PROJECT DESCRIPTION

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 or savannas to landscapes dominated by xerophytic shrubs, and are often accompanied by soil erosion and loss of biological resources, including aboveground production and biodiversity (Archer et al. 2017, D'Odorico et al. 2019). Such changes are referred to as state transitions, or regime shifts, when positive feedbacks lead to persistent, divergent states in otherwise similar climate and soil conditions (Petraitis 2013, Scheffer and Carpenter 2003, ***Bestelmeyer et al. 2018***). Because drylands occupy >40% of the Earth's land surface, dryland state transitions 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).

Established paradigms for understanding state transitions in drylands emphasize that: (1) shrub-dominated states are very stable under current climatic conditions as a result of positive feedbacks between woody plant dominance and nutrient availability to woody plants, such that grass recovery is rare and restoration is difficult (Schlesinger et al. 1990, D'Odorico et al. 2010); (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, mediated by soil properties interacting with local plant-scale processes (Asner et al. 2004, Geist and Lambin 2004, Reynolds et al. 2007, D'Odorico et al. 2013); (4) local disturbance to biological and physical soil crusts increases vulnerability of desert soils to wind and water erosion, with crust recovery following disturbance depending on weather, soil type, 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 (Seager et al. 2007, Schlaepfer et al. 2017).

Recent studies by the Jornada Basin (JRN) 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, Wilcox et al. 2012, Peters et al. 2012); (2) shrubland states may exhibit transient dynamics among dominant species that exhibit different functional traits (e.g., from deciduous to evergreen) at decadal time-scales (Lavorel et al. 1997, Gibbens et al. 2005, Porensky et al. 2016); (3) spatial and temporal variation in state transitions are caused by cross-scale interactions among disturbance intensity/duration, soil heterogeneity, and connectivity-mediated feedbacks between vegetation patches and transport vectors (wind, water, animals) (Bestelmeyer et al. 2011a, Ratajczak et al. 2017). Note that we define connectivity as the linkages between patches or other landscape units through the transfer of materials or energy by these transport vectors (Okin et al. 2015). The ecological responses to these interactions yield asynchrony in state transitions (D'Odorico et al. 2010, Turnbull et al. 2010, Browning et al. 2017) and produce spatial heterogeneity at multiple spatial scales (Fuhlendorf et al. 2017); (4) cross-scale interactions between soil properties and geomorphology with patch-scale wind and water erosion prevent vegetation and biocrust recovery in locations no longer subject to livestock trampling or similar disturbance (***Okin et al. 2018***, Pietrasiak et al. 2011; 2014); (5) climate non-stationarity interacts with the intrinsic non-linearities and heterogeneity to produce a range of ecosystem trajectories in drylands (Sala et al. 2012, Monger et al. 2015, ***Peters et al.*** 2012; ***2018*)**. [Note: references in **bold font** throughout the proposal identify the 10 most significant publications from the last 6 years of funding].

There is a critical need to integrate these recent science advances 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 of dryland state transitions and to 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 (Wooton 1908, Schlesinger et al. 1990, Archer 1994, Reynolds et al. 2004, ***Peters et al.*** 2004; 2006; ***2015; 2018, Bestelmeyer et al.*** 2011b; ***2018***, Peters and Okin 2017), (2) accessible legacy data extending to 105 years that quantify 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, ***Gherardi and Sala 2015b***), (3) established expertise in quantifying the effects of connectivity by wind, water, and animals (Peters et al. 2008, Monger et al. 2009, ***Schreiner-McGraw and Vivoni 2017, Okin et al. 2018, Schooley et al. 2018***) coupled with new expertise on the 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 transitions (Vivoni 2012, Hanan et al. 2014, Herrick et al. 2016, ***Okin et al. 2018***, ***Peters et al. 2018,*** Petrie et al. 2019a, Ji et al. 2019), (5) experience in transferring state transition concepts, information and technology to broad audiences, including K-12 students and teachers, the general public, and private and public land managers (Peters et al. 2013b, ***Herrick et al. 2017a, S. Bestelmeyer et al.*** 2015***; 2018***), and (6) expertise in describing the consequences of state transitions 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. 2019b).

The Jornada Basin is broadly representative of processes affecting drylands globally. The site exhibited classical grassland-to-shrubland transitions beginning in the 1850s (Buffington and Herbel 1965), which now affect virtually all areas. More recently, new alternative states are emerging, including a reversal from shrublands toward perennial grasslands (***Peters et al.*** 2012; ***2014***), 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 most extensive desert in North America, with transport vectors and soil variations that represent 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: (1) a shrubland endpoint to compare with the SEV LTER where large expanses of grasslands still persist (Collins et al. 2014), (2) a remnant subtropical desert grassland endpoint to compare with the temperate mesic grasslands at the Konza and Cedar Creek LTER sites (Peters et al. 2013b), (3) an arid rangeland node in the emerging Long Term Agricultural Research network (LTAR) (Spiegal et al. 2018), (4) 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, and (5) arid and semiarid sites globally (e.g., ILTER).

2. Research Questions and General Approach

In the next phase of LTER-VII, we will continue to explore how landscape-level spatial heterogeneity evolves in response to the effects of disturbance triggers, connectivity-mediated feedbacks, and their interactions with the soil-geomorphic template. We will integrate long-term observations and recent theoretical developments to improve a conceptual and predictive framework for drylands. We propose to expand our landscape linkages framework that we started modifying in Phase I of LTER-VII (***Peters et al. 2018***) to fill this need, and to contribute to emerging ecological theory on: (1) alternative states and transient dynamics, (2) ecosystem sensitivity under global change, and (3) cross-scale interactions. Our recent activities have positioned us to package disparate data types and process-based knowledge into a *Data Science Integrated System (DSIS)* that will allow analytical approaches developed at JRN to be translated to other locations in the Chihuahuan Desert and to drylands globally.

New research in the next phase of LTER-VII will address important unresolved questions:

(1) How do multiple environmental drivers operating at different scales (e.g., climate, livestock grazing) interact as *triggers* that initiate state transitions?

(2) How do *pattern-process relationships* interact across scales to control the rate and outcome of state transitions? Specifically, under what conditions in time and space are connectivity-mediated *feedbacks* important to state transitions? Under what conditions do *broad-scale drivers and transport vectors* overwhelm fine-scale feedbacks to cause state transitions?

(3) How can we use *knowledge of pattern-process relationships across scales* to manage state transitions? Specifically, how can we apply our understanding of alternative states from intensively studied locations *to under-sampled locations* across heterogeneous landscapes and *to predict future ecosystem states*?

(4) How can we *harmonize, integrate,* and *analyze* diverse multi-scale observations of flora, fauna, microbiology, soils, hydrology, and climate to enable process-based explanation and prediction across heterogeneous landscapes?

Our research plan builds on research initiated in Phase I of LTER-VII. We will use extensive short- and long-term datasets, numerical models, and multi-scale spatial analyses to explain and predict a variety of state transition types (encompassing long-term transient 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 state transitions via critical changes in (2) transport vectors (wind, water, animals) interacting with (3) patch structure to cause (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; our expanding network of weather stations will enable detailed measurements at a broad extent. 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 historical datasets include locations, intensities, and frequencies for different disturbance types (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 the next phase of LTER-VII are more challenging (Fig. 2). We seek to:

Obj. 1. quantify effects of interactions among triggers, connectivity-mediated feedbacks, and soil-geomorphic heterogeneity on the rate and nature of transitions between states,

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

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

Our research will result in four major products: (1) increased understanding of state transitions, especially in drylands, that lead to theory development, new hypotheses, and new experiments, (2) tools for predicting state transitions at regional extents under future environmental conditions, including assessments of their impacts on ecosystem services, (3) accessible data, derived data products, and visualization/analysis tools for examining relationships among diverse data types, and (4) usable information products tailored to science, management, policy-making, and the interested public. Our approach is to test hypotheses about driver-feedback-heterogeneity relationships, and hysteresis and resilience of alternative states using existing short- and long-term data from a suite of accessible databases and other lines of evidence in our DSIS as part of an iterative "Data-Analysis Loop" with human and machine learning (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, providing major improvements to our information management system (highlighted as a weakness in our last review) and continuing to develop our Data Science Integrated System (***Peters et al. 2018***) is a top priority. Our findings will contribute to ecological theory and to the development of strategies aimed at forecasting state transitions (Scheffer 2009, Carpenter et al. 2011, Dakos et al. 2013). We will also contribute to advances in restoration ecology, landscape ecology, ecohydrology, global change, and Earth system science while continuing our century-long contributions to the science underpinning desertification and land management. These products are timely for the transition from the United Nations Decade for Deserts and the Fight against Desertification (2010-20) to the Decade on Ecosystem Restoration (2021-30).

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

Our current 'landscape linkages' framework reflects the evolution of the Jornada LTER program. 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 pattern-process relationships might explain spatial variation in desertification dynamics (e.g., Peters et al. 2006; 2007, Okin et al. 2009). A conceptual framework for the role of cross-scale interactions in state transitions was developed (Fig. 1; Peters et al. 2004; 2006). State transitions can spread at an accelerating rate over time due to feedbacks between transitions extent and the connectivity of processes governing transitions (Peters et al. 2004). Spatial variability in land-surface or driver properties (e.g., local soil properties and adjacency to features such as seed sources) and temporal contingencies (e.g., legacies of land use or extreme events) control the heterogeneity of transitions 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 led by Peters).

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 transitions are a function of: *(i) temporal contingencies* (legacies: Reichmann and Sala 2014, Monger et al. 2015; future climate: ***Gherardi and Sala 2015b***), *(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. 2018***), 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 that control connectivity, erosion, and resource redistribution. We now routinely measure bare soil gap size distributions in our experiments and multi-scale analyses, and such measurements are systematically gathered by U.S. land management agencies in rangelands.

In LTER-VI, we also expanded our research to examine new types of transitions occurring in the region, including those from: (a) degraded shrublands towards perennial grasslands, (b) one to another shrub functional group, and (c) grasslands or shrublands towards novel ecosystems involving invasive species. For each transition type, we quantified patterns through time and initiated mechanistic studies to explain those dynamics (e.g., ***Peters et al. 2014***). 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 historical reconstructions. In the next phase of LTER-VII, we generalized our conceptual framework to accommodate this new perspective.

Our transition studies in LTER-VI provide qualitative support for the dynamics of our cross-scale interactions framework proposed in 2004 (Peters et al. 2004). Threshold-feedback processes involved in shrub encroachment also occur when grasses re-establish within degraded shrublands: perennial grass recruitment is triggered by a sequence of wet years followed by feedbacks allowing them to persist in subsequent dry periods (***Peters et al.*** 2012; ***2014***). Spatial variability in soil properties and other contextual components result in spatial heterogeneity in grass recovery across a landscape ***(Peters et al. 2018).*** While 'triggers' are at play in both types of state transitions, the nature of the triggers differs: grasses require a series of above-average precipitation years (***Peters et al. 2014***), whereas shrub encroachment is triggered by livestock overgrazing and drought (***Bestelmeyer et al. 2018***).

Next steps in our Conceptual Framework

In Phase I of LTER-VII, we began quantifying the components of this "trigger-feedback-heterogeneity" framework for our four transition types. Our goal is 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), push systems across critical thresholds and have effects at the finest spatial scales, for instance the level of individual plants or plant/crust patches (Scheffer et al. 2009, Bestelmeyer et al. 2013) (Fig. 1). These changes initiate connectivity-mediated **feedbacks** at expanding spatial scales that involve resource redistribution from bare soil to adjacent plant patches (Alvarez et al. 2012, Svejcar et al. 2015) or from one landform to another through hillslope and channel surfaces (Monger et al. 2015). Feedbacks create and reinforce patchiness (Rietkerk et al. 2004), and can lead to pronounced shifts in vegetation composition, soil function, and ecosystem processes resulting in complex patterns in heterogeneity at local to landscape scales (Fuhlendorf et al. 2017) 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, micro-topography) 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 the rate, type, and magnitude of change in 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 **spatial heterogeneity** in 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, Porensky et al. 2016). Contingency, time lags, thresholds, feedbacks, and spatial interactions are major obstacles to prediction in ecosystem science. In the next phase of LTER-VII, we propose to continue 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 prediction. We will resolve what heretofore have seemed like controversies, such as dominant causes of state changes, and we will address a large pool of unexplained variance (Archer and Bowman 2002, Peters et al. 2006, Archer et al. 2017).

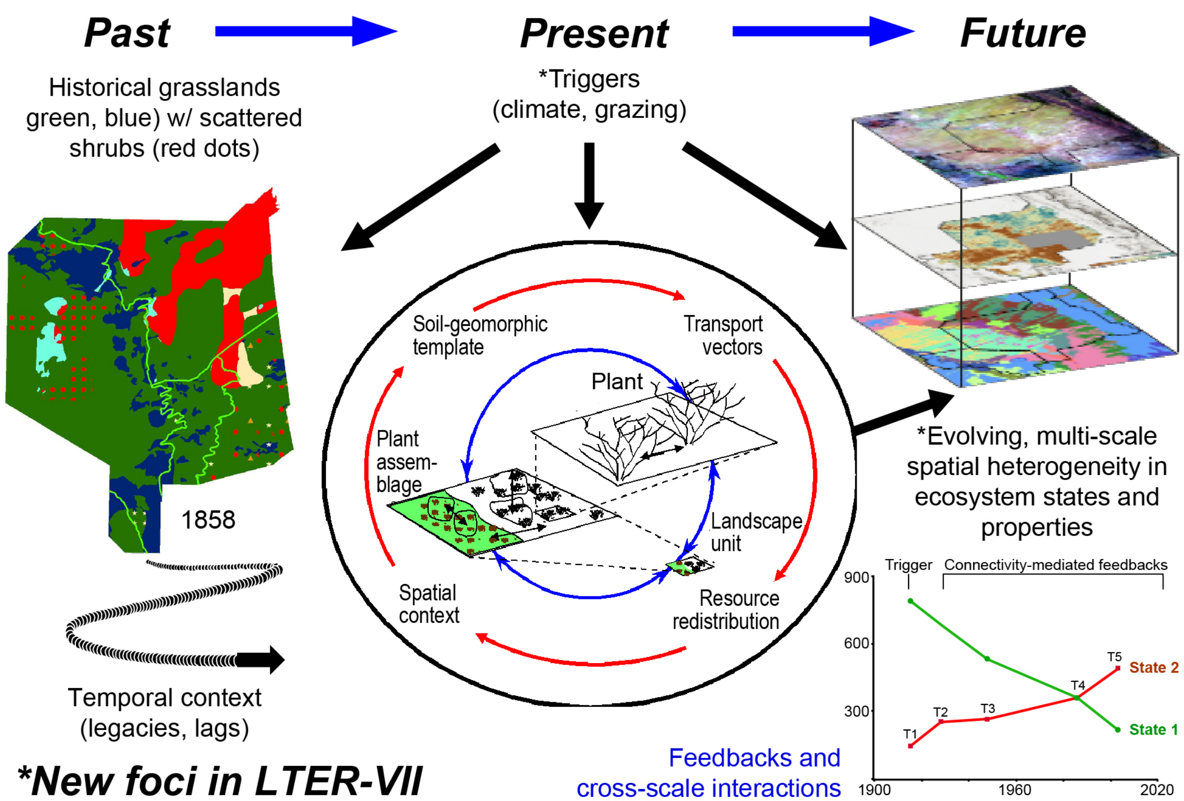

Fig. 1 Jornada framework for alternative states based on a hierarchy of interacting scales and connectivity-mediated redistribution of resources. Interactions among six key elements connect levels of the hierarchy and generate complex dynamics across heterogeneous landscapes: (1) legacies of past climate, management practices, and disturbance; (2) current and future environmental drivers (climate, grazing) that act as triggers of state transitions; (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 that 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 to culminate in multi-scale state transitions. **New studies in LTER VII** are designed to investigate: triggers of state transitions 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.

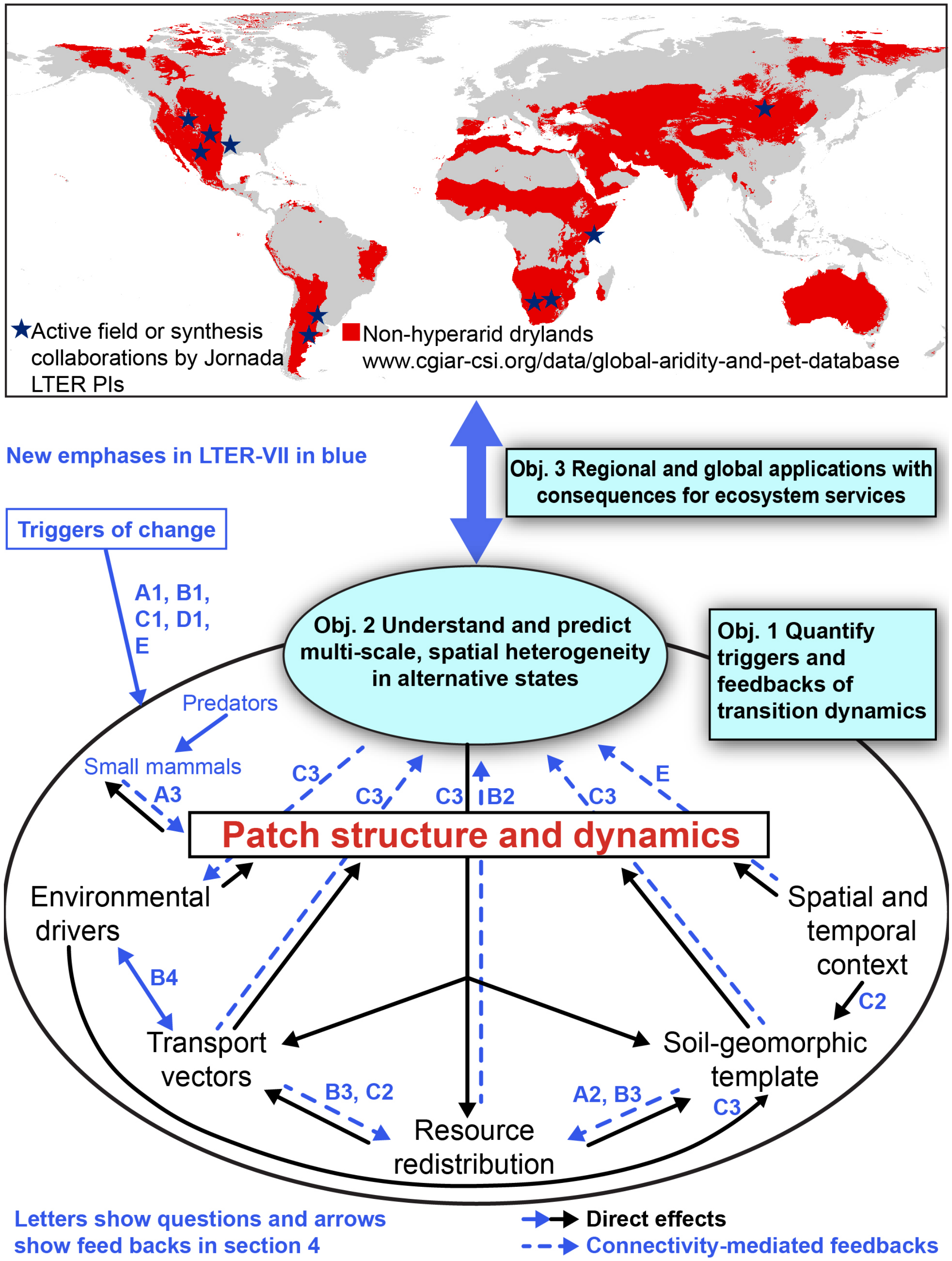

Fig. 2. Major objectives for the next phase of Jornada LTER-VII: to transform our understanding of alternative states in drylands by quantifying triggers and feedbacks that lead to spatial and temporal heterogeneity in transitions at multiple scales. Key LTER-VII Research Questions and feedbacks are shown in blue text and arrows, referenced to subobjectives (e.g., A1) in Section 4.2.

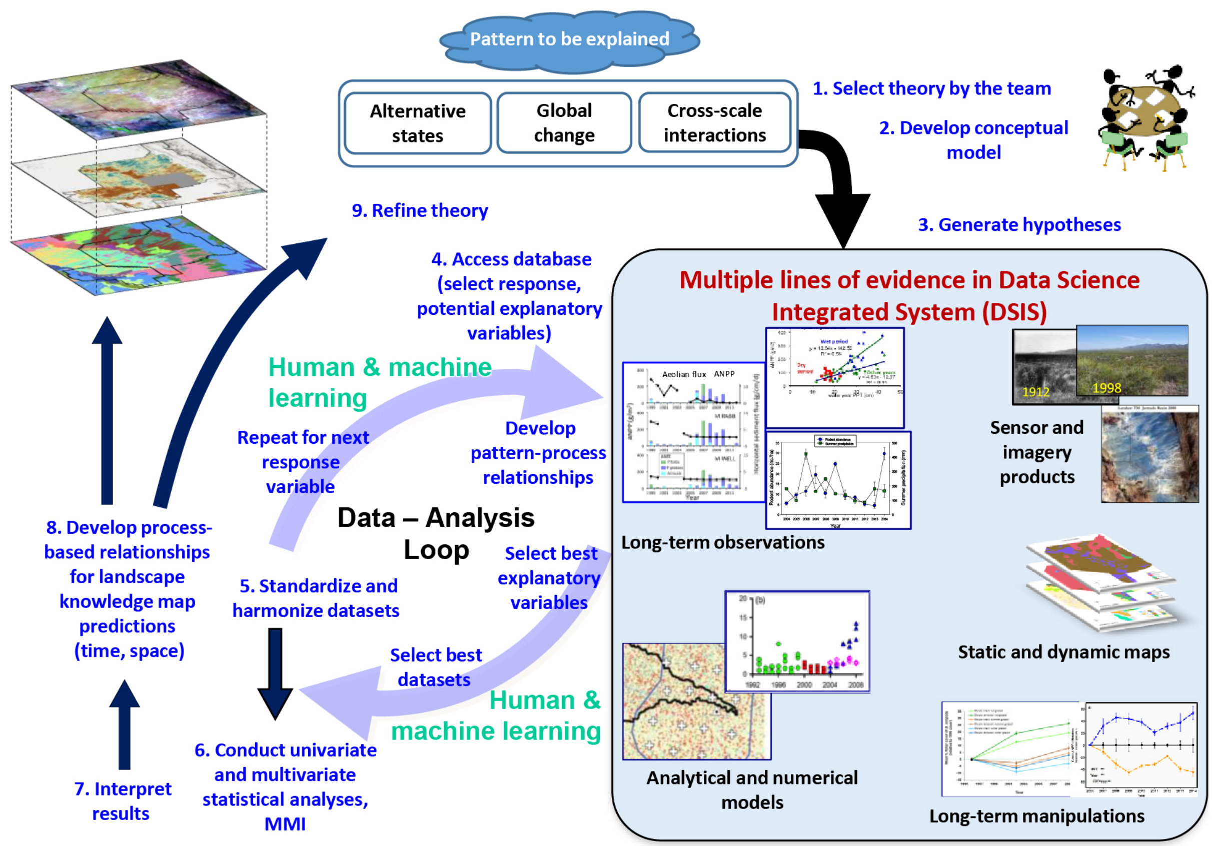

Fig. 3. Framework for data-model integration and hypothesis testing in trans-disciplinary research. An approach based on spatio-temporal modeling combined with human and machine learning to select, integrate, and analyze data and information drawn from multiple lines of evidence (i.e., short- and long-term 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 to select a response variable and potential explanatory variables; 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. in press). (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. 2018).

Response to Previous Review (Spring 2018 JRN-VII Proposal)

The major weaknesses identified in our 2018 LTER-VII proposal were related to issues with Information Management (IM). Specifically, signature JRN datasets were not listed on the project website or on EDI, public datasets were not up-to-date beyond 2015, and there were inconsistencies in data coverage between the project web site and EDI in terms of data coverage. To address these problems, we made major personnel changes in our IM team by hiring a new lead IM (Dr. Greg Maurer), a new project manager experienced in R (2018/19: Dr. Christy Meredith; 2020: Dr. Nina Joffe), and a half-time database analyst (Haneen Omari). This team worked with a statistician (USDA ARS) to create/update metadata and publish up-to-date data (2018/19) to EDI with a priority on our signature long-term datasets (Suppl. Table 1). We also worked with USDA ARS personnel to develop a new data catalog on the JRN LTER website that is directly synchronized with EDI. To-date, 100% of our signature long-term datasets have been updated, and we have added a significant number of new packages for a total of 211 data packages on EDI. In addition, our data scientist (Dr. Geovany Ramirez) and our site manager (John Anderson) developed a ML approach to QA/QC streaming meteorological data by extending the GCE Toolbox for MATLAB (Peters et al. in press). This new extension to the toolbox automates the QA/QC and EDI publishing process for continuous meteorological data and metadata, yet is sufficiently flexible to: (a) allow human guidance, (b) add more stations and variables, and (c) allow for non-stationarity in climate. These meteorological data are also available in provisional form on our Jornada web page, allowing users to view and download weather data for the Jornada Basin within a day of collection. We continue to add met stations to the system, and will make the code openly available at GitHub. Finally, we have improved communication between the IM team and JRN scientists through regular and impromptu meetings that help structure the IM system to support the ongoing and proposed science activities. We clarified in our proposal that the DSIS is undergoing development, and will be a valuable research tool for the Jornada and others. We will also provide public tools on our web site to allow users to easily visualize and download datasets with customized suites of response and driver variables as an initial step towards a generalizable tool kit for the community, similar to existing websites by JRN PIs.

The science in the proposal was viewed by panelists as very strong. The panel summary stated "Overall, the model fits the system, builds on past work, and leads to a new paradigm for vegetation change in drylands". Specific criticisms were addressed: (a) we clarified the terminology to better define triggers, feedbacks, and state transitions that lead to landscape heterogeneity; (b) we provided a better connection to plant functional traits that could mediate these transitions, in particular among different shrub species; (c) we explained that experimental exclusion of mammalian predators was impractical, and instead we will use structural equation modeling to quantify trophic dynamics.

4. Proposed Research for LTER-VII (2020-24)

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 13ºC in January to 36ºC 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). Experimental research dating to the 1920s 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 shrub species (mesquite, tarbush, creosotebush) with different functional traits (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 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 dominance and abundance under future environmental conditions.

Some 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 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

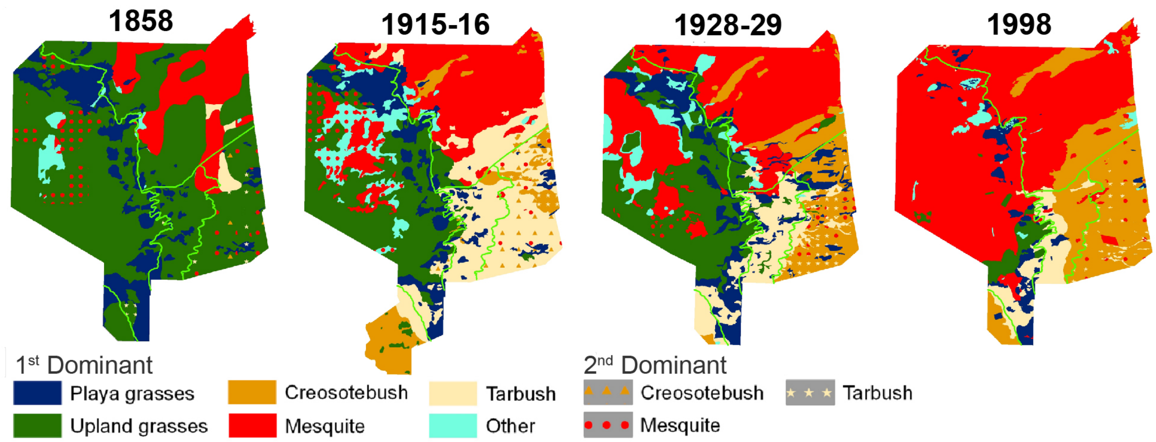

Fig. 4. Jornada vegetation maps showing first and second dominant species: (a) 1858, (b) 1915-16; (c) 1928-29, (d) 1998 (modified from Gibbens et al. 2005). Note major transitions from grasslands to shrublands and shifts between shrublands. We will create an updated species map in LTER-VII using a combination 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.

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 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 and, while we have observed landscape scale shifts in dominant species, the underlying population-demographic processes (spatial and temporal establishment and mortality dynamics) and landscape scale interactions with climate, soils and biotic processes, are poorly understood, constraining our ability to understand the past or predict the future. 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 types of state transitions occur in drylands worldwide; the knowledge gaps associated with them are being 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 and Phase 1 of LTER-VII 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 or simulations, 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:** A comprehensive, geospatial database linking 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 will allow us to apply 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:** LTER network participation, scientific leadership, and collaboration with our partners, which include local government agencies and international organizations, will extend our scientific products and insights to regional, continental, and global scales. Our goal is to apply the concepts and tools developed at the JRN to solve land management problems in global drylands, and to 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 for related data packages are shown in Suppl. Table 1, and signature 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. We 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 mobile app (available on Google Play and App store under ‘Jornada Arid

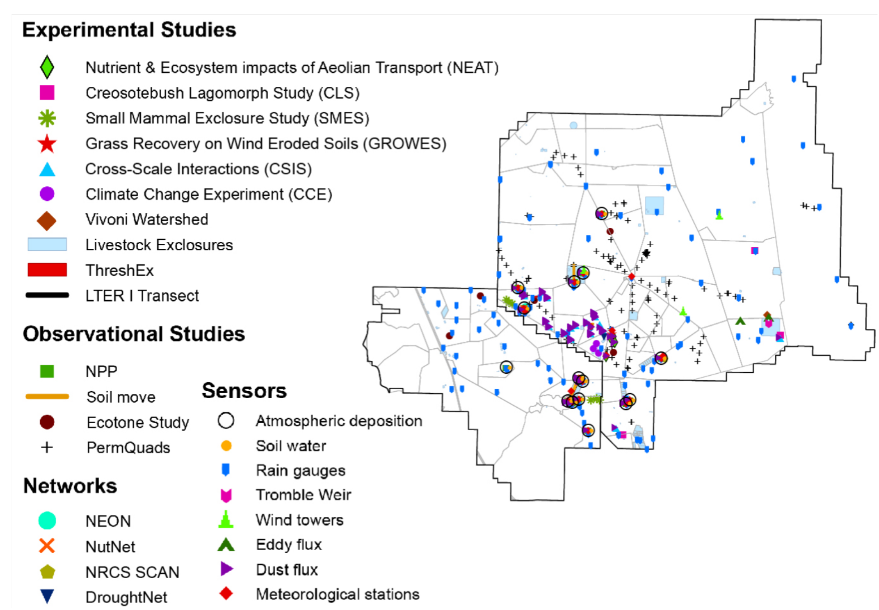

Fig. 5. Jornada research site showing locations of core long-term studies and sensor networks.

Land Research') contains Jornada base maps and allows users to add geo-tagged data acquisition, study locations, field notes, and photographs.

4.2 Integrated site-scale studies of state transition dynamics

Obj. 1 To quantify effects of interactions among triggers, connectivity-mediated feedbacks, and soil-geomorphic heterogeneity on the rate and nature of state transitions.

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 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) ignored the role of connectivity as a driver of change among geomorphic units across the landscape, (2)

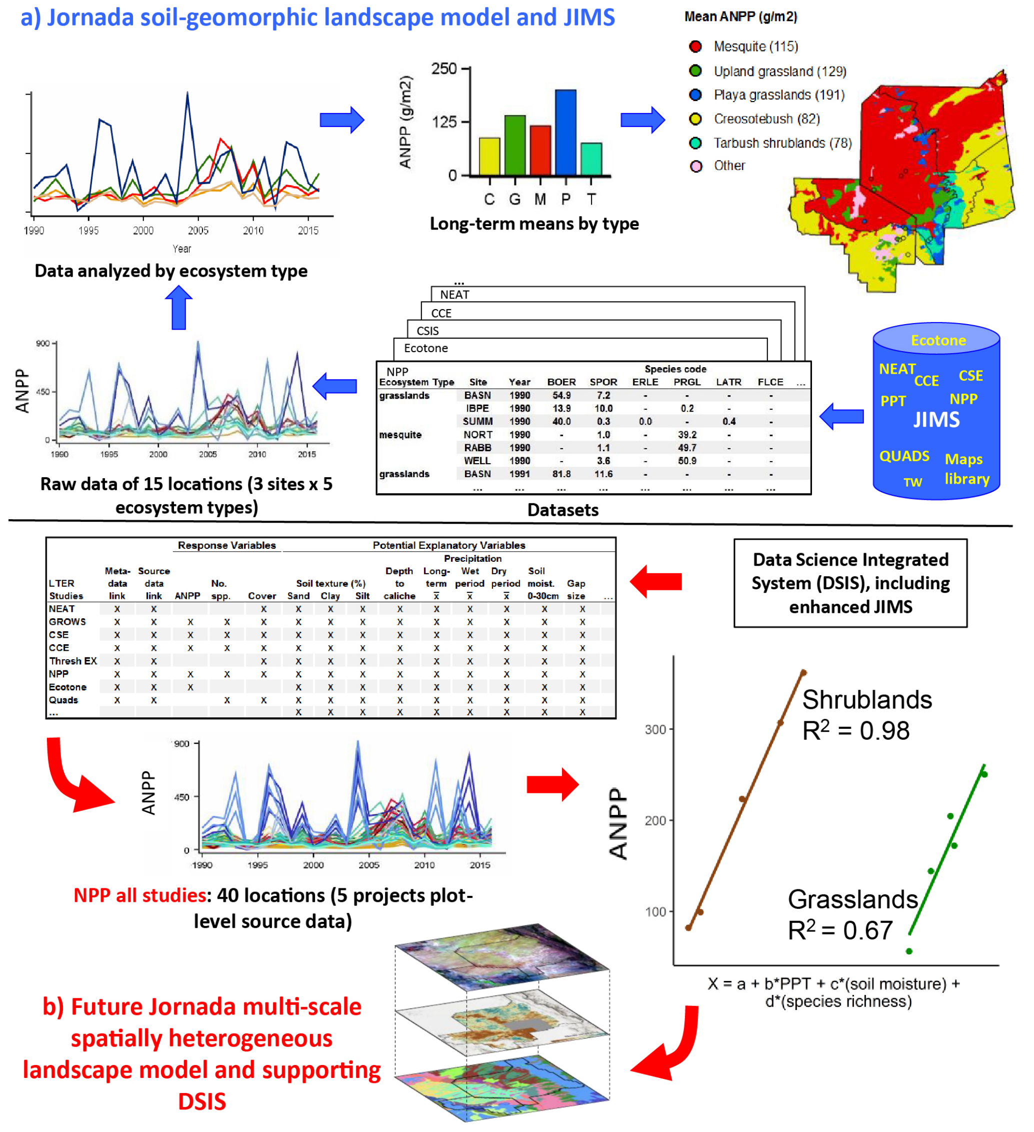

Fig. 6. Comparison of previous and future approaches: (a) Jornada I-VI model where the Jornada landscape was simplified by associating ecosystem processes (e.g. ANPP-PPT relationships) and state transitions to specific soil-geomorphic units. Our JIMS (Jornada information Management System) contains projects with associated data and metadata, and has limited ability for cross-project queries. (b) 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 new DSIS is being developed as a research tool with a common database structure containing links to source data and metadata that will allow queries, integration of data, and analyses across multiple projects. The example shown illustrates the power of our future DSIS.

assumed inferences can be reliably applied to other locations within a soil-geomorphic unit, (3) failed 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. 5), and (4) presented 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 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. 2006). 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 1), (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 models: 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 models 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). Multiple models will be used when 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. 2018***). 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. 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. We have actively worked to make our long-term data accessible through EDI over the past two years, and are developing data access, analysis and harmonization tools that will position us to develop a *Data Science Integration System (DSIS)* to support the integration needed to address our questions (Fig. 6b). 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

These transitions are triggered by overgrazing 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, wind and water erosion feedbacks are hypothesized to reinforce declines in grass cover and provide opportunities for shrub recruitment (Alvarez et al. 2012, D'Odorico et al. 2012). Grazing and soil erosion also diminish biocrust influences on 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 are unknown. Shrub proliferation also alters small mammal abundance and concentrates herbivory on grasses (Bestelmeyer et al. 2007). The proposed studies aim to quantify 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 *ThreshEx* (1996-present) experiment investigating grazing as a driver of state transitions showed a threshold response in only one paddock, yet all paddocks were dominated by the stoloniferous grass *Bouteloua eriopoda* (black grama) (Fig. 7) that historically was lost to grazing and drought across much of the Jornada (Fig. 4. upland grasses). Further analyses show that both grass cover *and* patch size need to be reduced to extremely low levels before G→S transition thresholds are crossed (Svejcar et al. 2015). Model simulations indicate that press duration (i.e., number of consecutive years) may be a more important determinant of transition thresholds than disturbance intensity (Ratajczak et al. 2017). A new experiment, *ThreshEx2,* will elucidate how grazing x drought x disturbance duration influence transition thresholds of this historically dominant grass species.

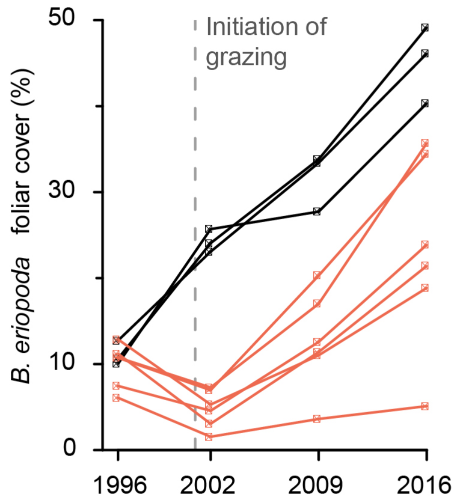

Fig.7. Change in black grama cover: with 'no grazing' (black lines) and summer or winter grazing (red lines) (Bestelmeyer et al. 2013).

Hypothesis**:** Thresholds in rates of grass decline and recovery will be controlled by the interaction of defoliation amount, drought severity, and press duration.

Study design**:** Six 0.5 ha paddocks with similar initial grass and shrub cover will be treated as blocks in *ThreshEx2*. Within blocks, treatments will include 3 levels of PPT reduction (*per* ***Gherardi and Sala 2015b)***, 3 levels of defoliation, and 3 levels of press duration (2, 4, and 8 consecutive years). Basal cover and ANPP will be measured prior to July defoliations.

Expected results**:** *ThreshEx2* will test theoretical tenets of factor interaction influences over rates of approach to ecological thresholds (e.g., Karssenberg et al. 2017, Ratajczak et al. 2017).

Q-A2. How do biocrust x wind erosion interactions feed back to affect crust establishment and soil stability? (augmenting the long-term *NEAT* experiment)

LTER VI results from the *NEAT* experiment (2004 -) demonstrated how aeolian transport drives and reinforces state change (***Okin et al. 2018***). Material deposited in upwind plots has unexpectedly begun to erode as scouring fronts advance downwind. Depletion of SOM and winnowing continues to deplete C and N (Li et al. 2017). We will investigate effects of ongoing wind erosion on vegetation (by continuing *NEAT* monitoring) and biocrusts, and their potential feedbacks to surface soil stabilization. As a new addition, we will quantify: (i) the fate of biocrust inoculum introduced on surfaces with contrasting erosion legacies, and (ii) feedback effects of differential crust cover on local erodibility. ***In LTER-VII Phase I,*** we completed the baseline work needed to produce biocrust inoculum by surveying microbial community composition and phototrophic biomass, isolating >20 strains of pedigreed local cyanobacteria for inoculation, and identifying pathogenic agents (Bethany et al. 2019) that could prevent inoculation.

Hypotheses**:** (a) Burial and scouring are spatially contagious and a non-linear function of total horizontal aeolian flux; the zone of grass mortality and loss of soil C and N are controlled by the zone of burial and scouring. (b) Survival of *in situ* inoculum and establishment of mature biocrusts is inversely related to total horizontal aeolian flux; (c) The threshold wind speed for erosion increases nonlinearly with cyanobacterial content (measured as areal chlorophyll concentration). These two factors combined result in a threshold of aeolian transport for biocrust success and their contribution to soil stability.

Study design**:** We will continue to monitor soils and vegetation [soil height (erosion bridge), horizontal aeolian flux, plant height, cover and bare gap distribution] on *NEAT* plots. High-resolution UAV imagery was added 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 nutrients. In winter 2020, crusts will be added in replicated 3 x 3 m subplots that span gradients of aeolian flux and monitored quarterly. Crust cover will be assessed by UAV with a multispectral IR-enabled camera (Rodríguez-Caballero et al. 2017), and biomass will be assessed by quantifying Chlorophyll a (Velasco Ayuso et al. 2017). The origin of developing crust components (from inoculum, from other sources, mixed) will be assessed by DNA sequencing and bioinformatics. Spatial constraints to biocrust recruitment will be assessed by quantifying fine-scale genetic pedigrees of dominant microbes (Garcia-Pichel et al. 2013).
Expected results**:** We are building an understanding of how wind-driven changes to soil height (burial and scouring) affect grass growth/mortality. The new biocrust activities will identify aeolian transport thresholds for biocrust survival/development, and ascertain how biocrust-mediated soil stability modulates 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 biopedturbations that disrupt seedlings (Brown and Heske 1990, Whitford and Bestelmeyer 2006). As shrubs proliferate, pressure on remaining grasses intensifies (Bestelmeyer et al. 2007, Abercrombie et al. 2019). Rodent abundance is mediated by PPT, with a ~1-yr time lag (***Schooley et al. 2018***). Mammalian predators track these changes, with an additional lag (Hernández et al. 2011) to mediate small mammal abundance (Letnic et al. 2011) and hence their impact on vegetation. Shrub encroachment also alters predator abundance (Blaum et al. 2007) and prey perceptions of predation risk ('landscape of fear', Laundré et al. 2014). However, black grama seedlings at the JRN suffered higher mortality from herbivores following shrub encroachment, but this was not a consequence of increases in core species of herbivores (Bestelmeyer et al. 2007). ***LTER VI results*** showed that wet periods with increased ANPP trigger lagged rodent irruptions and higher biomass of transient rodent species on shrub-dominated sites (Fig. 8). In contrast, rodent declines during drought are mostly among core species. Hence, bottom-up control of desert rodents depends on lagged responses to ANPP pulses and core-transient dynamics moderated by shrub cover (***Schooley et al. 2018***). Top-down control of small mammals by predators with feedbacks to state change at the JRN are unknown. Variable impacts of herbivore exclusion on black grama reproduction

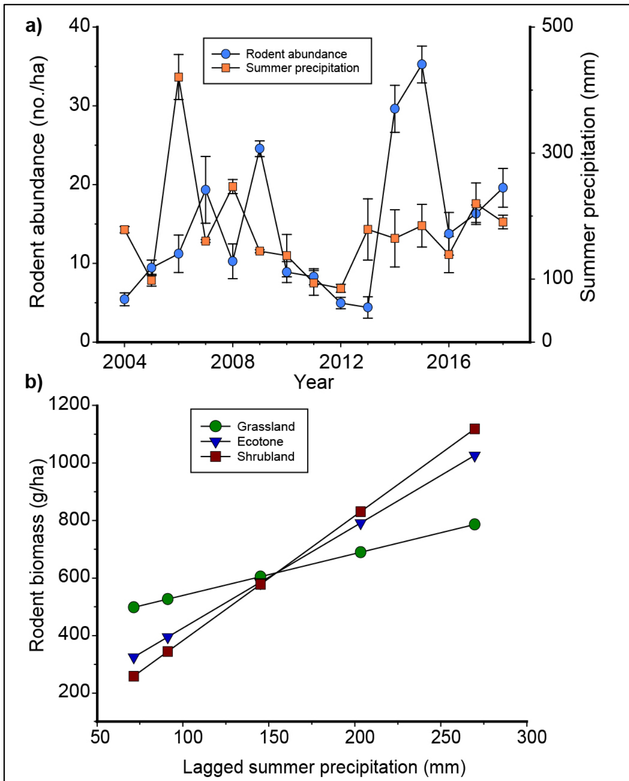

Fig. 8. Rodent abundance: a) lags PPT at the JRN, (b) is higher in shrublands in wet periods and higher in grasslands in drought (***Schooley et al. 2018***).

(Svejcar et al. 2019) might be related to top-down effects. However, initial ***LTER VII results*** indicate the dominant lagomorphs consider shrubbier habitats as safer, which could explain variations in herbivory pressure. Given these indirect effects, interactions, and lags, we are challenged to predict small herbivore influences on G→S transitions.

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

Study design**:** Experimental manipulation of PPT or predator densities is impractical given the spatial and temporal scales that would be required. Instead, we will use structural equation modeling using *Ecotone* data to quantify pathways linking trophic levels (Deguines et al. 2017). *Ecotone* includes 3 blocks, each with 3, 3-ha communities (black grama grassland, ecotone, mesquite shrubland) on which small mammals, plant cover, PPT, and ANPP have been documented since 2004 (***Schooley et al. 2018***). Cameras quantifying lagomorph and mammalian predator abundance have been deployed since 2014 on the *Ecotone* site plus 9 additional sites. Herbivory potential will be assessed with grass seedling trays at each site and tracking survival for 2 months (*sensu* Bestelmeyer et al. 2007, DaVanon et al. 2016).

Expected results**:** This study will advance a more 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 feedbacks to G→S transitions.

B. Shrubland to grassland (S→G) transitions

Grass restoration following woody plant encroachment is a major challenge in drylands (Arnalds and Archer 2000). Although climate-driven G→S→G transitions have occurred several times during the Holocene (Monger et al. 2009), the most recent G→S shift occurred at a much faster rate (100-150 y) as an unintended result of land-use practices acting in concert with drought (Havstad et al. 2006). Efforts to

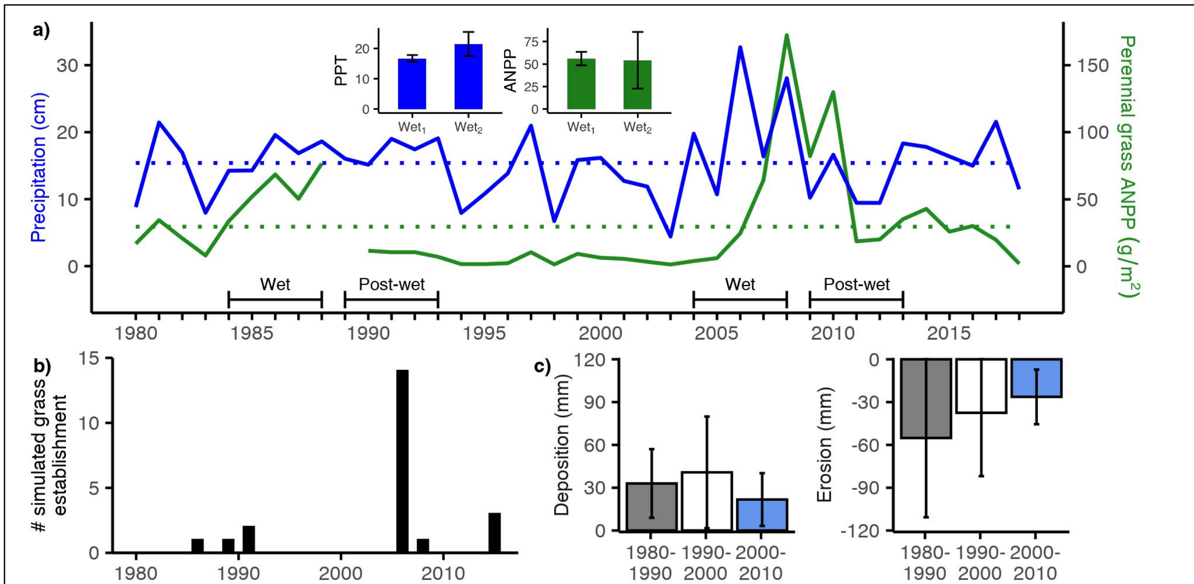

Fig. 9. Identifying triggers of perennial grass recovery in mesquite dunelands. (a) two wet periods with similar mean rainfall (insert) had different distributions and grass recovery: the first wet period (1984-88) had even distribution of rainfall between years; grasses recovered but ANPP was not maintained; the second period (2004-08) had two pulses of rainfall (2006, 2008), and more sustained grass recovery (Peters et al. in prep), (b) grass establishment was highest in the second wet period, (c) deposition and erosion were high throughout the first two decades (1980 to 2000) and lowest in the third decade (2000-2010), particularly when compared with the 1980s.

restore grasses following shrub encroachment either failed (Herrick et al. 2006, Archer et al. 2011) or required decades for a modest grass response (Allington and Valone 2011). 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 wherein perennial grass recruitment in shrub-invaded grassland was correlated with summer PPT, seed production 2y prior, and the number of consecutive wet years (Peters et al. 2012; 2014). Simulation models suggest another potential mechanism in wet periods: increasing herbaceous biomass and litter reduces bare-soil evaporation leading to positive feedbacks that increase water available to grasses (Peters et al. 2014). During this wet period, grass ANPP was not directly related to PPT as has been generally assumed (e.g., Lauenroth and Sala 1992, Knapp et al. 1998). Instead, ANPP increased nonlinearly with the number of consecutive wet years (Peters et al. 2012). In ***LTER VII Phase I*****,** we compared two wet periods [1984-88 (poor grass recovery) and 2004-08 (good recovery)] with similar growing season PPT, but different between-year distributions (Fig. 9). The first wet period triggered grass establishment and production, but ANPP crashed in the post-wet period and erosion-deposition remained high (1980 to 2000). In contrast, 2nd wet period with two distinct PPT pulses (2006, 2008) triggered higher grass establishment and ANPP that was sustained as sediment flux by wind decreased (2000-2019). This comparison helps explain the variable successes in grass seeding attempts (Herrick et al. 2006; Hardegree et al. 2012). The results also suggest a role for connectivity-mediated vegetation-aeolian feedbacks in triggering and maintaining grass recovery. We are examining these mechanisms with a new manipulative experiment: *TRIGGER*.

Q-B1: How do connectivity x rainfall interactions trigger grass recovery? (a new experiment in LTER-VII, *TRIGGER:* *T*hreshold *R*esponses *I*n *G*rass *G*rowth, *E*stablishment, and *R*ecovery**)**

This new experiment tests the proposition that grass establishment depends upon interactions between PPT and wind transport connectivity. During dry years with low soil-moisture availability (1999-03), grass recruitment rarely occurs (Fig. 9b), sediment flux is high (Fig. 10a,b) and there is little grass production response to PPT (Fig. 10a,c). Under these conditions, changes in connectivity should be of little consequence. However, in a series of wet years (2004-08), there is sufficient soil water for seed production and grass establishment/growth (Fig. 9b). Grass biomass and ANPP increases following

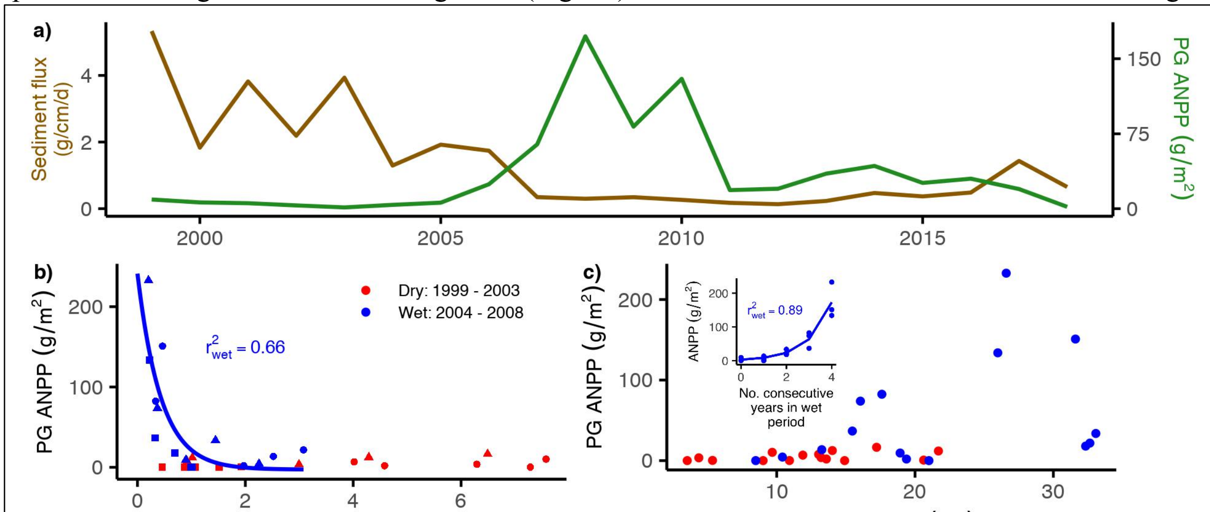

Fig. 10. Complex relationships among PPT, sediment flux, and grass ANPP have been observed in shrub-invaded grasslands. (a) High sediment fluxes during drought (2000-03) are followed by low fluxes during wet years (2004-08) that are maintained after ANPP returns to low levels. (b) ANPP is unrelated to sediment flux during drought and decreases exponentially during wet years; (c) ANPP is related to the number of consecutive wet years [insert], and not to amount of PPT in wet or dry periods.

subsequent PPT (Peters et al. 2012; 2014) to reduce bare soil connectivity and hence sediment flux (Fig. 10a, b). However, connectivity-PPT relationships at intermediate values of PPT are unknown. At intermediate PPT and soil-water availability, we predict reduced connectivity will substantively enhance recruitment. Connectivity in *TRIGGER* will be reduced via features (ConMods) shown to trap/retain wind-transported seeds and organic material, thereby creating microsites with greater plant-available soil moisture and grass seed banks, thus facilitating local recruitment (Peters et al. in press).

Hypotheses: (a) There is a lower level of PPT below which connectivity is ineffective in triggering grass recovery because no native grass seeds and too little water are available for recruitment. (b) There is an intermediate threshold of PPT below which connectivity by ConMods triggers grass establishment and above which (c) connectivity has little effect on grass recovery because water and seeds are sufficient for seedling establishment/growth in most microsites. (d) Effects of precipitation and connectivity are modulated by initial grass cover where the ConMod threshold effect increases with decreasing initial grass cover.

***Study design*: In LTER VII Phase I**, we established the TRIGGER rainfall-connectivity factorial experiment in a shrub (mesquite)-invaded site with minimal grass cover. We are manipulating PPT in zones between shrubs at levels representing 100-yr and 10-yr wet or dry sequences (+80%, +50%, -50%, -80%) using ARMS in 2.5m x 2.5m plots (*per* Gherardi and Sala 2013) and ambient conditions. Plots are divided into three sets of four replicates representing three levels (low, medium, high) of initial grass cover. At each PPT level, there are plots with ConMods present (0.8 m^{-2}) or absent (per Rachal et al. 2015; Peters et al. in press). PPT is collected at nearby weather stations within 0.8 km. ANPP, cover and plant density by species will be measured annually inside shelters; overhead photography of ConMods will quantify plant cover&density by species, litter cover, vegetation structure, and spatial distribution of biomass (*per* Peters et al. in press). Soils (0-30 cm; 10 cm-increments) collected near ConMods (T_0 and every 3y) will be analyzed for nutrients.

Expected results: We will produce ANPP response surfaces that vary as a function of connectivity, PPT, and initial grass cover. Effects of changes in connectivity on biomass distributions in plots with/without ConMods will be assessed with spatial statistics. The *TRIGGER* experiment will add a new dimension to our understanding of wind-water interactions in drylands: the interactive roles of wind transport of soil resources and propagules, and the amount of PPT required to establish and sustain grass cover.

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, *GROWES*)
A site cleared of vegetation in 1996 remained barren with high sediment flux until grasses appeared in 2007 following the 2004-08 wet period (Fig. 11). By 2017, grass cover was ~30% and mesquite cover <5%, reminiscent of conditions in the 1860s (Buffington and Herbel 1965). A new experiment was initiated in Phase I of LTER VII to leverage this manipulation to assess grassland recovery and feedbacks potentially driving alternate future states in the ansence of livestock grazing (*GROWES*: *G*rass *R*ecovery *O*n *W*ind *E*roded *S*oils).

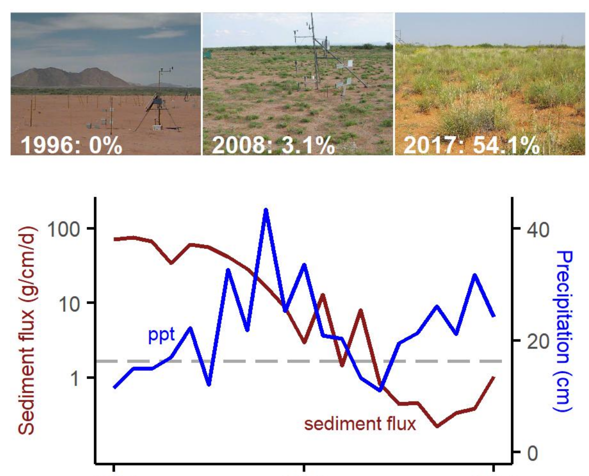

Fig. 11. Grass recovery after vegetation and surface soil removal in 1996. High sediment flux until 2004-08 wet period led to grass recovery and low flux that has persisted through time.

Hypotheses: (a) in the absence of mesquite, black grama-dominated grasslands will develop. With continued mesquite presence, the site will (b) transition to shrub dune-fields or (c) persist as grassland. ***Study design*: In LTER-VII Phase I,** the area cleared in 1996 was sampled to quantify: plant cover, density, and ANPP by species, bare gap size distribution (traditional, UAV), soil organic carbon and nutrients, net soil deflation/accumulation (soil erosion bridges), downwind dust fluxes (BSNE collectors), soil moisture (TDR) and texture, phenology (phenocams), seed availability (traps), and rodent densities (cameras). Mesquite plants in the northern part were then herbicided and left in place; the southern part had no herbicide treatment. Measurements will be repeated at appropriate temporal frequencies. ***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 Jornada ecosystems and vegetation-mediated feedbacks in S→G transitions.

Q-B3: At what threshold level of plant- and patch-scale connectivity do aeolian-driven feedbacks switch from driving grass loss to promoting grass recovery? (*CSIS*)

A 2008 pilot study quantified how physical barriers *ConMods*]) modify resource redistribution by water or wind to influence fine-scale patterns of grass recovery (Rachal et al. 2015). ConMod effectiveness varied with geomorphic surface (active vs stable), and erosive agent (wind vs water) (Peters et al. in press). 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 (Fick et al. 2016). In 2013, we initiated a long-term cross-scale interactions experiment on the sand sheet *(CSIS)* to determine: at what spatial scales and under what weather conditions (a) do fine-scale processes propagate to promote broad-scale processes leading to grass recovery? and (b) do broad-scale drivers (drought or wet periods) overwhelm fine-scale processes? The design includes individual plant (shrub) manipulations (dead/alive) of resources via competition, patch-scale redistribution via *ConMods*, plant and patch treatments combined, and controls distributed across a grassland-shrubland gradient. Broad-scale climate driver effects are examined by following plots through time. ***Hypotheses:*** (a) Gap size reduction leads to a change from patch-scale resource redistribution to dominance by plant-scale biotic processes and a decrease in soil resource heterogeneity. (b) A threshold amount of grass cover and bare gap size distribution exists, where plant-scale

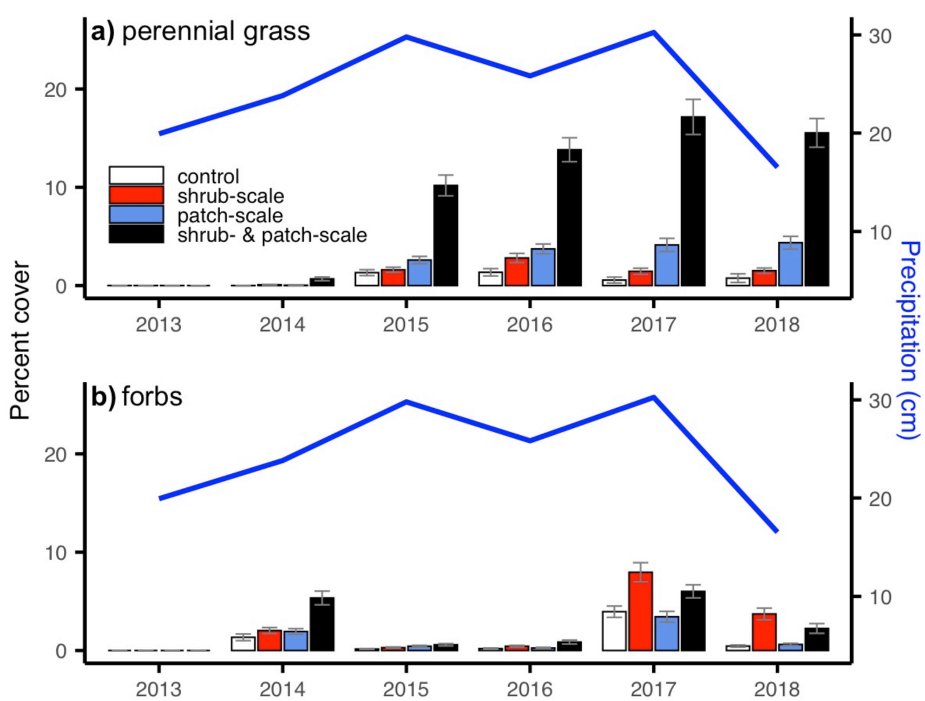

Fig. 12. CSI initial results: (a) nonlinear response by perennial grasses to multi-scale treatment compared to either treatment alone, in part as a result of (b) forbs effects on plant available water. Patch-scale is ConMod treatment.

biotic processes overwhelm patch-scale erosion/ deposition processes such that grass recovery is initiated and maintained. (c) Patch-scale redistribution of resources to grasses and/or the reduction of competitive effects of individual shrubs can offset negative effects of drought on grass recovery, belowground water/nutrient retention, and biological diversity. (d) During extended periods of high PPT, grasses will establish and persist over a larger part of the landscape than expected based on current climate.
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 where processes shift from the plant- to patch-scale dominance. Plant cover, ANPP, soil moisture, wind and energy balance are being quantified. New measurements include UAV imagery (RGB, multispectral) to comprehensively monitor species cover, and 3-D structure from motion (SfM) retrievals (Gillan et al. 2017). Belowground characterizations will include nutrients, soil water potential, seed bank, and microbial communities. These data will allow our aeolian transport (WEMO)-vegetation dynamics (Ecotone) models (linked in LTERVII Phase 1) to elucidate cross-scale thresholds. ***LTER VII Phase I results: Rapid (within 4y) grass recovery demonstrates that patch-scale resource redistribution, combined with shrub mortality, is an effective approach for restoration of aboveground processes (Fig. 12a). Shrub mortality alone generated a small perennial forb response (Fig. 12b), whereas a patch-scale redistribution of resources alone elicited a small perennial grass response (Fig. 12a). ***Expected results:*** We will continue this experiment to elucidate underlying processes and to quantify thresholds across the grassland-shrubland gradient. New measurements will allow our numerical models to leverage our long-term data to better understand connectivity-mediated feedbacks from surface soil properties to belowground responses.

C. Shrubland to shrubland (S→S) transitions

Our goal is to enhance understanding of how historic and ongoing transitions among shrub functional groups can be explained by interactions among plant functional traits, demographic processes, and water- and wind-driven redistribution of sediment, resources, and seeds. Topo-edaphic factors ostensibly control the broad-scale distribution and abundance of major shrub species (mesquite, creosotebush, tarbush) throughout the Chihuahuan Desert. However, time-series vegetation maps dating to 1858 reveal these shrub communities and the states they represent have been dynamic through space, and their distributions are not entirely controlled by soils (Gibbens et al. 2005). Here we present testable hypotheses to account for three observed patterns: (a) the increase in mesquite (*M*) in the wind-dominated portions of the basin, but not on the bajada, despite being present on both in 1858; (b) the shift on the upper bajada from a grassland in 1858 to a tarbush (*T*) state by 1915 followed by a shift to a creosotebush (*C*) state by 1928, and (c) the current dominance of a *C* state on the upper bajada, a *T* state on the lower bajada, and an *M* state on the basin. ***In LTER-VII Phase I***, re-analysis of historic vegetation maps revealed that the entire bajada was perennial grassland with scattered plants of *M, C* and *T* (Peters et al. in prep). Differences in long distance seed dispersal were thus not an explanation for contrasting patterns of proliferation. Because all three species are long-lived (decades to centuries), we evaluated explanations related to differences in functional traits related to seed germination/seedling survival responses to soils, PPT, and microbial interactions in lab/greenhouse experiments. These data are filling knowledge gaps in key shrub demographic parameters. However, little is known about the spatial/temporal processes influencing shrub distributions at fine spatial scales (plant, patch) within each geomorphic unit. Using a multi-scale approach, we will focus on: (i) seedling establishment as a key process underlying these transitions and (ii) competition and facilitation to explain S → S transitions.

Q-C1: How do shrub populations, spatial pattern, and their interactions vary with soil texture and depth, and as feedbacks change from hydrologic- to aeolian-driven across the bajada? (new field studies)

Hypotheses: (a) Spatial variability in surface soil texture (wind-blown coarse sands vs. hydrologically transported silty loams) drives $M \rightarrow C \rightarrow T$ transitions; (b) *C* and *T* dominate locations where hydrological-driven feedbacks prevail; *M* dominates where aeolian feedbacks prevail.
Study Design: Ten 25 m x 25 m plots will be established across a gradient of soil texture. These new plots will be anchored by our experimental watershed (**Q-C3**), with additional locations distributed northward across the bajada on areas with progressively more aeolian influence (i.e., wind-blown sand). Plots will be surveyed using UAV and field methods. Plant/stem and patch maps will be created, and the size (height, canopy dimensions) of each shrub quantified. Biocrust cover/composition will be quantified (per Section A.Q-A2), along with soil properties (texture, organic/inorganic C, N) to 1 m depth. Annual measurements will quantify shrub growth, mortality, and recruitment by species. Herbaceous vegetation (species, basal cover, density, patch size) will be monitored in 1 m x 1 m subplots. To place short-term growth and survival of shrubs into long-term perspective, we will re-analyze historic aerial imagery to quantify long-term dynamics at each site since the 1940s. Individual shrubs will be identified, geo-referenced, and field-verified to species then traced back in time to determine establishment dates. Earlier establishment and mortality events will be recorded. Analysis will determine long-term establishment/ mortality events and infer competition-facilitation among individuals and between species.
Expected Results: Quantification of the distribution, abundance, spatial pattern, growth and net recruitment by shrub species is a critical first step for understanding long-term responses to changes in climate and disturbance. Addressing the questions/hypotheses posed here will (*i*) put the controlled experiments (**Q-C2**) into a patch- and landscape-scale context, while *(ii)* enhancing our understanding of soil interactions and connectivity-mediated (wind or water) feedbacks to shrub dominance. Long-term image analysis will provide direct quantitative assessment of shrub demographic parameters and inference of intra- and inter-specific interactions impacting growth and survival.

Table 2. Functional traits of key C. Desert shrub species. ***LTER-VII Phase I*** results in lower section).

Attribute	***Prosopis glandulosa*** Honey mesquite	***Larrea tridentata*** Creosote bush	***Flourensia cernua*** Tarbush
Leaf habit	Deciduous	Evergreen	Tardily Deciduous
N_2 fixation	Yes	No	No
Root system	Lateral & deep	Lateral & deep	Leral & deep
Water use	Avoids drought	True xerophyte	Drought tolerant
Dispersers	Ungulates, rodents	Tumbling, rodents	Gravity, water
Livestock seed dispersal?	Yes	No	No
Vegetative regeneration?	Yes, observed at JRN	Yes, but v. rare at JRN	No, or v. rare at JRN
Seed prod. rate/frequency	High	High	Intermittent/infertile
Long-lived seed bank?	Yes	No	No
Lagomorph gran-/herbivory?	Yes (large impact)	Yes (minor impact)	Yes (minor impact)
Insect enemies	Twig girdlers, bruchids	Few	Episodic folivores
Soil O_2 (flooding) sensitivity	Moderate	High	Moderate
Adult longevity	Centuries	Centuries	Decades
Germination (not scarified)	~30 %	~10 %	~0 %
Germination (scarified)	92 +/- 7.9 %	85 +/- 11 %	0.5 +/- 1 %
Germination x soil microbes	Low sensitivity	Low sensitivity	-
Seedling baseline survival	52 +/- 10 %	81 +/- 9 %	-
Sapling baseline survival	92 +/- 20 %	100 +/- 15 %	-
Seedling x soil microbes	Yes (positive effect)	Yes (negative effect)	-
Seedling x drought	Yes (~ -20% survival)	Yes (~ -10% survival)	-
Sapling x drought	Growth suppression, but low mortality	Growth suppression but low mortality	-

Q-C2: How do soils, PPT, and microbes interact to influence recruitment of contrasting shrub functional types? Are current shrub distributions a consequence of differential seedling recruitment, of competitive interactions among adult plants or a combination of the two? (continuing controlled experiments)

Mechanisms underlying S→S transitions may include demographic and competition-facilitation interactions among grasses and shrubs (Dohn et al. 2013, Ji et al. 2019, Pierce et al. 2019). The direction/intensity of interactions depends on the expression of shrub traits (Table 2; Archer and Hanan in prep), mediated by edaphic controls on soil moisture (Barnes and Archer 1999, Donovan and Richards 2000). Inter-annual rainfall variability and disturbance can relax seedling establishment constraints, leading to recruitment events underlying current species distributions (Wiegand et al. 2006). Present-day shrub distributions may also reflect changes in soil texture/depth resulting from sediment redistribution following historic overgrazing- and drought-induced loss of grasses.

Hypotheses: (a) Spatial patterns among *M*, *T*, and *C* emerge as a consequence of differential germination and seedling survival, with *M* favored on sandy soils with water at depth, *T* on fine-textured soils with reliable surface water, and *C* on shallow soils not prone to water-logging. (b) Microbial communities differentially influence shrub species germination and seedling survival, amplifying species segregation by soil type. (c) Competition rather than facilitation predominates among adult shrubs such that *M* will suppress *C* and *T* on sandy soils (basin floor), *C* will suppress *T* and *M* on shallow soils (upper bajada), and *T* will suppress *C* and *M* on fine-textured soils (lower bajada).

Study design: (*i*) ***In Phase I of LTER-VII,*** we implemented seed and seedling experiments to assess establishment bottlenecks under different edaphic and biotic conditions and to quantify functional traits of demography, growth, and survival for *M, C*, and *T* in each soil type with varying PPT (dry, average, wet years) and with/without microbial interactions. (*ii*) ***In Phase II of LTER-VII***, field-based reciprocal transplants adjacent to **Q-C1** plots will be used to test for development of competitive interactions and density dependence as seedlings grow into adults. Seedlings will be transplanted into paired plots in exclosures (ambient PPT; supplemental PPT). Weekly watering in the summer to mimic the 2004-08 monsoon is expected to promote seedling establishment. Monthly measurements will record canopy dimensions, height, and survival. ***Expected Results:*** New insights into the degree to which soils, PPT, shrub-shrub and shrub-microbe interactions constrain recruitment of shrub functional types and the life-stage where these environmental filters have effect. Reciprocal transplants will quantify timing and intensity of density dependence and intra- and inter-specific competition as potential causes of species dominance.

Q-C3: How do plant and patch-scale characteristics on the bajada influence landscape-scale loss of water with feedbacks to S→S transitions? (enhanced long-term studies; *Vivoni watershed*)

LTER VI results revealed that 25% of incoming PPT on the bajada is lost via channel recharge (***Schreiner-McGraw and Vivoni 2017***), thus bypassing ecosystem water use and reducing rain-use efficiency (Biederman et al. 2018). This is consistent with low summertime ET in the eddy covariance footprint (Anderson and Vivoni 2016). In ***Phase I of LTER-VII,*** we quantified infiltration rates in soils associated with *C, T,* and *M* shrubs on varying landscape positions. Initial tRIBS simulations suggest vegetation change will overwhelm climate change effects on runoff on the bajada (Schreiner-McGraw et al. 2019). The extent to which fine-scale spatial variation in topography, soils, surface crusts, and vegetation mediate cross-scale interactions from plants to patches and the landscape scale is still unknown. We propose to identify thresholds in PPT characteristics (measured by rain gauges and a newly-installed rain-drop size/velocity sensor) and antecedent soil moisture needed to generate runoff and channel transport from different shrublands.

Hypotheses: (a) S→S transitions on bajadas alter runoff, ET, and subsurface losses which feedback to plant composition, groundwater recharge, and downstream flows of water and sediment. (b) Runoff in bare soil gaps is related to infiltration rates mediated by abiotic (soil surface texture, physical crusting)

and biotic (biocrusts, shrub species, litter) factors. (c) Runoff and channel flow are influenced by $CaCO_3$ horizons (caliche) that store water during wet periods at different depths to differentially benefit shrubs of different species (Duniway et al. 2010; 2018).
Study Design: Long-term eddy covariance and hydrological monitoring will continue, with enhancements including: (*i*) quantification of runoff and sediment yield on north- vs. south-facing slopes, (*ii*) new moisture sensors in and below caliche horizons, (*iii*) a 3rd profile of channel soil moisture sensors to track transmission losses at depths >2 m, and (iv) characterization of physical and biological crusts.
Expected Results: High resolution maps of vegetation, soil surface texture, crusts, and depth to calcic horizons will improve ecohydrological modeling (Schreiner-McGraw and Vivoni 2018) and quantify hydrologic connectivity between up- and down-slope areas. Improved representation of overland flow and hillslope-channel connectivity will allow tRIBS assessments of the hydraulic impacts of S→S transitions (e.g., Mueller et al. 2007). Model developments will allow evaluation of landscape-scale ecohydrology and feedbacks in response to plant- and patch-scale change and interactions with extreme rainfall events.

D. Transitions to novel ecosystems (G/S→N)

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. Imported into the SW US from South Africa in the 1930s, it now dominates much of the Sonoran Desert. Introduced to the Jornada in 1938, its spread has been slow and variable. Because Lehmann's produces prolific viable seed, and livestock, wind, and water are effective dispersal vectors, seed availability and dispersal constraints do not explain its lack of spread (Fredrickson et al. 1998). ***LTER VI*** model results suggest variable PPT and temperature increases will increase probabilities of recruitment, especially on sandy and silty soils (Burruss et al. 2018).

Q-D1: How do rainfall variability, grazing, and competition with native grasses interact to trigger non-native grass invasion? (continuing experiments)

We are conducting establishment-competition experiments to identify the environmental triggers and thresholds promoting Lehmann's recruitment and its displacement of native grasses. ***LTER VII Phase I*** tested the hypothesis that Lehmann's recruitment will be promoted by livestock grazing in concert with warmer winters and wetter summers. Lehmann's recruitment and competition with native grasses was quantified in plots (n=48) established in 2016 in black grama stands. Lehmann's seeds were placed in plots experiencing drought (-80% of ambient), ambient and increased (+80%) PPT, and with plots divided into halves, wherein native grasses were defoliated (to simulate grazing) or left intact. Results revealed that black grama defoliation promoted emergence, but only when growing season PPT was between 60 and 100 mm. Germination was nil when growing season PPT was <30 mm. Emergence was also promoted in plots with rodent/lagomorph access, suggesting small mammal activities enhance recruitment. We are now testing a second hypothesis associated with competition:
Hypothesis: Established Lehmann's will competitively suppress native grasses, and the effect will be more pronounced with drought stress.
Study design: Plots (n=18) were deployed in mixed stands of native black grama and established Lehmann's to quantify adult competitive interactions under wet (+80%), ambient and drought (-80%) conditions. Thus far, mature black grama and Lehmann lovegrass plants have responded similarly to experimentally altered precipitation in 2017-2018. Monitoring (cover, survival, growth, height) will continue in LTER-VII.
Expected results: Documentation of the combination of factors controlling Lehmann's recruitment, and its competitive interactions with native grasses in relation to PPT, will position us to predict how climate and grazing interact to trigger its spread.

E. Transitions under climate change (long-term experiments, *CCE*)

Climate change is a major driver of transitions in drylands, and it is expressed mostly in changes in the amount and variability of precipitation with consequences for local scale relationships between ecosystem structure and function. Changes in community structure and species composition can amplify the effects of extreme events via wind and water erosion (***Okin et al. 2018***). The frequency, intensity, and duration of extreme events (drought, heavy rainfall) are expected to increase in the future. We have been conducting long-term experiments (> 12y) in a mixed black grama-mesquite dominated ecosystem where we either manipulate: (1) PPT amount (-80%, ambient, + 80%) in a full factorial design with/without N fertilization or (2) PPT interannual variability via altering the sequence of wet or dry years under a constant PPT regime *(CCE).* These experiments are funded by an LTREB to Sala (DEB 1754106) with LTER support to graduate students and infrastructure. ***In LTER-VI,*** we showed that increased inter- annual PPT variability decreases ANPP regardless of PPT amount (Gherardi and Sala 2015a). Prolonged drought reduces the ANPP and cover of grasses more than shrubs (***Gherardi and Sala 2015b***). ***In Phase I of LTER-VII***, after 12 years of irrigation representing wet periods and added N, there was no effect of fertilization even though we detected additional N in the soil and leaves. We are conducting new experiments to address two new questions: (a) Does this Chihuahuan desert ecosystem respond linearly to climate change? Or are there thresholds associated with extreme climatic events that trigger abrupt transitions? (b) Does N fixation or a large N reservoir explain the lack of response to fertilization?

4.3. Landscape integration: Understanding spatial heterogeneity in alternative states

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 analyses of state transitions in a spatially-explicit context at broad (landscape) scales and 2) 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). Our approach will follow the data analysis approach described in Fig. 3. In year 2, we will invite our collaborators and others conducting research at the Jornada and in the Southwest to our week-long PI meeting to discuss, synthesize, and integrate the Jornada knowledge base about state transitions in aridlands. We will use information emerging from historical and ongoing experimental and observation studies, and numerical analyses from our studies in section 4.2 to expand on our conceptual model (Fig. 1). This conceptual model, alongside the Data Science Integration System (DSIS; see A below), will form the basis for hypothesis generation about the key controlling variables and their process thresholds for each transition type. The DSIS will house and harmonize multiple raster spatial data layers to serve as covariates. DSIS will also house multitemporal raster data representing ecosystem states, including remote sensing-based estimates of vegetation cover, composition, and production (e.g. Ji et al., 2019, Jones et al. 2018, Robinson et al. 2019) and point data from field studies of environmental covariates or long-term change in vegetation and other ecosystem attributes. With regard to vegetation point data, conventional analyses often test for mean differences among treatments, landforms, or ecosystem types featuring multiple observation locations. In contrast, we seek to explain spatiotemporal variation in observational units within and across multiple studies (e.g., NPP measurements) with standardized data. Hypotheses will be used to structure machine learning models that integrate multiple datasets to test and map predictions (see B-C below).

(A) Data integration. In the DSIS, we are compiling and integrating diverse types of data from multiple locations, time periods, and spatial scales across the Jornada to enable spatially-explicit tests of hypotheses relating key processes (e.g. climate, soil water availability, resource redistribution) to ecosystem responses (e.g., vegetation change) (Fig. 6b, ***Peters et al. 2018***). This Jornada-wide point and raster compilation, enabled by recent computational advances, will be a major advancement over the compartmentalized "soil-geomorphic unit" approach used in past funding cycles (Fig. 6a). The DSIS approach was recently used to explain temporal changes in landscape- to regional-scale animal disease patterns across the western US ***(Peters et al. 2018***). 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. A similar analysis of JRN NPP data was 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 press). Thus, we feel confident that the DSIS framework will be applicable for new questions and additional datasets. We also expect to publish the framework and coding used to develop DSIS and its associated machine learning models to serve as valuable examples such that parallel DSIS systems can be developed at other long-term ecosystem science research sites.

We have been compiling and organizing data from LTER I-VI and from USDA ARS collaborators into the 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. We will use the approach described in ***Peters et al. (2018)*** to standardize and harmonize data for analysis; the data needed for specific projects described below will have high priority. 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 consideration of resource redistribution by wind and/or water, and connectivity-mediated feedbacks at both plant and patch scales. In some cases, these data already exist and analyses have been conducted (e.g., Peters et al. 2010). Steps used to develop the DSIS are summarized below.

1) Collect data from geo-referenced locations into 'data suites'. Because the harmonization of site-specific data from multiple experiments conducted for different reasons is challenging, our initial step is to develop suites of diverse datasets collected from the same or nearby locations. These data suites will consist of response variables (e.g., ANPP, plant cover) and associated drivers (e.g., PPT, temperature, soil properties) collected at that location through time. Typically these datasets are found as different files at EDI such that users have to put them together manually. Using open-source scripting to collect multiple datasets into integrated packages is an important step in DSIS development, and providing data suites will assist users in the interpretation of patterns and dynamics.

2) Standardize data from PI-led studies. 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. 2017b). We are developing this list as a PI/collaborator project, and will begin collecting these standard data or adding sensors to study locations in 2020. This list of variables will be refined as our knowledge system evolves.

3) Develop or update landscape maps of missing or outdated variables. **In Phase I of LTER VII,** we assembled spatial data for select attributes. In the current phase, we will create: (a) a new vegetation compositional change map harmonized to historical map products dating to 1858 (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: soils will be characterized in detail in areas where the current dominant vegetation reflect historic vegetation in the 1850's. This sampling will occur on the JRN and White Sands Missile Range, 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. Detailed soil characterization will include exploratory characterization of stratigraphic and carbonate

isotopes (Monger et al. 1998; 2009) and silica pytoliths. (c) Digital soil map: Ongoing digital soil mapping activities (Brungard and Allan, in revision) will continue in close collaboration with the USDA-NRCS Soil Survey. In LTER VII Phase I, we developed key geospatial environmental variables, collated new and existing point soil data (n=~600 locations), and tested ground penetrating radar for mapping depth to petrocalcic horizon. Future work will include collating additional point soil data and testing other geophysical sensors. (d) Biological soil crust map: Hyperspectral imagery is being used to map biocrust cover (Weber et al. 2008, Rodríguez-Caballero 2015) and composition (Pietrasiak et al 2013). A UAV-mounted hyperspectral imager was assembled and deployed in LTER VII Phase I. Ongoing work will include multi-temporal and spatially distributed hyperspectral imaging of biocrusts and plants at select locations across JRN.

(B) Spatiotemporal analyses. Below we describe how the DSIS is being used to test several hypotheses pertaining to state transitions at JRN. Additional hypotheses will be added as our work evolves.

1) Spatially-explicit state transition simulations. ***In LTER-VII Phase I***, we began developing species-specific germination and establishment criteria from experiments, field studies (4.2 Transition studies), and the literature for multiple species and functional groups to simulate present-day recruitment, abundance, and composition using the Ecotone model. We will continue to 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. 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 types 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). 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.

2) Spatial analysis of state transitions in long-term monitoring data. We will use spatial data to map within-state transitions 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. 2014***). 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), 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 geo-register. 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).

3) 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 test the hypothesis that knowledge of hydrological connectivity in the watershed surrounding playas can explain variations in playa water depth and ANPP. In ***LTER VII Phase I***, we instrumented 18 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 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.

4) Net primary production (ANPP) and response to climate change. ANPP has been quantified in several studies (*NPP, CCE, Ecotone*), and has generated numerous publications (***Peters et al.*** 2012; ***2014***, 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. 2018). We propose that accounting for hydrological connectivity (similar to that described above) and aeolian redistribution will improve predictions of soil water availability, and ultimately ANPP during multi-year drought and wet periods. We are integrating ANPP through time for all studies where this variable is collected (e.g., *NPP, Ecotone, CCE*), and will obtain the necessary environmental (PPT, soil properties) and connectivity characteristics for each plot (described in 3. above). We will then use these relationships and machine learning (Peters et al. in press) to predict ANPP for other locations on the Jornada that have not been sampled directly, and for future time periods under alternative climate scenarios (wet vs drought periods).

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

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 Ecosphere (Dynamic Deserts). We also contributed individually to important collections (synthesis chapter on Desertification in Rangelands [Peters et al. 2013a], 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 (*Quads*), 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). 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. 2018), 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. 2017b). 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). In ***LTER VII Phase I,*** we initiated new research to apply landscape integration concepts and tools described in Section 4.2 to data collected in past projects and collaborative efforts. Specifically, we worked with the Jornada ARS and other partners to analyze vegetation monitoring data gathered by the BLM Restore NM Program (ca. 100 plots). We propose to continue these efforts in Phase II with analyses of selected data from the BLM Assessment, Inventory, and Monitoring program (ca. 30,000 plots across the western U.S.) and data from the Malpai Borderlands Group in NM and AZ (ca. 60 plots) and the government of Mongolia (ca. 1550 plots) to test for environmental controls over 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 NM restoration treatments indicate that success restoring total vegetation cover (compared with untreated controls) varies with elevation and temporal variations in rainfall or management (Fig. 13). Analyses 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. In addition, 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 Agroecosystem Research (LTAR) Network (Petrie et al. 2018) and JRN-associated scientists will lead a 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.

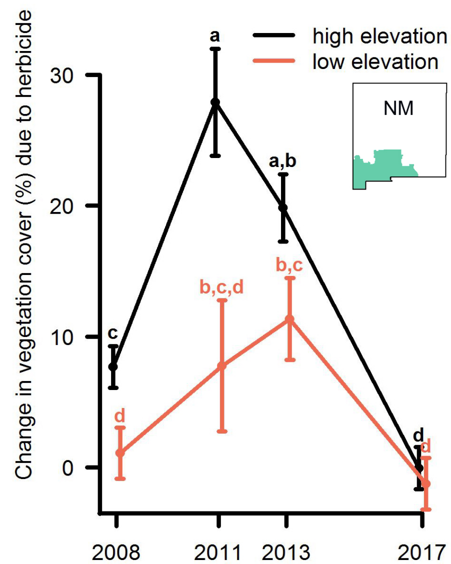

Fig. 13. Restore NM Project. Vegetation cover response to herbicide treatments at high (>5000') and low (<5000') elevations in NM (green counties on map) (Bestelmeyer et al. in prep).

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). In ***LTER-VII Phase I***, we published three articles depicting the relationship between management of rangelands and the provisioning of ecosystem services (Sala 2016, Sala et al 2017, Archer et al. 2017). 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 JRN 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.

5. Related Research Projects

Two related projects are essential to addressing the questions in this proposal. The NSF project led by Sala (DEB-1754106), "LTREB: Long-term ecosystem responses to directional changes in precipitation amount and variability in an arid grassland". This project is described on p24. A second NSF-funded project to Archer and Okin (DEB-1556735): "Aeolian Processes: An Overlooked Driver of State Change in Drylands?" is testing hypotheses about mechanisms of sandblasting from wind using a wind tunnel. These results will complement our desertification studies.

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 engaged 1,700 middle and high school students and served as a model for *Data Jams* in MD, NY, and Puerto Rico (Forster et al. 2018); (c) the Las Cruces Public School District (the largest in southern NM) funds our inquiry-based science lessons, reaching every 7th, 8th, and 9th grader in the district (~4,500 students/y); (d) our LTER children's book, One Day in the Desert, was published in 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. 2010a; Bestelmeyer et al. 2017). 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. ***In LTER-VII Phase I***, we continued to share updated LTER results with natural resource managers through our co-leadership of the "Interpreting and Managing Indicators of Rangeland Health" (IIRH) course that is conducted three times/year in locations throughout the western US, and an additional 4+ annual BLM "Assessment, Inventory and Monitoring" (AIM) trainings. The new training manual for the IIRH course (v.5) includes updated sections on landscape connectivity informed by LTER research. The results are communicated through global outreach and training associated with the LandPKS app, which is experiencing exponential growth in use (***Herrick et al. 2017a***). The app includes direct links to the new "Ecosystem Dynamics Interpretive Tool" (EDIT) developed by the Jornada to house national (and eventually global) site-based information on state transitions. Our monitoring manual and qualitative assessment protocols were applied at over 4,000 locations (Herrick et al. 2017b).

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 national education standards (e.g., Next Generation Science Standards), and (iv) participation 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 6 components of our program while adding one new component: (1) Field trips - 20 outings to the Jornada and/or the adjacent Chihuahuan Desert Nature Park, owned by AISE. Teachers choose three 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. 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 challenges students to examine ecological data sets collected by JRN and other researchers, identify a data trend, and develop a creative project (e.g., song, physical model, game) that communicates the data trend to nonscientist audiences (S. Bestelmeyer et al. 2015). More than 2,700 middle and high school students have participated in the DDJ. We will continue hosting the DDJ competition and supporting other LTERs that use our 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 3 to 10 hours of K-12 activities, including direct assistance during K-12 student programs as well as assistance with the creation 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 expect to engage at least 15 graduate students. (6) One Day in the Desert book (new) –We will develop a lesson unit and kits to allow local teachers to use our book to cover science, language arts, and math curriculum at the 2nd – 5th grade level. Teacher workshops and online, supplementary materials will introduce teachers to the new unit. (7) Evaluation -We will continue to use formative and summative evaluation tools (including teacher and student surveys, Draw a Scientist tool, and students comments) to assess achievement of program goals, which include increasing student science literacy, infusing more science into elementary classrooms, and increasing students' consideration of STEM careers. Prior evaluation has shown promise in all areas. For example, in a 2018 evaluation of the Data Jam, 76% of students reported a high or very high interest in the local environment after the Data Jam (compared with 15% prior to Data Jam) and 51% said participation in Data Jam increased their interest in pursuing college studies and/or a career in science (***S. Bestelmeyer et al. 2018***). Outcomes of these K-12 activities will include: (i) > 50,000 K-12 students with increased knowledge of desert ecology and data interpretation and decreased 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 *Jornada Fellowship Program* supports undergraduate and graduate students. 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 to present their research. Graduate students present a final research seminar to 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 web and mobile tools for sharing knowledge and information (EcoTrends, LandPKS, LandscapeToolbox,), in collaboration with the USDA Southwest Climate Hub 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 USDA collaborators' web site, 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 are provided to leadership of federal land management agencies and technical service providers in Washington, DC and national governments on other continents. For example, PIs 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.

III. 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 12-35828)

Peters, DPC, NP Hanan, BT Bestelmeyer. LTER: Long-Term Research at the Jornada Basin (LTER-VII). 2018-2020. $2,254,000 (DEB 18-32194)

Productivity and datasets overview. LTER-VI was highly productive, including 159 journal publications, 32 book chapters, 2 books and 13 graduate theses and dissertations. In Phase I of LTER-VII, we published 26 journal articles and 1 graduate thesis in year 1. 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 211 data sets derived from long- and short-term studies for six out of seven LTER core areas. Key LTER-VII studies are referenced in the previous paragraphs using italicized abbreviations (details in Suppl. Table A1). On average, one or more of our data sets are accessed more than 400 times per month. The LTER webpage is visited an average of 357 times/week by non-Jornada associated computers.

Sensors. We continue to expand and maintain 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), soilwater sensors (2 sites), dust collectors (2 sites), and remotely-triggered wildlife cameras to measure abundance of predators. We are also emphasizing new software to reduce the time downloading and analyzing imagery and met station data.

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. 2018***; 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 or Phase I of LTER-VII.

Table 1. Ten most significant Jornada Basin publications in last 6y

Authors	Year	Journal citation	Impact or significance	Study or Dataset* / Core Areas**
Gherardi and Sala	2015b	PNAS 112: 12735-12740	Prolonged drought reduces ANPP and cover of perennial grasses more than shrubs.	CCE / 1,3,5
Bestelmeyer B et al.	2018	BioScience 68: 691-705	Challenges grassland-shrubland transition paradigms; offers guidelines for management	knb-lter-hfr.170.9/ 3,4,5
Herrick et al.	2017a	Rangelands 39: 46-55	Land-PKS allows land managers/citizen scientists globally to collect/ share data via phones.	/ 1,4,5
Peters et al.	2018	BioScience 68: 653-669	Described DSIS and applied it to animal disease problem across western US, including the Jornada.	NPP / 1-5
Peters et al.	2014	Oecologia 174: 1323-34	Grass recovery in wet periods results from demo-graphic processes and plant/soil water feedbacks.	Phenology, NPP/1,2,3,5
Bestelmeyer S et al.	2018	BioScience 68: 706-714	Developed innovations in K-12 education; scaled programs to more diverse communities.	EcoTrends / 1-5
Okin et al.	2018	BioScience 68: 670-677	Connectivity by wind, water, and animals plays key role in state change dynamics.	TW,BSNE,NPP / 3-5
Peters et al.	2015	Front. Ecol. Env. 13: 4-12	Challenged desertification paradigm with alternative states based on cross-scale interactions.	Exclosures,NPP, VegMaps /1-5
Schreiner-McGraw and Vivoni	2017	Ecosphere 8(11): e02000	Sensor network & long-term data reveal runoff from bajada leads to deep percolation and ground water recharge during wet periods.	TW / 4,5
Schooley et al.	2018	Ecosphere 9(7): e02330	Long-term rodent populations depend on lagged responses to ANPP.	Ecotone / 1,5

*All datasets include PPT and Soils. **Core Areas: 1= primary production 2= SOM 3= disturbance 4= inorganic inputs and movements of nutrients 5= key populations 6= land use/land cover