Science Integration System (DSIS) to support the integration needed to address our questions (Fig. 6b).*

Long-term studies on specific geomorphic units will continue, but our approach will strategically fill knowledge gaps through additional: (a) experiments, (b) locations, (c) response variables, and (d) integrated analyses of our long-term datasets. This approach will enable us to develop general relationships that are not linked to specific ecosystem or geomorphic types. Below we describe the new and continuing experiments and analyses within each transition type to fill these knowledge gaps regarding the role of triggers and connectivity-mediated feedbacks.

A. Grassland to shrubland (G→S) transitions (B. Bestelmeyer, Okin, Schooley, Garcia)

Grassland to shrubland transitions are primarily triggered by overgrazing, especially in the context of acute drought (Peters et al. 2006, ***Bestelmeyer et al. 2013***). Once perennial grass cover is reduced below a critical, but as yet undefined threshold, feedbacks associated with wind and water erosion are hypothesized to reinforce declines in grass cover and opportunities for shrub recruitment and persistence (Alvarez et al. 2012, D'Odorico et al. 2012). Grazing and soil erosion also diminish ability of soil biocrusts to influence soil water holding capacity, fertility, and stability (Belnap and Gillette 1998, Rossi et al. 2012, Zhang et al. 2016), but the extent to which changes to biocrusts might differentially influence grass vs. shrub recruitment and persistence is unknown. Shrub proliferation also alters small mammal abundance and can lead to increased herbivory on grasses (Bestelmeyer et al. 2007). The proposed studies aim to quantify the roles of these triggers and feedbacks on G→S transitions.

Q-A1: How do the intensity and duration of grazing and drought interact to trigger grass loss? (a new experiment within an existing long-term experiment *[ThreshEx]*)

LTER VI results from the long-term experiment (*ThreshEx:*1996-) investigating heavy grazing as a driver of state transitions showed a threshold response in only one heavily grazed paddock (Fig. 7; ***Bestelmeyer et al. 2013***). Subsequent analyses suggest that both grass cover *and* patch size may need to be reduced to extremely low levels before thresholds are crossed (Svejcar et al. 2015). In other JRN studies without grazing, drought reduces cover and reproductive potential of grasses (Reichmann and Sala 2014). Based on mathematical simulations, the duration of the disturbance press (i.e., number of consecutive years) may be a more important determinant of threshold conditions than disturbance intensity in any given year (Ratajczak et al. 2017). New experiments are needed to elucidate how grazing x drought x disturbance duration interactions contribute to state transition thresholds. Our new experiment, *ThreshEx2*, will address these interactions within the existing *ThreshEx* paddocks.

Hypothesis**:** Grass basal cover decline will be fastest and its recovery after cessation of a grazing-drought press will be slowest with more intense drought, higher grazing pressure, and longer press duration.

Study design**:** Six 0.5 ha paddocks of the original *ThreshEx* experiment with similar initial grass cover and shrub cover will be treated as blocks in the *ThreshEx2* experiment. Treatments within each block will include three levels of rainfall reduction, three levels of defoliation, and three levels of press duration (2, 4, and 8 consecutive years). Rainout shelters will be established following protocols in Gherardi and Sala (2015b). Basal cover and ANPP will be measured prior to July defoliation events.

Expected results**:** This experiment will test recent theoretical developments regarding the role of interacting factors in determining the rate of approach to ecological thresholds (e.g., Karssenberg et al. 2017, Ratajczak et al. 2017).

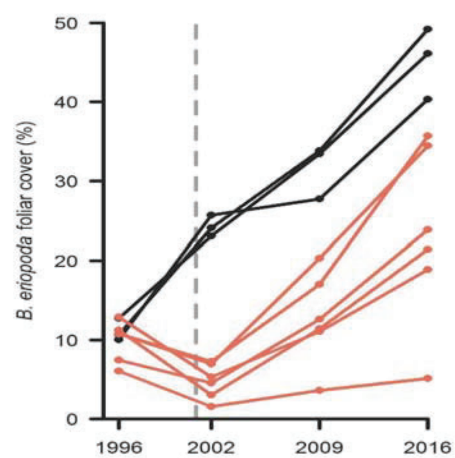

Fig.7. Change in black grama (*Bouteloua eriopoda*) cover in response to 'no grazing' (black lines) and summer or winter grazing (red lines) (*Bestelmeyer et al. 2013).*

Q-A2. How do biological soil crusts interact with wind erosion to feedback to crust establishment and soil stability? (augmenting a long-term aeolian experiment [*NEAT*])

LTER VI results from a long-term experiment (*NEAT:* 2004-) continue to show that transport by wind is an important component of feedbacks driving and reinforcing state change (***Okin et al. 2015***). Areas downwind of treatment plots continue to experience grass loss (Alvarez et al. 2012), and deposition of eroded material from upwind has begun to unexpectedly erode as the scouring front from the erosive area moves into the downwind area. Depletion of SOM in the eroded areas and winnowing of transported soil continues to deplete C and N in downwind areas (Li et al. 2017). We propose to investigate effects of ongoing wind erosion on vegetation and biocrusts, and their potential feedbacks to reducing erosion by stabilizing surface soil. As a new addition to *NEAT*, we will monitor the fate of crust inoculum introduced on surfaces with contrasting erosion legacies, and then quantify feedback effects of differential crust cover on local erodibility.

Hypotheses**:** a) Burial and scouring are spatially contagious and a non-linear function of total horizontal aeolian flux; the zone of grass mortality and losses of soil C and N are controlled by the zone of burial and scouring. b) Survival *in situ* of inoculum and establishment of mature biocrusts is inversely related to total horizontal aeolian flux. The threshold wind speed for wind erosion increases nonlinearly with cyanobacteria in crust (measured as areal chlorophyll concentration). The combination of these two factors results in a threshold of aeolian transport for the successful establishment and maintenance of biocrusts and their contribution to soil stability.

Study design**:** We will continue to monitor changes in soils and vegetation using established methods, including soil height (erosion bridge), horizontal aeolian flux, plant cover and bare gap distribution, and plant height. We will add high-resolution UAV imagery as a novel method to measure vegetation cover/ height and soil height (Zhang and Okin submitted). Soils will be resampled per Li et al. (2007) and analyzed for SOC, total N, and key cationic and anionic nutrients. In addition, we will obtain biocrust inoculum from remnant crusts near the NEAT site (year 1) propagate it in biocrust nursery (Velasco Ayuso, 2017), and add it to 3 x3 m subplots that encompass gradients of aeolian flux within the *NEAT* site. Plots will be monitored quarterly. Crust cover will be assessed by UAV equipped with a multispectral IR-enabled camera (Rodríguez-Caballero et al. 2017). Crust biomass will be assessed by discrete sampling for Chlorophyll a (Velasco Avuso et al. 2017). The origin of developing crusts (from inoculum, from other sources, mixed) will be assessed by DNA sequencing and bioinformatics analyses to trace the source of natural inoculum and establish spatial constraints to recovery by comparing fine-scale genetic pedigrees of dominant microbes (Garcia-Pichel et al. 2013).

Expected results**:** This experiment will build an understanding of how wind-driven changes to soil height (burial and scouring) can affect grass growth and mortality to amplify wind's role as a feedback in shrub encroachment. The new biocrust component will enable us to identify aeolian transport thresholds for biocrust survival and development, and their contribution to the soil stability facet of G→S transitions.

Q-A3. How do trophic interactions and time lags in small mammal and predator populations impact grass mortality across heterogeneous grass- and shrub-dominated landscapes? (augmenting a long-term small mammal study [*Ecotone]*)

Rodents and lagomorphs can reinforce G→S transitions via selective herbivory on grasses and through biopedturbation that disrupts seedlings (Brown and Heske 1990, Whitford and Bestelmeyer 2006). As shrubs proliferate, pressure on remaining grasses intensifies (Kerley et al. 1997, Bestelmeyer et al. 2007). Rodent and lagomorph abundance is mediated by PPT, with a ~1-y time lag (Lightfoot et al. 2012). Mammalian predators track these changes, with an additional lag (Hernández et al. 2011) to mediate small mammal abundance (Henke and Bryant 1999, Letnic et al. 2011) and hence their impact on vegetation. However, shrub encroachment also alters both predator abundance (Blaum et al. 2007) and prey perceptions of predation risk (their 'landscape of fear', Laundré et al. 2014). At the JRN, black grama seedlings suffered higher mortality from herbivores in shrublands than in grasslands, but this outcome was not explained by differences in herbivore abundance (Bestelmeyer et al. 2007). ***LTER VI results*** showed that wet periods with increased ANPP can trigger lagged rodent irruptions, and rodent biomass is higher on shrub-dominated sites due to transient dynamics of herbivores (Fig. 8; ***Schooley et al. in revision***). Herbivory exclosures increased reproductive potential of black grama during the wet period, but this did not translate into improved grass establishment (Svejcar et al. in revision). In contrast, rodent biomass during drought is produced mostly by core species. Hence, bottom-up control of desert rodents depends on the interplay between lagged responses to ANPP pulses and core-transient dynamics moderated by shrub cover (***Schooley et al. in revision***). Top-down control of small mammals by predators with feedbacks to state change dynamics at the JRN are unknown. Given these interactions and time-lines, we are challenged to predict small herbivore influences on G→S transitions.

Hypotheses: (a) Differential time lags to high-precipitation triggers for grasses (0 yr), consumers (1 yr), and predators (2 yr) will create unique windows when consumers can limit grass establishment (1 yr post trigger), and when predators limit prey (trophic cascades) and relax small mammal pressure (2 yr post trigger). (b) Small mammal effects on grasses will be stronger in shrublands than in grasslands.

Study design**:** The core *Ecotone Study* includes 3 spatial blocks each with 3, 3-ha ecosystems (black grama grassland, ecotone, mesquite shrubland) on which small mammal communities, vegetation cover, precipitation, and ANPP have been sampled since 2004 (***Schooley et al. in revision***). Wildlife cameras quantifying abundances of lagomorphs and mammalian predators have been deployed since 2014 (DaVanon et al. 2016). We will continue this monitoring, and expand camera-trap sampling to 8 new sites dominated by creosotebush. We will also quantify the landscapes of fear (Laundré et al. 2014) for lagomorphs across shrub cover gradients using flight initiation distances (Camp et al. 2012). Finally, we will assess herbivory potential via field experiments by placing grass seedling trays at each site and tracking survival for 2 months (Bestelmeyer et al. 2007, DaVanon et al. 2016).

Expected results**:** This study will provide a novel, comprehensive understanding of how G→S transitions and PPT variability influence bottom-up and top-down processes for mammalian consumers and their potential for herbivory of grasses with consequences for G→S transitions.

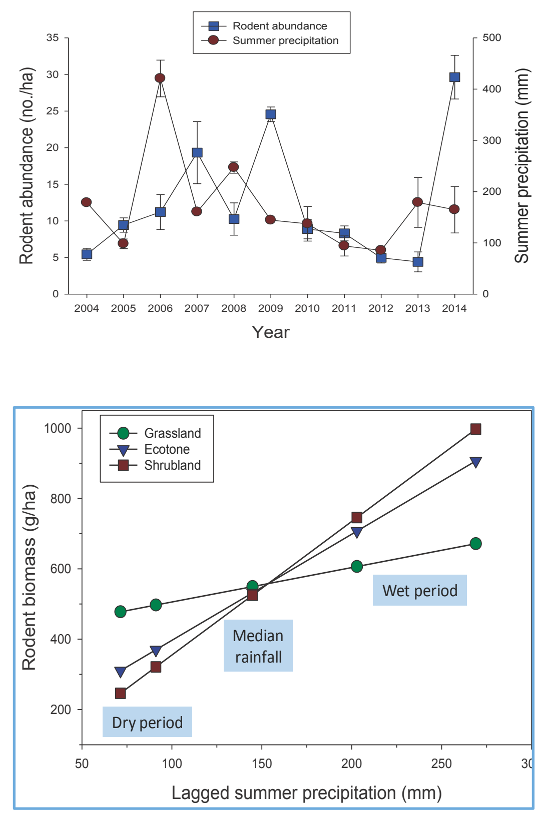

Fig. 8. (a) Rodent abundance lags PPT at the JRN, (b) rodent biomass is higher in shrublands in wet periods and higher in grasslands in drought (***Schooley et al. in revision***).

B. Shrubland to grassland (S→G) transitions (Peters, Sala, Okin, B. Bestelmeyer, Browning)

Grass restoration following woody-plant encroachment is a major challenge in drylands (Arnalds and Archer 2000, Reynolds et al. 2007). Although G→S→G transitions have occurred several times during the Holocene due to climate change (Van Devender 1995, Monger et al. 2009), the most recent S→G shift occurred at a much faster rate (100-150 years) as an unintended result of land use practices acting in concert with drought (Humphrey 1958). Efforts to restore grasses following shrub encroachment either failed (Herrick et al. 2006b, Archer et al. 2011) or required decades for a modest grass response (Allington and Valone 2011, Masubelele et al. 2014). Facilitation of S→G transitions has thus been elusive. ***LTER VI results*** showed that a multi-year (2004-08) wet period at the JRN triggered a sequence of demographic processes in degraded shrublands wherein perennial grass recruitment was correlated with summer PPT, seed production 2y prior, and the number of consecutive wet years (***Peters et al.*** 2012;

2014b). Simulation modeling suggested another potential mechanism: increasing herbaceous biomass and litter reduced bare-soil evaporation and led to **positive feedbacks** via increases in plant available water to grasses (***Peters et al. 2014b***). During this wet period, grass ANPP was not directly related to PPT as expected based on studies in other grasslands (e.g., Lauenroth and Sala 1992, Knapp et al. 1998), but ANPP increased nonlinearly with the number of consecutive wet years (Peters et al. 2012).

Q-B1: How does rainfall variability interact with grazing and soil context to amplify or suppress triggers of grass recovery? (new integrated analyses using long-term data)
Long-term data offer the opportunity to quantify triggers of grass recovery by comparing two wet periods [1984-88 (poor recovery) and 2004-08 (good recovery)] (Fig. 9). While water year PPT was above-average in both periods, its distribution was more even in 1984-88 compared with two major pulses in 2006 and 2008 (Fig. 9). Wind and dust data suggest grasses were more likely to have been buried by wind-blown sands in the 1980s, ostensibly accounting for their poorer recovery. Changes in livestock grazing through time may have influenced herbivory pressure on grass seedlings.

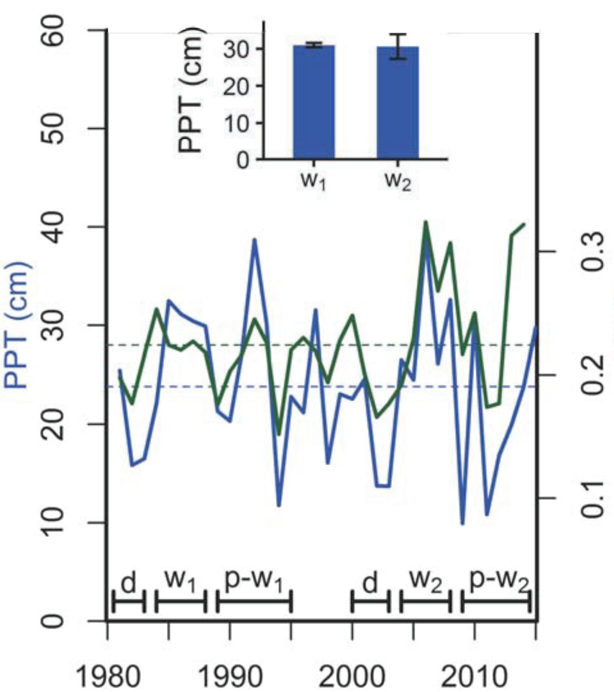

Fig. 9. Two wet periods with similar mean rainfall (insert) but the second period had two pulses of rainfall and good grass recovery based on NDVI (black) compared with even distribution of rainfall in first wet period and no grass recovery.

Hypothesis: Differences in grass ANPP or establishment in the two periods can be explained by differences in: (a) PPT characteristics that influence grass germination and establishment, (b) surface soil stability, (c) livestock grazing, or (d) a combination of environmental and biotic characteristics.
Study design: Long-term (1980-2008) ANPP or probability of establishment of black grama in grasslands will be compared to adjacent mesquite shrublands with similar soils (loamy sand to sandy loam) where recovery was observed in 2004-08, and related to PPT, temperature, wind speed, horizontal soil flux rates, plant phenology, and livestock grazing records. We will use the SOILWAT model to simulate probability of black grama establishment in each time period using climate and soils data for each location (methods in Peters et al. 2010). We will then determine the factors with the highest R^2 and AIC in a multi-model analysis to explain grass ANPP or establishment in periods with contrasting PPT regimes (similar but different; *Modoki Project*).
***Expected results*:** Integration of existing long-term datasets within a novel analytical framework will enable us to identify climatic and biotic triggers of grass recovery, and interactions with soils to inform restoration practices, and help explain why previous approaches have been unsuccessful.

Q-B2: How does shrub presence or absence interact with aeolian processes and climate drivers to feedback to future transitions (repurposing a long-term study into a new long-term experiment)
A sandy location cleared of vegetation and monitored for aeolian flux since 1996 remained barren with high sediment flux until grasses appeared in 2007 following the 2004-08 wet period (Fig. 10). By 2017, perennial grass canopy cover (mostly mid-successional perennial grasses) was ~50% and mesquite cover

<1%, reminiscent of conditions on the JRN in the 1860s (Buffington and Herbel 1965). This manipulation therefore provides a unique opportunity to study grassland recovery and feedbacks potentially driving alternate future states (*GROWS*: *G*rass *R*ecovery *o*n *W*ind Eroded *S*oils).

Hypotheses: Presence/absence of mesquite determines grass recovery via 3 potential pathways: (a) in the absence of mesquite, historic black grama grasslands will develop, (b) with continued mesquite proliferation, the location will transition to shrub dune-fields; or (c) the location will be maintained as a mid-successional native grassland.

***Study design*:** The cleared area will be divided into two parts. Shrubs will be removed as they establish in the north part, and allowed to invade and develop in the south parts. The parts will be separated by a sand fence to restrict soil movement from the south into the north (Cornelis and Gabriels 2005). Long-term monitoring will quantify plant (woody and herbaceous) cover and ANPP, and bare soil gap size distribution (via traditional and UAV approaches), soil moisture by depth (TDR), soil organic carbon and nutrients, net soil deflation/accumulation (soil erosion bridges), and downwind dust fluxes (BSNE dust collectors).

Expected results: This new experiment will: (i) quantify plant-soil and plant-water interactions underlying grass recovery or dune development, and (ii) provide insights into the historical development of the Jornada vegetation communities and vegetation-mediated feedbacks in S→G transitions.

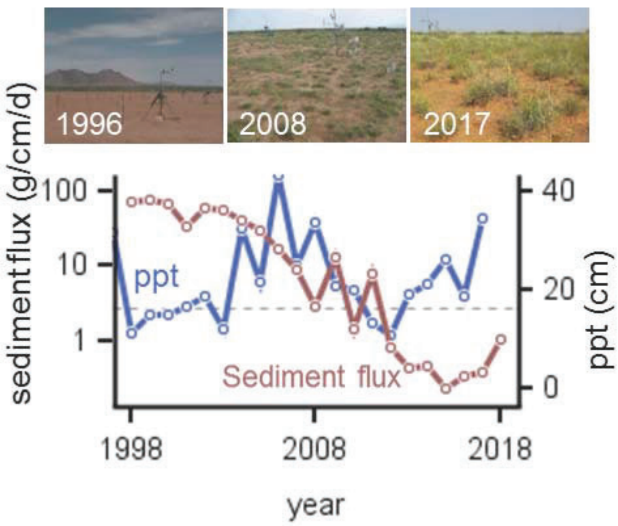

Fig. 10. Grass recovery following vegetation and surface soil removal in 1996. High sediment flux until wet period (2004-08) maintained by grass recovery. Images illustrate original condition, initial recovery in 2008, and persistent perennial grasses in 2017.

Q-B3: At what threshold level of plant- and patch-scale connectivity, do aeolian-driven feedbacks switch from increasing grass loss to promoting grass recovery? (enhancing a long-term experiment*)*

A pilot study began in 2008 quantified how physical plant canopies (small wire mesh structures [*ConMods]*) can modify resource redistribution by water or wind to influence fine-scale patterns in grass recovery (Rachal et al. 2015). *ConMods* have been adopted by others (USGS, Niwot LTER), and shown to be an effective patch-scale manipulation of litter, seeds, soil, and water (or snow) with feedbacks to plant establishment (e.g., Fick et al. 2016). In 2013, we initiated a long-term cross-scale interactions experiment *(CSE-SS)* on the sand sheet to address two questions: (a) at what spatial scales and under what weather conditions do fine-scale processes propagate to produce broad-scale impacts leading to grass recovery? (b) at what spatial scales do broad-scale drivers (drought or extended wet periods) overwhelm fine-scale processes? The design includes individual plant (shrub) manipulations (dead/alive), patch-scale manipulations of resources via *ConMods*, plant and patch treatments combined, and controls distributed across a grassland to shrubland gradient. Effects of broad-scale climate drivers are examined by following plots through time. ***LTER VI results:*** Perennial grasses responded significantly greater to shrub removal and patch redistribution of resources combined compared to the other treatments or the control likely as a result of an accumulation of litter and biomass (Fig. 11). We will continue this long-term experiment to elucidate underlying processes and quantify the thresholds across the grassland to shrubland gradient.

New measurements will allow our numerical modeling approaches to be used to integrate our long-term data to understand connectivity-mediated feedbacks at plant and patch scales.

Hypotheses: (i) Grasses are more effective than shrubs at reducing bare-soil connectivity and wind erosion. As grass patch density, size, and cover increase, connectivity, and aeolian transport will decrease. (b) A threshold level of grass patch connectivity occurs, above which resources are conserved, rather than being lost via lateral transport, with positive feedbacks on grass recovery, ANPP, water/nutrient retention.

Study design**:** Sixty 10 x 15 m plots were established in 2013 along a gradient of black grama and mesquite cover to examine effects of initial conditions, and to identify the grass cover and bare gap size at which dominant process shifts from the plant to patch scale. Plant cover and ANPP have been quantified along with soil moisture, wind and energy balance. New measurements will include UAV photogrammetry (RGB and multispectral) to more comprehensively monitor species cover, and 3-D retrievals using the structure from motion approach to quantify changes in soil and vegetation height and vegetation density (SfM, Gillan et al. 2017). These data will support our use of process-based modeling of aeolian transport (WEMO) and vegetation dynamics (Ecotone) to elucidate cross-scale thresholds.

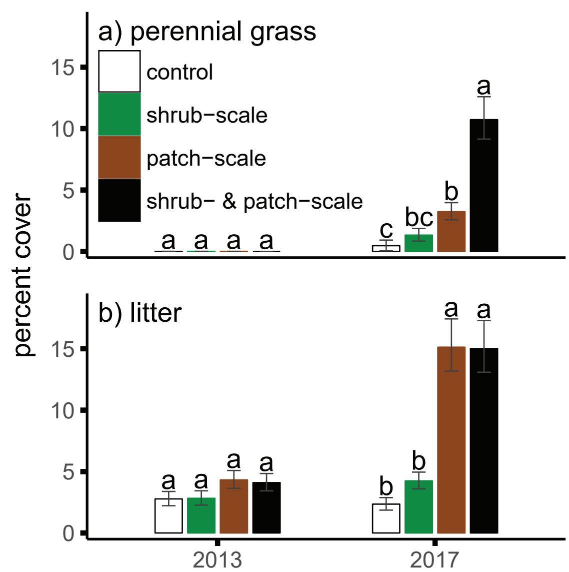

Fig. 11. Cross-Scale Experiment initial results: (a) nonlinear response by perennial grasses to multi-scale treatment compared to either treatment alone, in part as a result of (b) litter affects on plant available water. Patch-scale is ConMod treatment of Fig. 12.

Expected results**:** Surprisingly, perennial grass recovery occurred within 4y after the start of the experiment to show that fine-scale redistribution of resources is an effective fine-scale grass restoration approach. New modeling analyses will examine feedbacks between changes in surface soil properties to vegetation responses and possible threshold responses. This novel experiment will be reproduced on the bajada (Q-C2) in LTER VII to allow us to compare cross-scale interactions in aeolian and water-driven ecosystems.

Q-B4: How does grass recovery depend on interactions and feedbacks between rainfall variability and connectivity? (a new experiment)

We will build on and extend the *CSE-SS* to simultaneously manipulate PPT (i.e., water availability) and connectivity to determine how these broad- and fine-scale factors interact to influence grass recovery. We propose that grass recovery is the result of the interactive effects of water availability (over multiple years) and patch-scale, connectivity-related wind erosion. Under low PPT, grass recruitment is controlled by connectivity, where low bare-soil connectivity retains seeds, plant material, and water to facilitate local recruitment. Under wet conditions, the importance of this connectivity is overwhelmed, such that broad-scale recruitment occurs across broad ranges of patch connectivity.

Hypothesis: Connectivity x PPT interactions determine grass recovery, with patch connectivity exerting a greater influence during dry years and PPT exerting the dominant influence during wet years.

Study design**:** A PPT-connectivity factorial experiment will be established in a mesquite dune-field with minimal grass cover. We will manipulate PPT in zones between shrubs (ambient and -80%, -50%, +50%, + 80% of ambient; per Gherardi and Sala 2013). Plots will be divided into paired treatments with *ConMods* being either present (at a density of 2 m^{-2}) or absent. ANPP by species will be measured in each plot annually, and UAV photogrammetry (SfM) will quantify litter cover and vegetation structure. Soils will be sampled at T_0, and after 3 y to determine effects on soil nutrients, texture, and seed bank. ***Expected results:*** We will produce annual ANPP response surfaces that vary as a function of connectivity and PPT. This will transform our understanding of wind x water interactions in drylands.

C. Shrubland to shrubland (S→S) transitions (Vivoni, Archer, Hanan, Tweedie, Pietrasiak, Brungard, Browning)

Our goal is to enhance understanding of the water-driven, scale-dependent processes driving historic G→S and current S→S transitions on the bajada. We will test the overarching hypothesis that heavy grazing of the bajada in the late 1800s/early 1900s reduced grass cover leading to elevated rates of water erosion while also reducing the fine fuels needed to ignite and carry fires. These processes enabled expansion of tarbush shrubs that were present in low abundance. Shrub dominance subsequently shifted in response to spatial changes in soils and hydrology on the upper bajada (to creosote bush), but remained stationary on the lower bajada (tarbush-dominated). Given that G→S transitions have already occurred in many drylands, we need to advance our understanding of shrublands now occupying former grassland.

Q-C1: How do soils, PPT, and microbial conditions interact to trigger recruitment of contrasting shrub functional types? Are current shrub distributions governed by differential recruitment or by adult competitive interactions? (new experiments)

Mechanisms driving S→S transitions likely relate to a combination of demographic bottlenecks and competition-facilitation interactions (Miller and Huenneke 2000a;b, Sea and Hanan 2012, Dohn et al. 2013; 2017), with the direction and intensity varying with species traits, and mediated by edaphic controls on soil moisture and plant stress levels (Manning and Barbour 1988, Barnes and Archer 1999, Donovan and Richards 2000). In drylands globally, and at the JRN in particular, inter-annual variability in rainfall and disturbance can relax seedling establishment constraints, leading to historical establishment events underlying current species distributions (Wiegand et al. 2006). Shrub distributions observed today may also reflect changes in soil composition and depth resulting from erosion-induced sediment redistribution. ***Hypotheses:*** (a) Spatial patterns in dominance among mesquite (*M*), tarbush (*T*), and creosotebush (*C*) shrubs emerge as a consequence of differential seedling survival, with *M* seedlings preferring sandy soils with water at depth, *T* preferring fine-textured soils with reliable surface water, and *C* preferring coarse, shallow soils not susceptible to water saturation following rainfall. (b) Soil microbial communities will differentially influence shrub species seed germination and seedling survival, thus increasing shrub species segregation by soil type. (c) Competition among adult shrubs is such that *M* will suppress *C* and *T* on sandy soils (basin floor), *C* will suppress *T* and *M* on coarse-textured soil (upper bajada), and *T* will suppress *C* and *M* on fine-textured soils (lower bajada).
Study design: (i) In Years 1-2, in a greenhouse study, we will quantify germination/survival of *M, C,* and *T* on three soil types representing bajada soils, under three PPT scenarios (dry, average and wet years), and with sterilized/untreated soils (i.e., with/without the soil microbial community; 54 treatment combinations; 100 reps). (ii) In Years 3-5, we will implement a field-based reciprocal transplant experiment to quantify recruitment (without grass competitors) of the *M, C,* and *T*, when cross-planted in three soils, and with two PPT scenarios. Seedlings will be transplanted into paired plots, one receiving ambient rainfall and the other receiving supplemental water. Watering will occur ~weekly in Year 3 (only) to represent monsoon rainfall during 2004-08 (a wet period at JRN). Monthly measurements (manual and UAV SfM) over 3y will record growth (canopy dimensions, height) and survival. Mortality in Year 3 will be replaced by seedlings of the same species. In Years 4-5, mortalities will be replaced by the most successful species in each plot to setup this experiment to assess long-term competitive interactions experiment in Years 6 onwards.
Expected Results: These experiments will provide insights into the degree to which soils, PPT, and microbial conditions interact to differentially constrain recruitment of contrasting shrub functional types.

The long-term experiment will provide direct quantitative measurements of both intra- and inter-specific interactions, competition/facilitation, and self-thinning on soils occurring along the bajada gradient.

Q-C2: At what threshold level of plant- and patch-scale connectivity, do hydrologic-driven feedbacks switch from promoting grass loss to promoting grass recovery? (a new cross-scale interactions experiment, *CSE-B*)

Runoff produced during PPT events on low infiltration capacity and sloping soils redistributes sediments and creates spatial variability in plant-available moisture at plant and inter-plant scales that cascade to larger patches of vegetated and bare soil. **Results from our *LTER VI*** pilot study revealed that small *ConMod* structures simulating plants can effectively reduce water flow on active alluvial surfaces as well as aeolian surfaces (Q-B3) to enable perennial grass recovery (Fig. 12). At broader spatial scales, hillslope runoff events (> 6mm) driven by PPT overwhelm local storage capacity leading to transport of water and sediment into ephemeral channels (***Schreiner-McGraw and Vivoni 2017***). Because vegetation transitions impact channel transmission losses and runoff yield (Schreiner-McGraw 2017), cross-scale interactions are central to the overall dynamics of water and soil resources on bajada landscapes. We propose to use a *CSE-B* experiment across variable alluvial surfaces on the bajada dominated by creosotebush (shrub) and bush muhly (perennial grass) to determine the generality of results from black grama-mesquite transitions where interactions between plant and patch scales are leading to grass recovery for the aeolian system (*CSE-SS*).

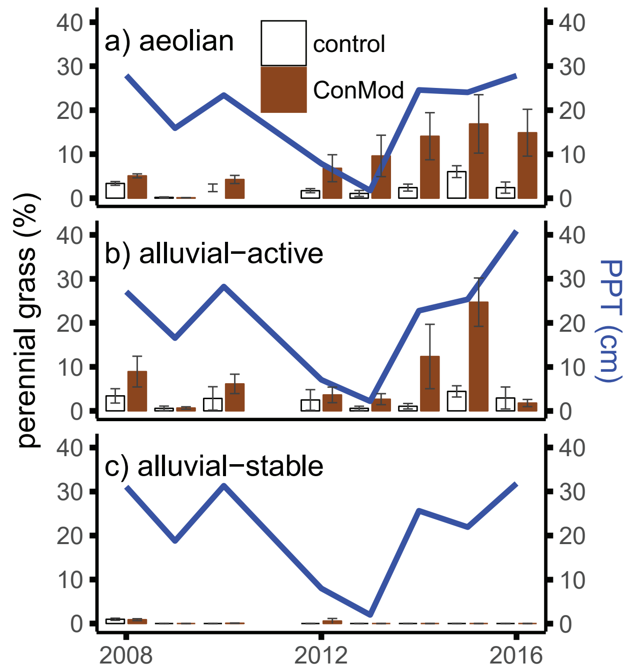

Fig. 12. ConMod Pilot Results. Response of perennial grasses to redistribution of resources following addition of ConMods on three surfaces. Each blue point is 6-mo cumulative PPT prior to a grass measurement. Stable alluvial surfaces did not respond to modified water redistribution over this time period (9y); multiple decades are required for grass responses on these stable surfaces (Havstad et al. 1999).

Hypotheses: (a) Regardless of the grass or shrub species or the spatial context, grasses are more effective than shrubs at reducing connectivity by wind or water. As grass plant and patch density, size, and cover increase, bare soil connectivity and sediment transport will decrease. (b) A threshold level of connectivity in grass patches can occur, above which water resources infiltrate and sediments accumulate within the patch, rather than being lost via lateral transport, with positive feedbacks on grass recovery.

Expected Results: Data will enhance ecohydrologic modeling (tRIBS, Ecotone) and improve our ability to predict how bare-soil connectivity impacts grass recovery across scales, and the connectivity threshold for positive feedbacks promoting grass recovery and reducing runoff and sediment loss. Comparing these results with those from Question B3 will determine the generality of the importance of cross-scale interactions to grass recovery.

Q-C3: How do plant and patch-scale characteristics interact with the soil-geomorphic template to lead to landscape-scale loss of water in channels with feedbacks to S→S transitions? (enhanced bajada watershed studies)
LTER VI results revealed that 25% of incoming precipitation is lost to channel transmission during wet periods (***Schreiner-McGraw and Vivoni 2017***), thus bypassing ecosystem water use and potentially promoting groundwater recharge (Biederman et al. 2018). This is consistent with the muted summertime ET in the eddy covariance footprint (Anderson and Vivoni 2016). We will continue to use the bajada experimental watershed to identify thresholds in PPT characteristics (intensity, duration, frequency) and antecedent soil moisture needed to generate runoff and transport through channel systems across scales, and the role of fine-scale spatial variability in topography, soils, biological/physical surface crusts, and vegetation in mediating cross-scale interactions.
Hypotheses*:* (a) Vegetation transitions on bajada landscapes alter runoff, ET, and subsurface losses to feedback to influence vegetation composition, channel reaches, and downstream areas. (b) Shrub encroachment promotes overland flow losses owing to shrub-induced changes in infiltration rates mediated by abiotic (soil surface texture, physical crusting) and biotic (biocrusts, plant stems, litter) factors. (c) Runoff is a function of soil depth and depth to calcium carbonate horizons (caliche); water storage by caliche in wet periods benefits shrubs over grasses during dry periods (Duniway et al. 2010).
Study Design: Long-term eddy covariance and hydrological monitoring efforts will be continued with enhancements, including: (i) quantification of runoff and sediment yield on north- and south-facing slopes (n=4), (ii) additional moisture sensors that penetrate into and below the caliche horizon, and (iii) a third profile of channel soil moisture measurements to track transmission losses. Infiltration rates of soils associated with the major shrub species (*C, T, M*) will be quantified on varying landscape positions with varying amounts of physical and biological crust. High resolution maps of vegetation by species, soil surface texture and crust characteristics (manual sampling; UAV-based spectral measurements), and depth to the caliche horizon will be developed. Relationships between shrub species, patch structure, and explanatory variables will be used to extrapolate findings beyond the watershed.
Expected Results: The tRIBS model will be used to simulate impacts of S→S transitions on hillslope-channel connectivity using an improved representation of overland flow (e.g., Mueller et al. 2007). Model developments will allow the evaluation of landscape-scale ecohydrology and feedbacks involved in long-term vegetation change.

D. Transitions to novel ecosystems (G/S→N) [Archer, Pietrasiak, Lehnhoff]

Q-D1: How do rainfall variability, grazing, and competition with native grasses interact to trigger non-native grass invasion? (continuing experiments)
Invasions of non-native grasses in response to changing climate and land use can lead to novel ecosystems lacking historical analogs (Hobbs et al. 2006), and create new management and conservation challenges (Seastedt et al. 2008, Hobbs et al. 2014). LTER VII will build on the novel ecosystem perspectives in LTER VI by focusing on Lehmann's lovegrass (*Eragrostis lehmanniana*), an exotic perennial C_4 bunchgrass. Lehmann's was imported to the SW USA from South Africa in the 1930s, where it now dominates much of the Sonoran Desert. Introduced to the Jornada in 1938, it is now locally dominant in small patches, but its rate of spread has been slow and variable. Seed availability and dispersal do not explain the lack of spread, since Lehmann's produces prolific viable seed; livestock, wind, and water are effective dispersal vectors (Fredrickson et al. 1997). ***LTER VI*** model results suggest that variable PPT and temperature increases will increase probabilities of seedling establishment, especially on sandy and silty soils (Yao and Peters 2016). Here, we will conduct establishment-competition experiments to identify the environmental conditions (triggers, thresholds) promoting Lehmann's recruitment and competitive dominance over native grasses.
Hypotheses**:** (a) Lehmann's recruitment is favored by the combination of warmer winters, wetter summers, and livestock grazing. (b) Established Lehmann's will competitively suppress native grasses.

Study design: In Yr 1-3, we will jointly assess the bottlenecks for Lehmann's seedling establishment and adult plant competitive interactions using rainfall manipulation shelters. A total of 48 plots were established during 2016-2017 to study Lehmann's seedling survival and competition with native grasses. Plots (n=30) are located in black grama stands, wherein Lehmann's seeds were introduced to quantify recruitment under reduced (-80% of ambient), ambient and increased (+80%) precipitation, and with plots divided into halves in which native grasses were defoliated (to simulate grazing) or left intact. Additional plots (n=18) were deployed in mixed communities of native black grama and established Lehmann's to quantify adult competitive interactions under wet (+80%), ambient and drought (-80%) conditions. Lehmann's and native grasses will be monitored (survival, growth, tillering, flowering). Expansion or contraction of existing Lehmann's patches mapped by the USDA will be monitored with UAVs. Soil texture and depth in plots/patches will be quantified, and a nearby weather station will quantify PPT and temperature. Data will be used to validate Lehmann's dynamics in our landscape modeling (Section 4.3). ***Expected results:*** Documentation of the combination of factors controlling Lehmann's recruitment, and its competitive interactions with native grasses, will position us to predict how climate, grazing, and soil texture interact to trigger its spread.

E. Transitions under climate change (continuing long-term experiments) (Sala)

Climate change is a major driver of change for drylands with consequences for ecosystem structure-function relationships. The frequency, intensity and duration of extreme events (drought, heavy rainfall) are expected to change, and our prior work has shown that prolonged drought reduces the ANPP and cover of grasses more than shrubs. An experiment, initiated in 2006, is testing the hypothesis that climate change effects are mediated by microbial communities and plant-plant and plant-microbe interactions, rather than by direct impacts on individual species. This hypothesis was tested by manipulating PPT amount (-80%, ambient,+ 80%) in a full factorial design with N fertilization. ***In LTER-VI***, we showed that shrub and grass ANPP responded to changes in PPT, but not to N addition (*CCE*, Reichmann et al. 2013a). Changes in PPT amount did not affect N mineralization, but N immobilization led to increases in soil and plant N in dry years (Reichmann et al. 2013b). ANPP in a given year was strongly related to PPT the preceding year (Reichmann et al. 2013a) as manifested by changes in tiller density (Reichmann and Sala 2014). Legacies in ANPP from previous years was a general phenomenon that occurred globally for the grassland biome ***(Sala et al. 2012).*** Our second experiment started in 2009 was an inter-annual precipitation variability experiment wherein mean PPT is kept constant under contrasting wet and dry sequencing. Response variables monitored included above- and belowground NPP, species composition, recruitment and mortality and soil moisture, N-availability and pools, microbial community composition, and soil respiration. This ***LTER-VI*** experiment showed that increased inter- annual PPT variability decreased ANPP regardless of precipitation amount (Gherardi and Sala 2015b). Functional diversity increased with increasing PPT variability conferring higher ecosystem stability (Gherardi and Sala 2015a). Modeled PPT variability effects increased from intra- to inter-annual to decadal scales (Sala et al. 2015). Transpiration increased on arid sites, but decreased on mesic sites with increases in PPT variability (Sala et al. 2015). These experiments were recently recommended for funding via an LTREB award to PI Sala; infrastructure support has been provided by the LTER through time as an integral part of our program.

4.3. Landscape integration: Spatial heterogeneity in Alternative States [all]

Obj. 2 to explain and predict multi-scale spatial heterogeneity in alternative states

Our goals for this objective are to: 1) organize data from disparate studies conducted over many years such that they can be contextualized with respect to common biophysical variables, and standardized and harmonized to permit new analyses, 2) generate new data products and make integrated data available to test state transition hypotheses in a spatially-explicit context at broad (landscape) scales, and 3) conduct new, integrative tests of the causes and constraints to state transitions based on hypotheses corroborated by or emerging from fine-scale studies (e.g., Section 4.2).

(a) Data integration. A Data Science Integration System (DSIS) will compile and integrate diverse types of data from multiple scales and disparate locations. The DSIS is a trans-disciplinary analytical framework linking diverse, spatially-explicit data with theory and conceptual models to explain and predict dynamics across heterogeneous landscapes, and will enable spatially-explicit tests of hypotheses relating key processes (e.g. climate, soil water availability, resource redistribution) to ecosystem responses (e.g., vegetation change) that vary over space and time (Fig. 6b, Peters et al. in revision). This Jornada-wide point and raster compilation, enabled by recent advances in computational power and procedures, will be a major advancement over the compartmentalized "soil-geomorphic unit" approach used in past funding cycles (Fig. 6a). The DSIS was recently used to explain temporal changes in landscape- to regional-scale animal disease patterns across the western US (Peters et al. 2017). Spatio-temporal modeling of cross-scale interactions via user-guided machine learning identified key processes underlying disease incidence, and generated spatially-explicit predictions of future outbreaks. DSIS analyses of long-term JRN NPP data were successful in generating a continuous estimate of grass recovery rates across the Jornada based on soil properties and initial grass biomass (Peters et al. in revision). Thus, we feel confident that this framework will be applicable for other questions and can incorporate additional datasets. We will analyze historical and newly collected data within the DSIS framework to: (a) explain the historical and current spatial distribution of alternative states across the JRN, (b) produce spatially-explicit forecasts of transitions, and (c) develop a data-driven approach to identify under-sampled locations for future research. Working with our Data Science Team, we will modify our Information Management System toward the DSIS structure (see S2. Data Management Plan).

We have been compiling and organizing data and other lines of evidence from LTER I-VI and with our USDA ARS collaborators needed to advance our DSIS (Fig. 5, 6b). These sources include long-term data from spatially-distributed experiments, observational studies, sensor networks, imagery products (land, drones, air, space), and analytical and numerical model outputs. These data first must be *standardized* in format and *harmonized* in scale across the JRN site. In some cases, these data already exist and analyses have been conducted (e.g., Peters et al. 2010). Steps needed to develop the DSIS are summarized below (see Data Management Plan for details). We anticipate that the DSIS will offer harmonized data at a scale of 30 m. This scale will encompass multiple vegetated and bare soil patches, allow for resource redistribution by wind and/or water, and connectivity-mediated feedbacks at both plant and patch scales.

<u>1. Standardize data from PI-led studies.</u> A common set of response and environmental variables related to key processes is needed to integrate our short- and long-term studies. Many variables are already part of existing studies (e.g., PPT); others are not (e.g., soil texture and moisture by depth; depth to caliche) (see Fig. 6b for an example). Protocols are readily available (Herrick et al. 2006). We will develop this list as a PI/collaborator project over the winter of Y1 and begin collecting these standard data or adding sensors to study locations in the first field season of LTER VII. This list of variables will be refined as our knowledge system evolves.

<u>2. Develop or update landscape maps of missing or outdated variables</u>. A number of maps already exist and are available on our web site and mobile applications on Google Play and iTunes. Key maps to be added are described below; others are referred to in specific analyses. All maps will become part of our new DSIS and broadly available. (*a) Update vegetation (species) map* (Gibbens et al. 2005) using a combination of remotely-sensed data, geo-referenced species data from numerous ongoing studies, maps of static environmental variables, machine learning (presence/absence) and multi-model inference (abundance) approaches (e.g., Burruss et al. 2017). Maps of additional environmental variables will also be created (e.g., flows/fluxes of water/sand, water movement, distance to watering points, grazing

intensity, small animal density/abundance, patch size distribution). Vegetation maps compared through time will extend previous analyses and show where state transitions occurred. *(b) 1850s soil map:* We will characterize soils on the White Sands Missile Range (WSMR) where historic grassland and shrubland states have persisted. The WSMR is a nearby military reservation where livestock grazing has been excluded since at least the 1940s and where large stands of native perennial grasses remain on similar soils and geomorphic units as those on the Jornada where transitions occurred in the 1930s-50s. Stratigraphic and carbonate isotopes (Monger et al. 1998; 2009) will be used to infer pre-desertification soil properties. $\delta^{13}C$ and ^{14}C age of soil organic carbon (SOC) will show where/when present-day C_3 shrublands displaced C_4 grasslands (Boutton et al. 2009). *(c) Digital soil map:* Digital soil mapping techniques (Brungard et al. 2015, Hengl et al. 2017) will be used to predict the current distribution of key soil properties (e.g., surface texture, water holding capacity, depth to petrocalcic layer) at finer spatial resolution than is available from existing soil and landform maps (Monger 2006). This new soil map will integrate landform/parent material mapping (Gile et al. 2007), existing soil pedon observations, our expanding point-database of soil texture and depth, and terrain and remotely-sensed geospatial data products. New field work will target areas of high uncertainty. Soil characterization and mapping will be conducted in cooperation with the Natural Resource Conservation Service (NRCS) Soil Survey Division using standardized methods. *(d) Biological soil crust map:* Hyperspectral imagery will be used to map biocrust cover (Weber et al. 2008, Rodríguez-Caballero 2015) and composition (Pietrasiak et al 2013).

(b) Spatiotemporal analyses. The DSIS will be available to the broader community to enable a wide range of new analyses. Below we describe how it will be used to test state transition hypotheses at the Jornada.

<u>3) Spatially-explicit state transition simulations</u>**.** We will integrate our growing knowledge base with new and existing spatial data layers to evaluate controls on spatial heterogeneity in the recruitment and dominance by key perennial grass (black grama, mesa dropseed, Lehmann's lovegrass) and shrub (mesquite, tarbush, creosotebush) species in three different time periods: (i) the 1850s using our historic soils map (previous subsection), historic vegetation cover (Gibbens et al. 2005), and modeled climate, (ii) current conditions, and (iii) future with warming and wetter to drier PPT scenarios. We will use species-specific germination and establishment criteria estimated from experiments and field studies (4.2 Transition studies), additional field studies on mesa dropseed, and our previous studies and the literature for other species and functional groups to simulate present-day recruitment, abundance, and composition using Ecotone. Model simulations in the 1850s will be conducted to provide new insight and finer spatial resolution on the spatial distribution of the two historic dominant upland grasses (black grama, mesa dropseed), and shrub species across the upper and lower bajada. Simulations under downscaled GCM projections will predict future landscape dynamics based on species-level interactions. These simulations are particularly relevant to the hypotheses guiding research in Section 4.2. Ecotone, a model that simulates recruitment, competition, and mortality of individual plants at fine scales (1-10 m^2) at an annual time step will be used for all simulations. Daily to monthly information will be used as needed for specific processes. Ecotone will be linked with tRIBS to allow hydrologic connectivity and with WEMO for aeolian transport. We will create one parameter file for key species or functional groups at JRN and in the Chihuahuan Desert. This contrasts previous attempts to simulate Chihuahuan Desert systems where different species parameters were used for different soil-vegetation associations (Peters 2002, Rastetter et al. 2003). We will first simulate soil properties, elevation, and patch characteristics across the JRN and determine if the model spatially distributes grass-shrub dominance and composition reflecting fine-scale variation in soil water, biotic crusts, and resource redistribution feedbacks. This output will be evaluated against our new species map, revised and refined, and then used to probe historic and future scenarios.

<u>4) Spatial analysis of state transitions in long-term monitoring data</u>. We will use spatial data to map within-state changes observed in monitoring data and likelihoods of specific between-state transitions (methods follow Levi and Bestelmeyer 2016), and create spatially-explicit climate-based forecasts. We

will model spatial variation in vegetation cover and ANPP using chart quadrat (*QUAD*) (Yao et al. 2006, Chu et al. 2016) and *NPP* datasets (***Peters et al. 2014b***). The *QUAD* dataset includes 122-1m^2 quadrats distributed across the Jornada and spans 102 years (1915-2016). The *NPP* dataset includes 15 permanent locations established in 1989 and sampled non-destructively to estimate ANPP by species (see Peters et al. 2012 for details). We will standardize and integrate these disparate plot (point) datasets and build a geodatabase of environmental and related response variables to a common raster resolution, including 1) the new digital soil map, 2) hydrologic indices based on a high resolution (5m) DEM (Interferometric Synthetic Aperture Radar [IFSAR]), 3) PPT data based on the Jornada rain gauge network (1915- present) and federated, widely-available climate data (e.g., PRISM), 4) land use (e.g., stocking rates, brush management treatments), and 5) Landsat NDVI (30-m; 1989-present), and 6) 4-band Digital Globe imagery (1 m^2 resolution, 2009-present). We will first assemble, standardize, and harmonize these datasets; historical land use will require considerable effort to georegister. We will use clustering algorithms to classify distinct patterns in vegetation cover and ANPP time-series (Williamson et al. 2016, Bagchi et al. 2017) and user-guided machine learning approaches to ask if environmental data can explain observed differences in state transition trajectories and reconcile seemingly contradictory responses in experiments conducted in different locations. Likelihoods of specific transitions will be spatially mapped (Levi and Bestelmeyer 2016) and spatially-explicit forecasts under contrasting climate scenarios will be generated (*sensu* Peters et al. 2010).

5) Dynamics of hydrologically-enhanced ecosystems. Hydrological studies at the JRN have quantified sediment transport and runoff at scales ranging from plots and small catchments to large watershed complexes (Templeton et al. 2014, McKenna and Sala 2018). Surface hydrological transport is especially important for explaining nonlinear vegetation dynamics on downslope, low-lying positions, colloquially known as swales, bottoms, or playas. These hydrologically-subsidized areas are often the most productive and C-rich locations in desert landscapes (Peters et al. 2012, McKenna and Sala 2016). Their water budget is dependent on levels of runoff which depends on vegetation patches, soil characteristics, and topography (Vivoni 2012). ***LTER VI results*** show that playas (lowest parts of desert watersheds with no hydrological outlet) account for a small fraction of landscape area, yet accumulate C and nutrients at high rates controlled primarily by geomorphic variables (slope, watershed surface area), and weakly related to biotic factors such as plant cover (McKenna and Sala 2016). LTER VII will extend this work to to test the hypothesis that knowledge of hydrological connectivity in the watershed surrounding playas can explain variations in playa water depth and ANPP. We recently instrumented 30 playas across the JRN with pressure sensors recording daily water depth. We will relate variations in water depth and ANPP (estimated from satellite imagery) to structural connectivity, flow direction, runoff volume and sediment flux assessed using a combination of very high resolution satellite data (f30-50 cm through the Federal NGA Commercial Data Agreement), digital soil data, high-resolution DEM and the tRIBS model.

6) Net primary production (ANPP) and sensitivity to climate change. ANPP has been quantified in several studies (*NPP, CCE, Ecotone*), and has generated numerous publications (***Peters et al.*** 2012; ***2014b, Sala et al. 2012***; 2015, Reichmann et al. 2013a; b, Reichmann and Sala 2014, Gherardi and Sala 2015a; b, Petrie et al. 2018). However, we are only intensively sampling a small proportion (<1%) of the Jornada in any given year. Recent analyses of long-term soil water data suggest that water availability to plants is related to rainfall and water holding capacity (WHC), but considerable variation remains unexplained in both time and space, and the relationship with ANPP is unclear (Duniway et al. in press). We propose that accounting for hydrological connectivity (similar to that described above) will improve predictions of soil water availability and ultimately ANPP sensitivity to drought and extremely wet conditions. We define ANPP sensitivity to drought as the decrease in ANPP per unit decrease in PPT relative to average PPT and sensitivity to wet conditions is the increase in ANPP per unit increase in PPT relative to average PPT. We will integrate ANPP through time for all studies where this variable is collected (e.g., *NPP, Ecotone, CCE*), and obtain the necessary environmental and connectivity

characteristics for each plot (described in 5. above). We will then use these relationships to predict ANPP for other locations on the Jornada that have not been sampled directly, and for future time periods under alternative climate scenarios.

4.4. Research at regional, continental, and global extents

Obj. 3 to apply new analytical concepts and tools developed at the Jornada to broader extents (regional to global) and examine consequences for ecosystem services through our collaborations

Regional to global applications. JRN approaches and insights are being applied at regional to global scales. ***LTER VI results*** included literature syntheses (Shifting Paradigms in Drylands Special Issue in *Frontiers in Ecology and the Environment;* Big Questions Emerging from a Century of Rangeland Science and Management Special Issue in *Rangeland Ecology and Management)*. In 2017-2018, we initiated work on special features in *BioScience* (new analytical approaches for dynamic landscapes) and *Ecospher*e (Dynamic Deserts). We also contributed individually to important collections (synthesis chapter on Desertification in Rangelands [Peters et al. 2013], PPT legacy effects on ANPP [***Sala et al. 2012***], an invited paper in the *Ecosystems* centennial journal issue [Peters and Okin 2017]). Our long-term ANPP, chart quadrat data, and ThreshEx data contributed to numerous cross-site comparisons (e.g., Munson et al. 2013; Ponce-Campos et al. 2013; Moran et al. 2014; Chu et al. 2016, Shackelford et al. 2017, Ratajczak et al. 2017). Network-wide activities included hosting the EcoTrends site of long-term data for 50 US (2004-present) (www.ecotrends.info). Contributions to collaborative research networks and meta-analysis projects, include the Ameriflux eddy covariance flux network (Biederman et al. 2018), a global PPT manipulation study (DroughtNet), a global desert analysis (Biodesert), a global study of plant-large herbivore interactions (The Grazing Consortium, Koerner et al. in review), a network focused on comparative ecology of global temperate and tropical savannas (Lehmann et al. 2014), and a global network of nutrient addition effects (NutNet, Borer et al. 2014). JRN assisted government agencies in Mongolia, Argentina and several African countries in land assessment, monitoring, and state-and-transition model development (Bestelmeyer et al. 2017, Herrick et al. 2017). Finally, we collaborated with Malpai Borderlands landowner-agency collaborative to explain soil- and climate-related spatial variations in the use of fire to manage shrubs (Levi and Bestelmeyer 2016), and worked with the Bureau of Land Management (BLM) to evaluate/interpret grassland restoration treatments (Coffman et al. 2014).

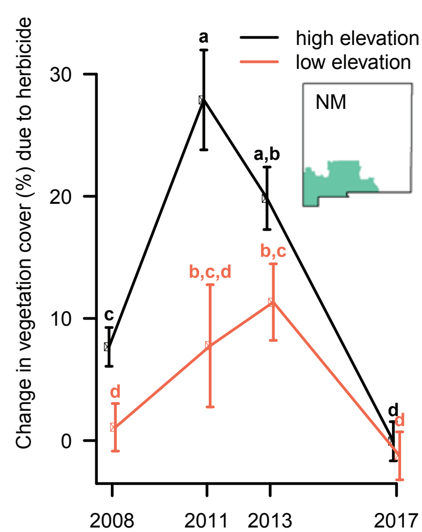

Fig. 13. Restore NM Project. Vegetation cover response to herbicide treatments at high (>5000') and low (<5000') elevations in NM (green counties on map) (Bestelmeyer et al. in prep).

In LTER VII, our new research will apply landscape integration concepts and tools described in Section 4.2 to data collected in past projects and collaborative efforts. Specifically, we will work with the Jornada ARS and other partners to analyze vegetation monitoring data gathered in the BLM Restore NM Program (ca. 100 plots), the Malpai Borderlands Group in NM and AZ (ca. 60 plots), and the government of Mongolia (ca. 1450 plots) to test for state transitions. Digital climate, landform, soil, and land use data will be used to evaluate drivers of vegetation transitions hypothesized from locally-developed state-and-transition models. For example, preliminary analysis of 10 years of monitoring data from Restore New Mexico restoration treatments indicates that success restoring perennial grass cover (compared with untreated controls) varies with elevation (Fig. 13).Intensive analyses of a larger dataset will elucidate how initial vegetation cover, soil surface properties, and topographic setting influence restoration success. These results can prioritize site selection for future treatments and inform adaptive management. This represents a real-world application of our landscape integration framework.

We will continue to provide data and support for numerous network and *ad hoc* collaborative activities. We initiated a collaboration with the USDA Long Term Agro-ecosystem Research (LTAR) Network (Petrie et al. 2018) and JRN-associated scientists will lead wind-erosion network comprised of sites throughout the western U.S. (Webb et al. 2016). The latter activity will enable JRN wind erosion modelling efforts to be applied to a variety of other ecosystems.

Consequences for ecosystem services. Under LTER VI, we evaluated the impact of woody-plant encroachment on livestock production in the US and Argentina (Anadón et al. 2014), and the influence of shrub management on a broad portfolio of ecosystem services (Archer and Predick 2014). Under the auspices of LTER VII, we will evaluate the impact of state transitions on ecosystem services related to C-sequestration and ground water recharge using a combination of tools. A network of recently deployed sensors in playas will quantify impacts on run-off and water table dynamics (McKenna and Sala 2018), and long-term soil data will assess impacts on C sequestration. Effects of woody-plant encroachment on livestock production initiated in LTER VI (Anadón et al. 2014) will be extended to China to test the robustness our approach in a contrasting bioclimatic and socio-economic setting.

II. BROADER IMPACTS

LTER VI Results. ***(1) JRN Schoolyard LTER program***: (a) 87,042 K-12 students and 3,012 K-12 teachers participated in 128 field trips, 3,083 classroom/schoolyard lessons, and 29 teacher workshops; K-12 students are from underserved populations in southern NM: approximately 80% are economically disadvantaged and 75% are Hispanic, (b) the innovative *Desert Data Jam* program initiated in 2012 has served 1,700 middle and high school students and served as a model for *Data Jams* in MD, NY, and PR; (c) the Las Cruces Public School District (the largest in southern NM) funds our inquiry-based science lessons, reaching every 7th and 8th grader in the district (~3,200 students/y); (d) our LTER children's book, One Day in the Desert, was published in Nov 2017; and (e) we published a paper on innovations in LTER K-12 education with colleagues from several LTER sites (***Bestelmeyer S al. 2015***). ***(2) Student Fellowships*** in our Jornada Fellowship Program supported 12 REUs; 8 additional undergrads, and 31 grads. All students participated in LTER research with guidance from LTER PIs, benefitted from our annual *Desert Ecology* short-course, led or co-authored 34 peer-reviewed publications, and presented their research at 53 conferences (the majority as lead author). ***(3) Outreach to Land Management Agencies and Policymakers.*** We conducted monitoring, research, and training activities through our collaborations with government agencies, including the BLM, NRCS, US Agency for International Development (USAID), The Instituto Nacional de Tecnologia Agropecuaria (Argentina), and the Swiss Agency for Development and Cooperation in Mongolia (Herrick et al. 2005; 2010a; Bestelmeyer et al. 2017). Our monitoring manual and qualitative assessment protocols were applied BLM and NRCS personnel at over 4,000 locations (Herrick et al. 2006a). The Land-Potential Knowledge System (LandPKS, ***Herrick et al. 2013***) enabled citizen scientists throughout the world to collect and share data via cell phones. JRN conceptual models have been adapted and applied to inform management decisions in the US, Mongolia, and Argentina.

LTER VII will continue these activities: ***(1) JRN Schoolyard LTER*** will provide place-based science education to K-12 students and teachers in multiple formats. Programs share several characteristics: (i) a tight connection to LTER research on state change in deserts, (ii) hands-on and inquiry-based activities, (iii) alignment with state and national education standards (e.g., Next Generation Science Standards and Common Core State Standards in language, arts, and math), and (iv) involvement by students underrepresented in science. S. Bestelmeyer leads K-12 efforts through a longstanding collaboration between the nonprofit Asombro Institute for Science Education (AISE) and the JRN LTER. We propose a continuation and expansion of 7 components of our program while adding one new component: (1) Field trips – 24 outings to the Jornada and/or the adjacent Chihuahuan Desert Nature Park, owned by AISE. Teachers will choose three to five grade-level-specific, hands-on activity stations where students collect and analyze data mirroring JRN research. New activity stations will be developed based on LTER VII projects. (2) Classroom/schoolyard lessons. AISE staff visit regional classrooms to present one-hour, inquiry-based science programs based on JRN research and aligned with education standards. Many lessons use our *Schoolyard Desert Discovery* curriculum, with 40 indoor/outdoor activities for the schoolyard and/or classroom. Most student worksheets are available in both English and Spanish, allowing teachers to choose the version best meeting their students' needs. We expect to deliver at least 30 one-hour programs per month. (3) *Desert Data Jam* (DDJ). This unique competition, started at JRN in 2012, challenges students to examine ecological data sets collected by JRN researchers, identify a data trend, and develop a creative project that communicates the data trend to nonscientist audiences (***S. Bestelmeyer et al. 2015***). More than 1,600 middle and high school students have participated in the DDJ. We will continue hosting the DDJ competition with middle school and/or high school students, and supporting other LTERs that would like to use this model. (4) Teacher workshops. Eight workshops for an average of 15 teachers each workshop will focus on Schoolyard LTER and other lessons to engage students and enhance their science literacy. (5) Graduate student integration in K-12 education. Beginning in LTER VI, we involved JRN graduate students in 5 to 10 hours of K-12 activities, including direct assistance during classroom / schoolyard lessons, field trips, and teacher workshops as well as assistance with the creation and testing of new activities. Modeled after NSF's GK-12 program, this component of our education program gives graduate students the skills to communicate science to diverse audiences while simultaneously giving K-12 students role models and access to up-to-date ecological science. We envision engaging at least 24 graduate students. (6) One Day in the Desert book –We will develop a **new** curriculum unit and kit to allow local teachers to use our book to cover science, language arts, and math curriculum. Three teacher workshops will introduce teachers to the new unit. We will also develop online, supplementary materials that can be used by educators around the world who use our book to teach about Chihuahuan desert ecological research. (7) Evaluation. We will continue to use formative and summative evaluation tools to assess achievement of program goals for each K-12 education component. Tools include teacher surveys, Draw A Scientist tool, and student comments that highlight misperceptions and form the basis for modifying or developing new programs. (8) Outcomes. Engage: (i) > 56,000 K-12 students with increased knowledge of desert ecology and data interpretation, as well as debunking stereotypes about scientists that will encourage students from underrepresented groups to consider science as a career option; (ii) > 180 teachers with lessons and materials needed for hands-on classroom /schoolyard; (iii) JRN LTER graduate students with an appreciation for the joy and challenges of working with the K-12 community to promote broader impacts from their own research. **(2) *Student Fellowships.*** Our successful *Jornada Fellowship Program* that supports undergraduate and graduate students will be continued. In addition to mentoring by LTER PIs, students will participate in our annual 2-day *Desert Ecology* class taught on-site by LTER PIs and attend our Jornada Symposium with opportunities to present their research. Graduate students present a final research seminar to the LTER PIs prior to graduation. ***(3) Outreach to land management agencies and policymakers***. We will continue our dozens of cooperative research agreements via the USDA with a cross-section of clients and stakeholders, including US land management and international development agencies, international governmental agencies, ranchers, non-governmental organizations, and the military. Targeted interactions with resource management practitioners (private, public) promoting two-way communication and collaboration will include workshops, seminars, and service on their science committees. Topics include rangeland health evaluations, data collection and analyses associated with the USDA National Resource Inventory, and development of Ecological Site Descriptions that translate research results into actionable management recommendations via the USDA Natural Resources Conservation Service. Each year, >1000 hours are devoted by JRN PIs and collaborators to these outreach activities. Outreach to science, management and policy audiences includes our annual Jornada research symposium, the development of internet- and mobile-phone (APP)-based systems for sharing knowledge and information (www.EcoTrends.info, www.LandscapeToolbox.org, www.LandPotential.org), and collaboration with the USDA Southwest Climate Hub (www.swclimatehub.info) to disseminate climate adaptation information, based in part on our LTER research, via university cooperative extension programs and workshops. We also promote access to our research via our web site (http://jornada-www.nmsu.edu) and are expanding international outreach through the internet with documents available in multiple languages, including representation as the US Science and Technology Correspondent to the UNCCD (lead science-related negotiations Herrick). Direct consultation and advice is provided to leadership of federal land management agencies and technical service providers in Washington, DC, and national governments on other continents. For example, we directly provide science-based recommendations for resource assessment and monitoring programs across the US and Mongolia, development of Ecological Site Descriptions in Argentina, and serve on the UN International Resource Panel (IRP) and on the BLM National Science Committee (Herrick).

III. Response to 2015 Mid Term Review

The mid-term review panel was very complimentary regarding Jornada science, including congratulating the site for "advancing understanding in ecology and ecosystem science…" taking "excellent advantage of long-term data… addressing the objectives and goals of the 2012 proposal…" in a "highly productive research environment… with participation of under-represented groups and highly effective K-12 outreach". However, the review panel also identified several areas of concern, including: (i) the long-term decline in NMSU faculty and student participation in the program; (ii) lags between data collection and posting of long-term datasets; (iii) a perceived need for additional population/demographic studies, especially of shrubs; and (iv) the need to leverage remote sensing products. In response: (i) NMSU actively recruited new faculty, and we engaged three of those faculty as new co-PIs in this proposal (Hanan, Pietrasiak, Brungard) and additional new faculty as collaborators (Lehnhoff, Prihodko); (ii) LTER datasets are up-to-date and accessible via the website (www.lter.jornada.nmsu.edu) and discoverable via DataOne. In addition, the Jornada developed a mobile application that provides geospatially tagged information on research locations; (iii) In LTER-VII, we propose new studies of shrub population dynamics and the role of demographic bottlenecks versus density dependent competition in driving transitions; and (iv) we continue to expand development of UAV technologies, and explore synergies between ground, UAV, airborne and satellite imagery for state change analysis.

IV. Synthesis

The goal of the Jornada LTER program is to understand and quantify the key factors and processes controlling ecosystem dynamics in Chihuahuan Desert landscapes. In collaboration with the Jornada Experimental Range (USDA ARS), studies initiated in 1915 have been incorporated into our program. Previous research focused on desertification, a state change from perennial grasslands to woody plant/bare ground dominance that occurs globally. More recently, our research has explored the role of spatial interactions (wind and water connectivity) in driving multiple types of transitions, including grassland recovery, non-native plant invasion, and changes in dominant shrub species. These transitions have profound implications for processes reflected in the 5 core LTER research themes. In LTER-VII, we introduce the "trigger-feedback-heterogeneity" framework for understanding dynamics of state-change in dryland landscapes. The overall goal of Jornada LTER-VII (2018-2024) is to develop robust principles governing dryland state changes and apply them across spatially heterogeneous landscapes to forecast future states in response to changing climate and land use. In LTER-VII, we will explore how spatial heterogeneity of dryland landscapes evolve over time in response to disturbance triggers, positive feedbacks, and their interactions with the eco-geomorphic template. We will address the critical need for integration of long-term observations into an evolving conceptual and predictive framework for drylands. We propose to expand our landscape linkages framework to fill this critical need, and to contribute to emerging ecological theory on: (a) alternative states and resilience, (b) ecosystem sensitivity to global change, and (c) cross-scale interactions. Our recent observations indicate the need to conceptually and computationally integrate data and knowledge into a Data Science Integrated System (DSIS) that will allow Jornada results to be translated to other locations in the Chihuahuan Desert and to drylands globally. Our research will result in five major products: (1) new understanding of state changes, in particular in drylands, that lead to theory development, testable hypotheses, and new experiments; (2) accessible data, derived data products, and visualization tools applicable at multiple scales; (3) explanatory and predictive relationships among drivers, patterns, and processes that can be used to (4) predict dynamics of alternative states at new locations or future conditions with assessments of their impacts on ecosystem services; and (5) training, outreach and information transfer to broad audiences locally, nationally and internationally.

V. Results from Prior NSF Support

Peters, DPC, BT Bestelmeyer, S Bestelmeyer, N Hanan, HC Monger, Jornada Basin LTER: Long-term research at the Jornada Basin (LTER-VI). 2012-2018. $5,880,000 (DEB 1235828)

Productivity and datasets overview. LTER-VI was highly productive, including 159 journal publications, 32 book chapters, 2 books and 13 graduate theses and dissertations. Jornada personnel also led/edited 4 journal special issues/features, highlighting dryland ecology and ecological theory. We published in high visibility/impact journals, including *Ecology, Ecosystems, Frontiers in Ecology and Evolution, Global Change Biology, Nature, Oecologia, Proceedings of the National Academy of Science, Science, and Trends in Ecology and Evolution*. Our 10 most significant publications (shown in ***bold italics*** in the proposal and summarized below in Table 1) were selected based on: impact on Jornada research development in LTER VI, significance to drylands research, contribution to ecological theory and general understanding of ecological systems, and impact on land management. Our database contains 150 data sets derived from long- and short-term studies for all five LTER core areas. Key LTER-VI studies are referenced in the following paragraphs using italicized abbreviations (details in Suppl. Table A1). On average, one or more of our data sets are accessed more than 117 times per month. The LTER webpage is visited an average of 206 times per week by non-Jornada associated computers. 96% of our core long-term datasets are available online and the remaining data are available by request.

Sensors. We expanded and maintained our environmental sensor network. New sensors constitute a ~100% increase in meteorological infrastructure, and a ~60% increase belowground, with notable increases in continuous measurements. New initiatives include wind towers (3 new), phenocam sites (4 new), eddy covariance towers (2 new), instrumented playas (18 new), and remotely-triggered wildlife cameras to measure abundance of predators (coyotes kit fox).

Sensor development: UAV and satellite remote sensing for ecological insight. We contributed to development of novel technologies using Unmanned Aerial Vehicles (UAV) for ecological research (Duniway et al. 2012). JRN is leading development of UAV technologies as alternatives for rapid assessment of not only traditional ecological metrics (e.g. vegetation cover and biomass), but also for assessment of wind and water connectivity at multiple scales (***Okin et al. 2015***; Rachal et al. 2015), and direct measurement of soil erosion processes (Gillan et al. 2016). We also integrated our long-term ANPP data with MODIS data to develop new techniques to identify state changes in imagery (Williamson et al. 2012; Browning et al. 2017).

Supplemental Support: we did not receive NSF supplements during LTER-VI.

Table 1. Ten most significant Jornada Basin LTER-VI publications from 2012-2018

	Authors	Journal citation	Impact or significance	Datasets/Core Areas*
1.	Sala et al. 2012	Phil. Trans. R. Soc. B. 367: 3135-3144.	Developed theory to explain legacies in ANPP; data synthesis showed same result from deserts to mesic grasslands.	NPP, PPT/1,3,5
2.	Bestelmeyer B et al. 2013	Ecol. Lett. 16: 339-345.	Heavy grazing alone does not trigger G→S transitions	ThreshEx, PPT/3-5
3.	Herrick et al. 2013	J. Soil Water Conserv 68: 5A-12A.	Land-Potential Knowledge System (LandPKS) developed to allow citizen scientists globally to collect/ share data via phones.	/1,4-5
4.	Peters et al. 2014a	Ecosphere 5: 67.	Developed KLAS, a novel *k*nowledge, *l*earning, *a*nalysis *s*ystem for discovery and problem solving.	VegMaps, NPP, PPT, SoilMaps, StockRate, Quads/ 1-5
5.	Peters et al. 2014b	Oecologia 174: 1323-34.	Grass recovery in degraded shrublands in wet periods results from sequential demographic processes and plant-soil water feedbacks.	NPP, Jornex, SoilMove, Phenology/1-2,4-5
6.	Bestelmeyer S et al. 2015	Front. Ecol. Environ. 13: 37-43.	Developed innovations in LTER K-12 education with colleagues from several LTER sites.	EcoTrends data in Data Jams/1-5
7.	Okin et al. 2015	Front. Ecol. Environ. 13(1): 20-27.	Connectivity by wind, water, and animals plays key role in state change dynamics.	ConMod, PPT, Quads/3-5
8.	Peters et al. 2015	Front. Ecol. Environ. 13: 4-12.	Challenged desertification paradigm with alternative states framework based on connectivity; cross-scale interactions; legacies	NPP, StockRate, Exclosures, PPT,SoilMaps, VegMaps,/1-5
9.	Schreiner-McGraw and Vivoni 2017	Ecosphere 8: e02000	Sensor network and long-term data revealed runoff from bajada watershed contributes to deep percolation and ground water recharge during wet periods.	TW, PPT/4-5
10.	Schooley et al.	Ecosphere in revision	Long-term data showed rodent population dynamics depend on lagged responses to ANPP moderated by shrub cover.	Ecotone, PPT/1,5

*Core Areas: 1= primary production 2= organic matter accumulation in surface layers 3= disturbance 4= inorganic inputs and movements of nutrients through soils 5= populations selected to represent trophic structure

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