LTER: Advancing ecological understanding of drylands through integrated research at the Jornada Basin (JRN-8)

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Project Summary

Overview

Since its inception, the Jornada Basin LTER (JRN) has expanded knowledge of ecosystem dynamics in drylands. Historically, research at JRN focused on the shift from perennial grassland to shrublands occurring in the Southwest and globally, capitalizing on data extending nearly 110 years from the USDA Jornada Experimental Range. More recently, JRN has elucidated how cross-scale interactions and feedbacks govern several types of state change, including grass recovery. In this proposal, we build on and expand JRN's long-term field-based, conceptual, and theoretical research. **Our objectives are to: (A) understand how changing precipitation, atmospheric humidity, temperature, and land management control ecosystem state change in drylands, (B) assess how carbon and nutrient cycling, and nutrient co-limitations, respond to and control dryland vegetation states, (C) quantify how spatial connectivity with respect to wind and water transport can reinforce or reverse ecosystem state change, and (D) characterize the biotic interactions underlying vegetation state change, including demographic processes, plant-microbe interactions, and trophic feedbacks.** We organize JRN-8 research under themes corresponding with these objectives, including ongoing long-term measurements and new field experiments. We also introduce a new focus on numerical and statistical dryland modeling that will leverage long-term JRN data to model dryland dynamics and state change, with potential for prediction and management of drylands in the US Southwest and globally.

Intellectual Merit

We propose a new theory-driven framework for ecological processes and state change in drylands, the Pulse-Interaction-Reserve-Feedback-Change Theory, integrating the role of changing climate and land management pulses (exogenous drivers), with the biogeochemical, spatial, and biotic interactions (endogenous feedbacks) that mediate pulse-responses. In JRN-8 we will extend our research on key dryland processes relating to climate and management disturbances, the processes controlling primary production, carbon and inorganic nutrient cycles, population and trophic interactions with state change, and the critical role of connectivity to wind and water driving state change. JRN-8 will resolve key questions towards our overarching goal to identify the mechanisms and consequences of abrupt and persistent state changes in drylands, and advance our ability to predict dryland futures under global change. Parallel development of process-inspired numerical models will translate JRN long-term data and theories into spatially explicit simulations of past and future ecosystem state changes at JRN and other dryland regions. Advances in understanding state change in drylands will provide new insight into the occurrence of abrupt state changes, tipping points, and hysteresis in other ecological systems.

Broader Impacts

We will expand our award-winning education and outreach programs, with a particular focus on broadening participation by underrepresented minorities in our programs for K-12 students, teachers, and community members, and increased engagement with undergraduate students, graduate students, new investigators, and collaborators. Through a unique partnership, JRN science education programs reach tens of thousands of students each year in a region dominated by Hispanic populations. JRN also has a long history of research co-production with land managers in the Southwest and internationally, informing land health monitoring and decision making through integration of dryland state change frameworks into land management programs. These broader impacts to dryland management will expand in JRN-8, with dryland modeling tools providing new opportunities for JRN research to inform earth system models for prediction and management of dryland responses to global change. Loss of grasslands has numerous, often detrimental, impacts on human well-being. Moreover, multiple studies point to drylands as dominating critical aspects of Earth's biogeochemical cycles, including a dominant role in the interannual variability and trend in atmospheric CO_2 concentrations. Thus, long-term data, theoretical and empirical insights, management tools, and earth system model applications from JRN research have significant potential to produce societal benefits for US and global dryland communities.

LTER: Advancing ecological understanding of drylands through integrated research at the Jornada Basin (JRN-8)

Section 1: JRN-8 Purpose

The mechanisms of ecosystem state change (including transitions, regime shifts, and tipping points) in response to global change drivers is a primary concern of contemporary ecosystem ecology (Turner et al. 2020, Zinnert et al. 2021, Williams et al. 2021). Drylands, defined as regions where annual rainfall is less than 65% of annual potential evapotranspiration (Zomer et al. 2022), are particularly vulnerable to state changes that are defined by the replacement of plant functional types (PFT), loss of overall plant production, and soil degradation occurring in response to increasing aridity and climate variability and management-related changes (D'Odorico et al. 2013, Hanan et al. 2021, Berdugo et al. 2022b). Abrupt and persistent state changes are often associated with loss of herbaceous vegetation, woody plant encroachment, and increases in exotic grasses (Millennium Ecosystem Assessment 2005). Biological soil crusts, which are increasingly acknowledged as foundational elements of dryland systems (Weber et al. 2016, Chen et al. 2020), may also undergo functional type replacement or overall loss during state change (Garcia-Pichel et al. 2013, Reed et al. 2016, Phillips et al. 2022). Strategies to forecast and prevent, reverse, or adapt to state changes based on knowledge of ecological mechanisms are a critical societal need (Lynch et al. 2021). **Thus, the overarching goal of our research is to identify the mechanisms and consequences of abrupt and persistent state changes in drylands, providing a framework for prediction and future management of Southwestern and global drylands.**

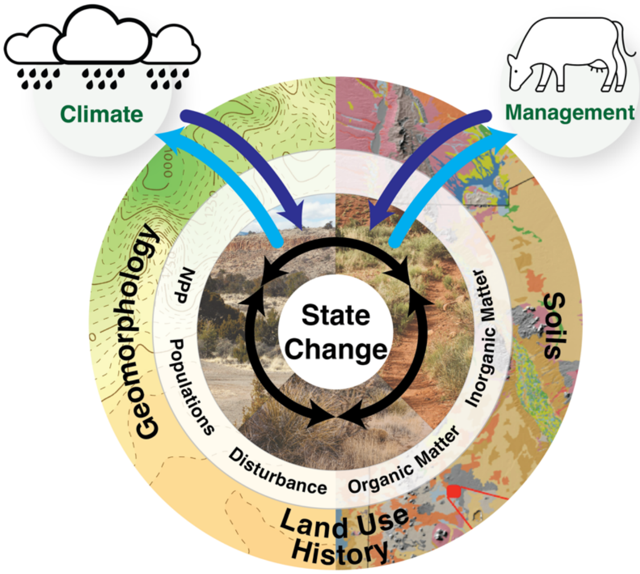

Figure 1: *The Jornada Basin LTER (JRN) has focused on how climate and land management in drylands can trigger changes in vegetation structure ("state change"). Such changes are represented by shifts from grassland to mixed lifeform to shrubland states (and in some case the reverse; center photos), with implications across the LTER program's five core areas (net primary production (NPP), organic matter dynamics, inorganic/nutrient cycles, disturbance, and population dynamics and trophic interactions). The nature and rate of state change varies spatially, depending on landscape context (e.g., soils, geomorphology and land use history; outer circle).*

Changes occurring at the Jornada Basin LTER site (JRN), located in the Chihuahuan Desert of southern New Mexico, exemplify challenges facing drylands across the western United States and globally (Fig. 1) in response to changing land use, elevated temperatures and increased evaporative demand, long-term trends in rainfall, and increasingly variable precipitation (Reynolds et al. 2007, Gherardi and Sala 2019, Hoover et al. 2020, Burrell et al. 2020). Shifts in abundance and dominance of different PFT strongly affect the ecosystem services provided by drylands, including net primary production (NPP), carbon sequestration, forage provision, hydrological function, and biodiversity maintenance, with potential feedbacks to climate and land management decisions (Sala et al. 2017, Maestre et al. 2022). While drylands are home to over 2 billion people, ecosystem research to support sustainable livelihoods in these systems is chronically limited (Hoover et al. 2020). Since its inception, JRN has played a foundational role in filling these critical knowledge gaps (Schlesinger et al. 1990, 1996, Reynolds et al. 2007, Okin et al. 2009b, Bestelmeyer et al. 2015, Peters et al. 2015).

In this proposal for continued JRN research (denoted "JRN-8"), we build on the legacy of long-term research and data, extending to 1915 through our association with the USDA Jornada Experimental Range (JER). We will extend long-term studies and initiate new long-term research organized according to a new integrated, theoretical framework to explain state change in drylands, which emphasizes the roles of biogeochemical, spatial, and biotic interactions mediating dryland responses to climate and land management "pulses" (Section 2). We organize JRN-8 field-based research under four themes (Climate and Management, Biogeochemical Interactions, Spatial Interactions, and Biotic Interactions; Section 3), building on our long-term data and including new field-based emphases on biogeochemical, microbial (biocrust), and trophic interactions associated with state change. We also introduce a new dryland modeling approach, leveraging multiple sources of JRN data to provide spatially-explicit predictions of state change at landscape and basin scales, with potential for management applications in other US and global drylands.

Section 2: JRN Conceptual Framework

2.1. Conceptual foundations

The historical focus of JRN has been on understanding the mechanisms of "desertification," which broadly refers to the loss of ecosystem services associated with loss of functionally and economically important PFTs (D'Odorico et al. 2013, Bestelmeyer et al. 2015). In the US Southwest and much of northern Mexico, perennial grasslands have shifted abruptly to patchy shrublands or unvegetated ground, reducing forage for livestock, increasing soil erosion and dust emissions, and degrading habitat that supports grassland biodiversity (Schlesinger et al. 1990, Ravi et al. 2010, Coffman et al. 2014). Since 2006, JRN has studied these shifts through the lens of state transition and tipping point theory (Peters et al. 2004, Bestelmeyer et al. 2017; Figure 1). Grassland-shrubland transitions, for example, are triggered by interacting drivers, including heavy grazing co-occurring with drought (Bestelmeyer et al. 2018a, Christensen et al. 2023). Resulting changes in vegetation cover have profound effects on nutrient availability and sediment and water connectivity, with amplifying feedbacks on the establishment and survival of native perennial grasses and shrubs (Okin et al. 2009a). Trophic interactions involving small mammal populations create additional feedbacks that reinforce and accelerate ecosystem transitions (Bestelmeyer et al. 2007, Schooley et al. 2018). Work at the JRN has elucidated multiple types of transitions, including from shrublands back to grasslands or savannas, between dominant species of shrubs within shrublands, and from native vegetation to novel ecosystems dominated by invasive species (Archer et al. 2022, Burruss et al. 2022, Peters and Savoy 2023).

JRN science has contributed to mechanistic and cross-scale understanding of tipping points, documenting multiple interacting processes that contribute to triggers and feedbacks (Peters et al. 2006, 2020, Bestelmeyer et al. 2011, Okin et al. 2015). Concepts of state change and connectivity long emphasized at JRN are now unifying concepts for dryland ecology and across diverse LTER sites (Iwaniec et al. 2021, Zinnert et al. 2021). Meanwhile, JRN experimental approaches developed to understand drought and climate variability controls on state transitions (e.g., Gherardi and Sala 2015a) are now widely applied in drylands (Smith et al. 2024). JRN science has also influenced international environmental policy, notably the IPCC Special Report on Climate Change and Land (Mirzabaev et al. 2019).

2.2. Existing dryland conceptual models

Despite the theoretical advances made by JRN and others, dryland ecosystem change remains difficult to characterize, model, and forecast, particularly in the face of accelerating climate change (Berdugo et al. 2020, 2022a). We contend this is caused by a lack of theoretical integration, which we propose to remedy. Our new conceptual model organizing JRN-8 research integrates three core paradigms (pulse-reserve, spatial interaction, and alternative states) that have historically guided research in dryland ecology.

(a) The "**pulse-reserve paradigm**" (Noy-Meir 1973, Reynolds et al. 2004) considers how temporal heterogeneity of dryland precipitation and soil moisture ("pulses") drive variations in the production of biomass and propagules ("reserves") and the habitats and resources these reserves create for animal populations. Since originally outlined by Noy-Meir (1973), this approach has been re-interpreted and expanded by several authors (e.g., Ludwig and Tongway 2000, Reynolds et al. 2004, Collins et al. 2014, Garcia-Pichel and Sala 2022). While not all moisture pulses produce reserves (e.g., in the case of heterotrophic respiration), the spatial patterning of reserves produced by moisture pulses is key to spatial interactions in drylands, which links "pulse-reserve" to the next core paradigm.

(b) The "**spatial interaction paradigm**" considers the powerful role exerted by spatial heterogeneity at multiple scales in the flux of resources, biotic and biogeochemical interactions, and spread of disturbances. At the plant-interspace scale, movement of nutrients from areas of low fertility in plant interspaces to areas of higher fertility beneath perennial plants ("islands of fertility") was a transformative early JRN finding (Schlesinger et al. 1990, Schlesinger and Pilmanis 1998). At microbial scales, recent JRN research describes biocrusts as "mantles of fertility" (Garcia-Pichel et al. 2003). More generally, the concept of landscape connectivity (Ludwig et al. 2005, Okin et al. 2009b) quantifies the role of connected pathways for 1) movement of water (van de Koppel and Rietkerk 2004, Saco et al. 2018), 2) movement of nutrients, sediment, and propagules by wind and water (Okin et al. 2018, Throop and Belnap 2019), and 3) the spread of fire (in drylands that support it) (Allen 2007, Abades et al. 2014, Kahiu and Hanan 2018) that collectively govern feedbacks between reserves and pulse responses. Connectivity also applies to the movement of animals that affect plant propagule transport, herbivory and predation (Ansley et al. 2017, Abercrombie et al. 2019, Schooley et al. 2021). In addition, the vertical stratification of surface biocrust and roots of different plant functional types ("Walter's two-layer hypothesis"; Walker and Noy-Meir 1982) may explain coexistence of different PFT and the spatial and temporal patterns of water uptake, primary production, and respiration (Peters et al. 1997, Brown et al. 1997, Scanlon et al. 2002, Garcia-Pichel et al. 2003).

(c) The "**alternative state paradigm**" (Westoby et al. 1989, Bestelmeyer et al. 2017) considers drylands to be multi-equilibrium systems with discrete alternative communities ("states") that can occur on the same site, each stabilized by internal feedbacks (Ratajczak et al. 2014). Shifts between states ("transitions") in response to exogenous drivers (e.g., weather, land-use) can be smooth and gradual when endogenous feedbacks are relatively weak, or abrupt and hard to reverse when feedbacks are strong. This paradigm is linked to mathematical models (e.g., "cusp-catastrophes" and "critical transitions") that aim to predict the conditions under which abrupt state transitions occur (Scheffer et al. 2015).

2.3. PIRFCT: A new conceptual framework for dryland research

The relationships between the above three paradigms have been examined in a few cases (Ludwig et al. 2005, Collins et al. 2014, Peters et al. 2020), but a comprehensive theory of ecosystem change in drylands must incorporate ecosystem processes represented by all three paradigms occurring at multiple scales. In JRN-8, we propose the organization of new and existing research, synthesis, and modeling efforts under the **Pulse-Interaction-Reserve-Feedback-Change Theory (PIRFCT)** that represents our efforts toward a more integrated theoretical approach (Fig. 2).

In PIRFCT, we conceptualize alternative ecosystem states as having different qualitative and quantitative **reserves** (e.g., biomass of different plant functional types and biocrusts), thus allowing conceptual integration with the pulse-reserve theory. The identity of a state depends on the types of organisms and the abundance of their reserves, which will also control the response of an ecosystem to a **pulse** or sequence of pulses. Unlike traditional pulse-reserve theory, **PIRFCT allows pulses to be either positive** (as in the impact of a precipitation pulse on plant growth or a pulse of grass productivity on granivore reproduction) **or negative** (as in a pulse of grazing or fire on standing biomass). Since management actions can remove biomass and disturb soil crusts with variable frequency and intensity (e.g., rotational grazing), allowing negative "pulses" provides integration with management decision-making. PIRFCT also allows pulses to include temporal patterns or cycles (e.g., dry-wet or grazing-resting periods) as well as infrequent extremes (e.g., temperature/freezing, drought, intense winds, flooding).

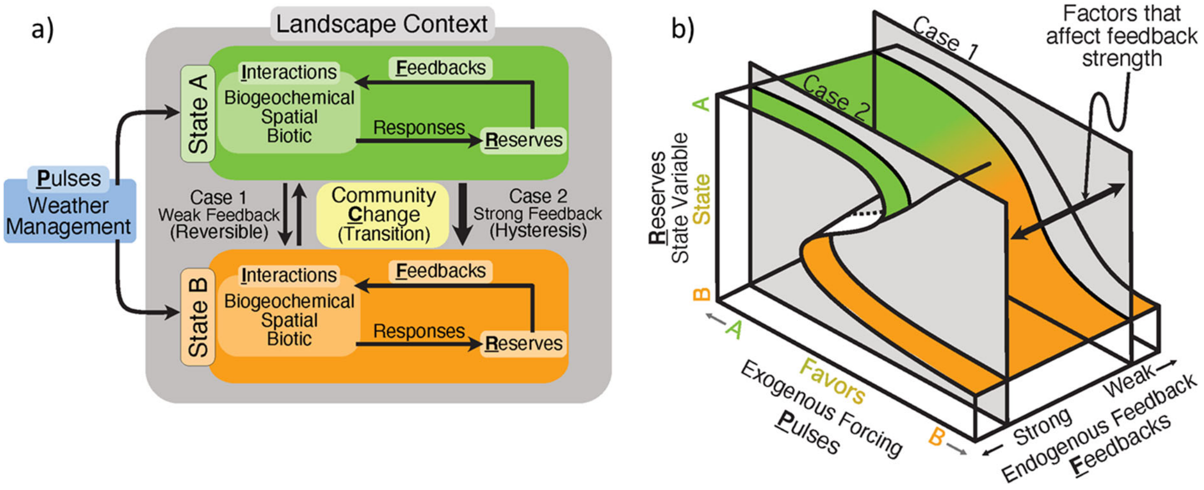

Figure 2. Conceptual framing for JRN-8 research*. (a) The Pulse-Interaction-Reserve-Feedback-Change Theory (PIRFCT) shows two states of an ecosystem, with pulse-reserve dynamics modulated by biogeochemical, spatial and biotic interactions, which alter reserves (e.g., cover or biomass of woody and herbaceous PFT and biocrust communities) through multiple interactions and feedbacks. (b) Alternative states and thresholds, showing the interaction of exogenous forcing (pulses) and endogenous feedbacks, which determine whether state changes follow reversible (Case 1) or persistent/hard to reverse (Case 2) trajectories. Biogeochemical, spatial and biotic factors influence the strength of endogenous feedbacks.*

The amount and identity of **reserves** sets up **spatial**, **biogeochemical,** and **biotic** interactions underlying key ecosystem **feedbacks** that can buffer against or promote state change (Fig. 2a). **Spatial interactions**, for example, include the lateral redistribution of water and sediment transported by wind or water (Okin and Gillette 2001, Okin et al. 2009b, Turnbull et al. 2012) that may favor growth and establishment of shrubs over grasses (Schlesinger and Pilmanis 1998). Similarly, the "landscape of fear" for small mammals includes reduced perceived risk in shrublands, directly impacting grass reestablishment and thus reinforcing the shrubland state (Wagnon et al. 2020). Spatial interactions are modulated not only by vegetation structure but also by landscape heterogeneity due to variation in soils and landforms (Monger and Bestelmeyer 2006). **Biogeochemical interactions** impact biomass reserves through their influence on and feedbacks with productivity. In the original fertile island model, for example, loss of nutrients in some areas and gains in others directly influence vegetation response to precipitation (Schlesinger et al. 1990). More recently, nutrient enrichment experiments have shown differential responses of plant and microbial communities to rainfall, nitrogen (N), and phosphorus (P) additions, with positive feedbacks on plant growth and establishment (Sala et al. in preparation; Jia et al. 2021). **Biotic interactions** include but are not limited to: 1) plant-herbivore feedbacks (where small mammals may favor shrublands, limit grass establishment and reinforce the state change from grassland to shrubland (Bestelmeyer et al. 2007), 2) competition for resources within and between PFTs (which may influence grass and shrub establishment and growth (Pierce et al. 2019, Wojcikiewicz et al. 2024), and 3) interactions between cyanobacteria and their predators, which mediate the state of the biological soil crust as well as its response to future moisture pulses (Bethany et al. 2022, Nelson et al. 2022).

These interactions are key to determining whether and how ecosystem change occurs. The reversibility or irreversibility of state **change** depends on the strength of the endogenous **feedbacks** that stabilize the states (Fig. 2b, Case 1 vs. Case 2), where feedbacks can encompass one or more spatial, biogeochemical, or biotic interactions. A system that has weak endogenous feedbacks (Case 1) might see a temporary change in productivity as a result of a drought pulse, but productivity can recover when the drought is over. Under the same conditions, a system with strong endogenous feedbacks (Case 2) might experience a change in state that does not recover when the drought pulse is over. Restoration actions involving "connectivity modifiers" (Peters et al. 2020), for example, manipulate the strength and direction of key spatial and biogeochemical feedbacks to enhance reversibility (from Case 2 to Case 1) that can occur under the right exogenous pulse conditions (e.g., during wet years).

In JRN-8, the specific processes driving pulses, interactions, and feedbacks will be evaluated using observational, experimental, and modeling studies at patch, landscape (multiple states within a limited geomorphological context), and basin (multiple geomorphological contexts) scales (Fig. 3). We will conduct field research and synthesize long-term data representing elements of the PIRFCT framework (Fig. 2). Our work will advance theoretical understanding of dryland systems, the prediction of ecosystem state change, cascading consequences of state change across trophic levels, and impacts on carbon, water and nutrient fluxes. Furthermore, synthesis following the PIRFCT framework will support a new dryland modeling approach to predicting ecosystem responses to climate and management change, with potential to improve global ecosystem models that are known to perform poorly in drylands (MacBean et al. 2021, Fawcett et al. 2022).

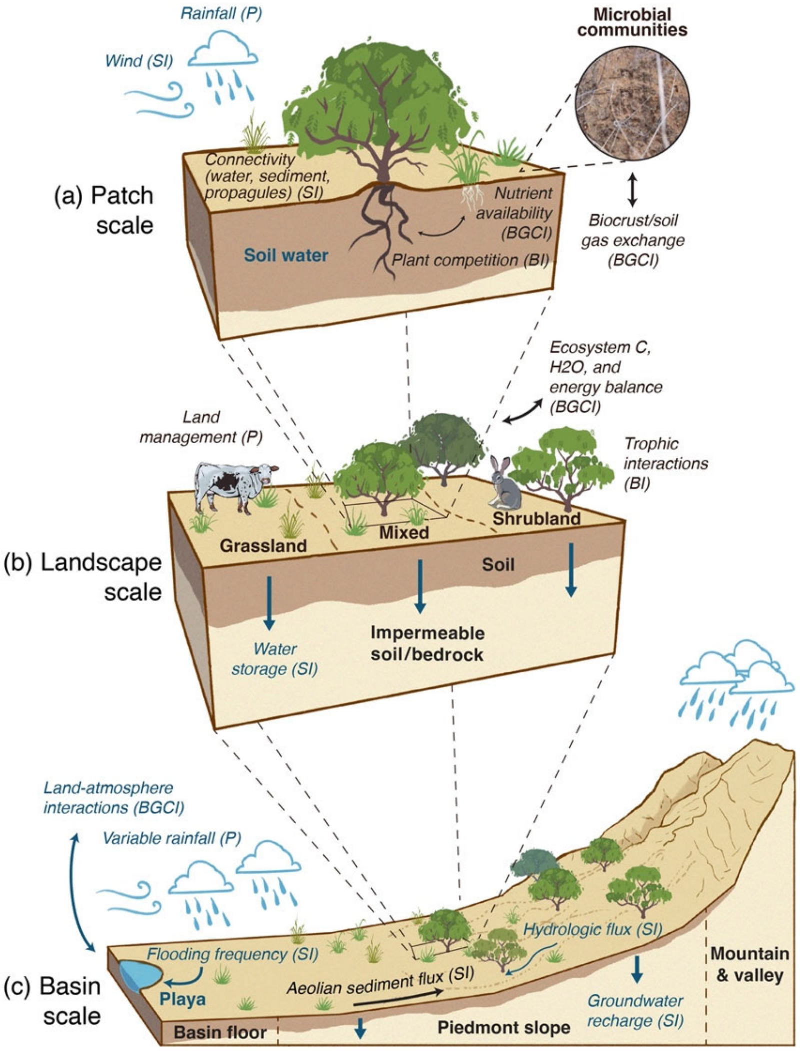

Figure 3. A multi-scale approach to dryland dynamics *integrating (a) patch scale processes, (b) landscape scale states, and (c) basin scale topographic and edaphic context. The PIRFCT framework (Fig. 2) is represented here by pulse processes (P), and biogeochemical (BGCI), spatial (SI) and biotic (BI) interactions impacting shrub, herbaceous and microbial reserves (R; not labeled in the figure) with potential feedbacks on critical processes influencing state change.*

Section 3: Proposed Research

3.1. Jornada Basin LTER (JRN-8) Research Context

In JRN-8, we will build on and extend JRN's long-term study of dryland responses to climate and land use, continuing our focus on the mechanisms of abrupt and persistent state change observed in drylands worldwide. However, we plan more than just incremental additions to our existing research. The adoption of the more holistic PIRFCT framework (compared to conceptual lenses used at JRN in the past), will allow significant advances in understanding and predicting diverse aspects of dryland system dynamics. As our primary conceptual framework for JRN-8, refinements to PIRFCT and testing of its constituent parts will also contribute substantively to ecological theory in drylands and beyond. Compared to recent JRN proposals, JRN-8 explicitly a) considers biocrusts in defining alternative states and regulating primary production, carbon, and nutrient cycling; b) integrates biogeochemical cycles, recognizing the coupled nature of water and nutrient pulses in drylands; c) analyzes complex biotic interactions associated with state change, including plant-microbe interactions and plant-herbivore- predator trophic cascades; d) uses empirical results to parameterize and validate a new dryland process model that can provide spatially-explicit predictions of state change in dryland landscapes; and e) develops new technical approaches for measuring ecosystem change (e.g., one of the densest networks of dryland eddy flux towers in the world, plant cover estimation using automated ground photographic and uncrewed aerial systems (UAS), and process-informed neural network modeling).

3.2. JRN site characteristics

Land acknowledgement: JRN research takes place on lands now known as the Jornada Basin, which are the traditional homelands of the Piro, Tampachoa (Mansos) and Tiwa Peoples and the Mescalero Apache. We acknowledge that these lands were occupied without consent. As part of JRN research, education and outreach activities, we respect indigenous understanding of these lands and will seek to collaborate, learn from and share findings with Sovereign Indian Nations and local indigenous communities.

The 104,000 ha Jornada Basin site is located in the northern Chihuahuan Desert (Fig. 4). The lands of the JRN are managed by the USDA Agricultural Research Service and New Mexico State University, with the ~78,000 ha USDA Jornada Experimental Range (JER) established in 1912, and the adjacent ~26,000 ha Chihuahuan Desert Rangeland Research Center (CDRRC) established in 1927. Ecological data collected by the USDA and instrumented climate observations began in 1915. JRN's climate spans arid to semiarid and is the warmest (mean annual temperature = 15.6 °C) and among the driest (mean annual precipitation = 242 mm) LTER sites (Petrie et al. 2018). The vast JRN landscape encompasses a variety of contrasting soil types and landforms that are characteristic of the Basin and Range Physiographic Province (Monger et al. 2006). Landform variation has strong effects on plant community composition, with perennial grasslands historically dominant on basin floor and lower piedmont landforms and isolated shrublands occurring in ancient dune systems and upper piedmont landforms. Soil variations produce changes in the dominance of plant species and functional groups in space, with cascading effects on ecosystem processes, biodiversity, and land use.

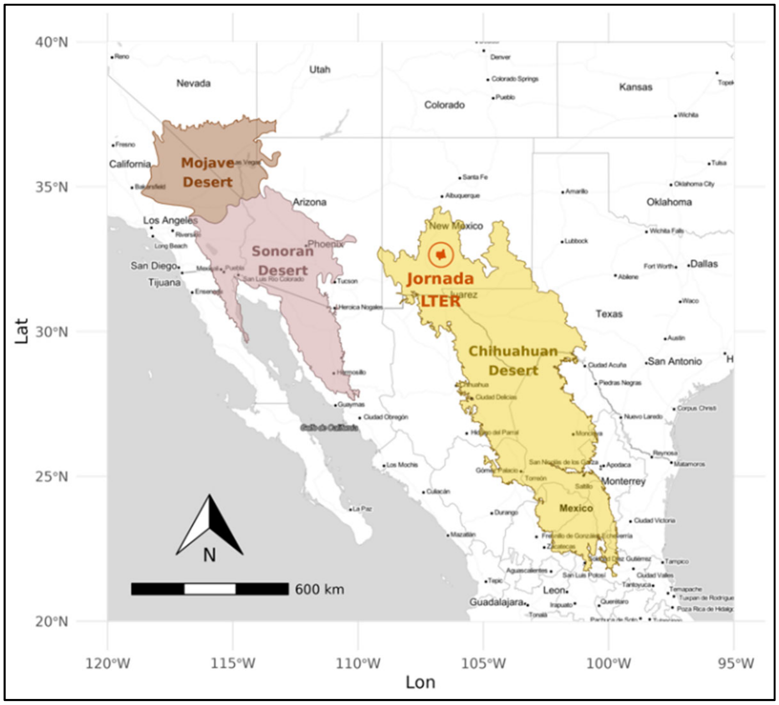

Figure 4. Location of the North American warm deserts and the Jornada Basin LTER *(circled in red). Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL.*

Both the JER and CDRRC were established to understand rapid ecological changes in Southwestern US grasslands that were detected at a regional scale beginning in the late 19th century (Bestelmeyer et al.

2018a). The most important changes were transformations of perennial grasslands to shrublands (decreasing from an estimated 83% of the site in 1858 to less than 10% in 1998; Archer et al., 2022), caused by poorly managed livestock grazing during drought episodes, characteristic of many arid and semiarid drylands worldwide. JRN's location in an area that is marginal for perennial grass dominance has enabled detailed analysis of the mechanisms of abrupt transitions and restoration in drylands, which have been directly observed over the century-long record (Buffington and Herbel 1965, Gibbens et al. 2005, Christensen et al. 2023). The site's large area and heterogeneous vegetation, soils, and landforms enable a unique focus on the roles of soil-geomorphic heterogeneity and multi-scale connectivity with regard to wind, water, and animal vectors in creating variation in the rate and outcomes of transition.

Table 1: *Organization of Proposed Field Research, Objectives, Research Questions, Measurement Scale*

Section 3.3 A: Multiscale ecosystem responses to climate and management (Core areas: Primary Production, Disturbance)	**Scale**
Objective A: To understand how changing precipitation, atmospheric humidity, temperature and land management control ecosystem processes in drylands	
✓ **Question A1:** How are ecosystems changing in response to directional climate change and cyclical climate variability?	Basin
✓ **Question A2:** How do long-term changes in rainfall amount and variability affect ecosystem function and grassland-shrubland transitions?	Plot
✓ **Question A3:** How do dryland vegetation communities respond to changes in soil moisture and atmospheric vapor pressure deficit?	Plot
✓ **Question A4:** How do grazing and drought intensities interact with disturbance durations to trigger grass loss and vegetation state change?	Plot
Section 3.3 B: Biogeochemical interactions and pulse-reserve feedbacks (Core areas: Inorganic/Nutrient Cycles, Organic Matter Dynamics, Primary Production)	
Objective B: To assess how carbon and nutrient cycling, and nutrient co-limitations, respond to and control dryland vegetation states	
✓ **Question B1:** How do ecosystem states and edaphic heterogeneity control carbon and water flux responses to rainfall pulses across ecosystems?	Basin
✓ **Question B2:** How do biocrust and bare soil contribute to rapid rainfall pulse responses and are these responses determined by ecosystem state?	Landscape
✓ **Question B3:** Do dryland carbon and nutrient cycling reflect patterns of nutrient limitation associated with vegetation state change?	Landscape
Section 3.3 C: Spatial interactions and connectivity feedbacks (Core areas: Inorganic/Nutrient Cycles, Disturbance, Population/Trophic Dynamics)	
Objective C: To quantify how spatial connectivity with respect to wind and water transport can reinforce or reverse ecosystem state change	
✓ **Question C1:** How does hydrological connectivity on dryland hillslopes impact runoff, with potential feedback on vegetation dynamics?	Basin
✓ **Question C2:** How does aeolian connectivity interact with competition for water in controlling grass recovery in degraded drylands?	Landscape
✓ **Question C3:** How do vascular plant and biocrust cover impact and respond to aeolian transport of sediments in drylands?	Landscape
Section 3.3 D: Biotic interactions and trophic feedbacks (Core area: Population Dynamics/Trophic Interactions)	
Objective D: To characterize the biotic interactions underlying vegetation state change, including demographic processes, plant-microbe interactions, and trophic feedbacks	
✓ **Question D1:** How are the critical demographic rates underlying long-term changes in shrub communities impacted by varying climatic and edaphic interactions?	Basin
✓ **Question D2:** Are patterns in grass recovery controlled by plant-microbe interactions impacting establishment and survival probabilities?	Plot
✓ **Question D3:** How do changes in vegetation state impact higher trophic levels and are there feedbacks on vegetation dynamics that amplify or suppress state changes?	Landscape

3.3. Proposed long-term observational and experimental research

We organize our research objectives and observational, experimental, and modeling activities following PIRFCT (Fig. 2). No single study will test PIRFCT in its entirety, but individual objectives and studies will address elements of PIRFCT, and together, they will significantly advance our understanding of dryland **change**. For example, plant or microbial **reserves** are measured in nearly every experiment and many explicitly address **feedbacks**. The **pulse** forcing provided by climate and land management are tested in several observational and experimental studies (Section 3.3.A) and we describe research exploring **biogeochemical, spatial, and biotic interactions** in Sections 3.3.B - 3.3.D. Each sub-section (3.3. A-D) has an overarching objective and within each we pose specific observational and experimental questions motivating the proposed studies (Table 1). For each study, we provide background information, hypotheses, study design, and expected outcomes.

3.3.A. Multiscale ecosystem responses to climate and land management pulses (Core areas: Primary Production, Disturbance)

The purpose of these studies is to understand how changing precipitation, atmospheric humidity, temperature and land management control ecosystem processes in drylands **(Objective A)**.

QA1: How are ecosystems changing in response to directional climate change and cyclical climate variability? (continuing long-term observations)

Background: The Southwest is experiencing an intensifying megadrought that has no precedent since the 16th century (Williams et al. 2022), driven in part by the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO) (Seager et al. 2023). At the JRN, this megadrought has resulted in the lowest recorded perennial grass cover ever observed in our 101-year record (Christensen et al. 2023). The next six years will shed light on how this intensifying drought could affect ongoing vegetation change. The Chart Quadrat study provides one of the longest records of vegetation dynamics in the world, with quadrats distributed across JRN and measured for cover of vascular plants starting in 1915 (Christensen et al. 2021). Since 1989, JRN has also developed a continuous record of species-level, seasonal aboveground vascular plant NPP at 15 locations across the basin, in distinct grassland and shrubland vegetation states, using non-destructive methods (Peters et al. 2012, Peters and Savoy 2023). First, we will extend and use the Chart Quadrat and NPP datasets to model the effects of ENSO, PDO, AMO, and local climate on vegetation, considering soil type and aeolian/hydrological connectivity at sites as additional variables. This effort will revisit the conclusions of Christensen et al. (2023) that the close relationship of grass cover with PDO observed for much of the 20th century has recently broken down due to hot droughts and grassland-shrubland transitions that drive grass cover dynamics independently of PDO. Second, we will assess biocrust primary productivity in the NPP study using low-cost proxies empirically calibrated to measured biocrust production (QB2, below). Direct comparisons between vascular plant and biocrust NPP dynamics will thus be possible for the first time, allowing us to assess the relative contribution of biocrusts to patterns of NPP across the Jornada Basin.

Hypotheses: A) Continued negative PDO/positive AMO conditions and soil drying (Seager et al. 2023) will drive grassland-shrubland transitions that further decouple grass production from expected gains in favorable periods. B) Biocrust NPP will contribute significantly to total ecosystem NPP but microbial and vascular NPP will be temporally decoupled because biocrust can make rapid use of rainfall pulses and superficial soil moisture (Garcia-Pichel 2023), while vascular plants respond more slowly to deeper soil water pulses/stores for longer productive periods.

Study design: Chart Quadrat data collection will continue at five-year intervals, reaching 111 years in 2026. NPP measurements will continue every year, reaching 40 years in 2029, with multiple seasonal samples each year. We will also quantify biocrust contributions to ecosystem-scale NPP in 12 of the 15 NPP sites, 3 each in 4 different types of vegetation states: *Prosopis glandulosa* (mesquite) shrubland, mixed perennial grassland, *Flourensia cernua* (tarbush) shrubland, and *Larrea tridentata* (creosotebush) shrubland. In each, we will analyze automated, recurrent photographic images of 1 m^2 quadrats linking biocrust greenness, fractional cover, and hydration state to NPP (Bethany et al. 2022). To link biocrust observations at the NPP sites to high temporal frequency net soil CO_2 exchange chamber measurements, additional biocrust cameras will be established at the PCNAS site (See QB2). Blue/red color ratio analyses will provide semi-quantitative assessment of the extent of N_2-fixing cyanobacteria and cyanolichens, thus providing insight into N-fixation potential (Couradeau et al. 2016). **Expected outcomes:** We will extend our understanding of long-term vascular plant responses to cyclical and directional variations in soil moisture pulses, with enhanced understanding of the contributions to NPP associated with biocrust.

QA2: How do long-term changes in rainfall amount and variability affect ecosystem function and grassland-shrubland transitions? (augmentation of a long-term experiment)

Background: Long-term Climate Change Experiments (CCEs) use a rainout shelter design (Yahdjian and Sala 2002) to intercept varying percentages of rainfall from “drought” plots and redistribute water to “deluge” plots. CCEs at JRN have provided critical evidence of the mechanisms by which drought and increased precipitation variability affect NPP and plant community change. Our flagship CCE is a 17-y manipulation of precipitation amount (CCE1; Reichmann et al. 2013a, 2013b, Reichmann and Sala 2014); Fig. 5). In JRN 6-7, we showed that extreme drought led to an initial decrease in NPP with a minimum in 2015 and, from then on, ANPP increased relative to controls. This unexpected pattern was explained by the demise of grasses around year 8 of the experimental drought and the surge of shrub NPP, due to a much higher rain-use efficiency in shrubs. The shift from grass to shrub dominance therefore moderated the effect of extreme drought on NPP. Similar CCEs of shorter duration include CCE2 (6 y), focusing on soil fauna (Franco et al. 2019), and CCE3 (2 y), focusing on root ecology.

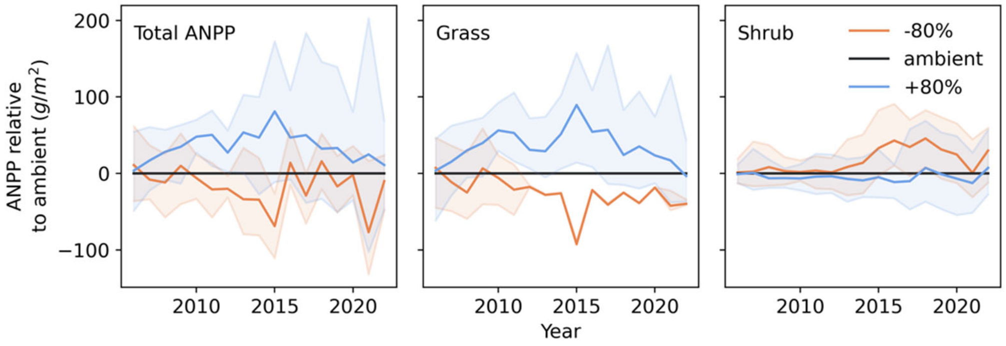

Figure 5. *Total, grass, and shrub NPP during a rainout shelter experiment (CCE1) with 80% decreased or increased annual precipitation (Sala et al in prep).*

In a second type of experiment, CCE4 (15 y), precipitation variability is manipulated by increasing or decreasing ambient precipitation by 50% and 80% and then flipping these treatments each year, resulting in a precipitation inter-annual variability range from 39 to 120% while mean annual precipitation remains similar (Gherardi and Sala 2015a, 2015b). Enhanced precipitation variability decreased total productivity by reducing grass productivity, which was partially offset by an increase in shrub production and an unexpected increase in plant species diversity. In JRN-8 we aim to continue these long-term studies and provide new information on a) biocrust responses and b) the interaction of the duration of rainfall manipulations with ongoing aridification.

Hypotheses: A) Multi-year drought and increased precipitation variability will reduce grass cover/production leading to increased shrub dominance that may offset drought effects across all CCEs. B) Biocrust NPP will increase by taking advantage of shallow soil moisture during prolonged drought and offset declines in grass production.

Study design: CCE1 (initiated in 2007) features a factorial design of -80%, + 80%, and control, crossed with nitrogen fertilization 10 gm^{-2} y^{-1} in 12, 2.5 x 2.5m plots (72 total plots). CCE2 (initiated in 2017) simulates two types of drought reducing incoming precipitation by 20% and 50% and simulating deluges that increase precipitation by 120% and 150%, and controls, in 8 5x5 m plots (40 total plots). CCE3 (initiated in 2021) is the same design as CCE1 but with a focus on roots, with 10 plots each (30 total plots). CCE4 (initiated in 2009) manipulates variability while maintaining constant long-term mean precipitation, including 20 and 50% reduction of precipitation and treatments with increased precipitation by 20 and 50% as well as controls. Plots that receive drought in even years receive increased precipitation in odd years. Plots are 2.5 x 2.5 m, with 10 plots/treatment (50 total plots). In all experimental treatments, we will characterize precipitation, air temperature, wind speed, solar radiation, relative humidity, and soil water content (via the Time Domain Reflectometry method). As in other JRN studies, NPP is measured non-destructively. We will continue to monitor belowground NPP using minirhizotron tubes (Milchunas et al. 2005). Biocrust NPP will be estimated as described in QA1. **Expected outcomes**: These experiments provide a robust test of the mechanisms of climate change effects on state change, including sensitivity of plant and biocrust communities to future climate change. **Cross-site activities:** Data from this experiment will contribute to regional and global DroughtNet analyses.

QA3. How do dryland vegetation communities respond to changes in soil moisture and atmospheric vapor pressure deficit? (a new experiment)

Background: Recent research suggests that changes in vapor pressure deficit (VPD) may be more important than changes in precipitation in driving change in ecosystem function (Konings et al. 2017, Li et al. 2023). Elevated VPD reduces stomatal conductance, and therefore transpiration water losses, but can also reduce photosynthesis (Novick et al. 2024). As yet, there are no experiments that manipulate VPD and its interaction with precipitation in drylands. In this new CCE experiment (CCE5), we will test the independent and interactive effects of variation in VPD and precipitation on different ecosystem processes from NPP to population dynamics of shrubs and grasses.

Hypotheses. A) Increasing VPD reduces NPP with VPD effects being similar for grasses and shrubs; B) VPD effects will be greater when rainfall and soil moisture levels are high (e.g., when there are no soil moisture limitations to stomatal opening and C-cycling). Recent analyses of FLUXNET data support the latter hypothesis (Wang et al. 2022), which predicts that when soil moisture is low and thus stomata are mostly closed, decreasing VPD will have much less impact on ecosystem functioning. Conversely, high evaporative demand may reduce photosynthesis and productivity the most when soil moisture levels are low by exacerbating water limitations (Dannenberg et al. 2022).

Study design. We will independently modify water availability in the atmosphere and in the soil in a factorial design and will measure grass and shrub NPP through non-destructive means. We will modify soil water using a design similar to CCE1 with rainout shelters that intercept 50% of incoming precipitation that is then collected and used for irrigation in the +50% treatments (Gherardi and Sala 2013). We will modify atmospheric water content using misters that reduce water vapor pressure deficit. Our pilot study showed that we were able to significantly reduce seasonal VPD by ~10%, whereas irrigation had no significant effect on VPD. We will have 3 soil-water levels (+50%, control, -50%), and two VPD levels (control and reduced) with 8 replicates each (48 total plots). **Expected outcomes:** Understanding of how drought and VPD impact grass and shrub NPP is essential as drylands are rapidly moving into novel climatic conditions.

QA4: How do grazing and drought intensities interact with disturbance durations to trigger grass loss and vegetation state change? (augmentation of a long-term experiment).

Background: While it is widely understood that high levels of grazing defoliation (especially of perennial grasses) substantially influence ecosystem function in drylands (Maestre et al. 2022), little is known about how the duration of heavy grazing pressure interacts with varying degrees of drought to create abrupt state change. The Threshold Experiment (ThreshEx; now in its 27th year) evaluates thresholds in the recovery of perennial grasses (mostly *Bouteloua eriopoda*) following a 4-y seasonal grazing press perturbation (1996-2000; summer or winter defoliation), with or without shrub removal (Bestelmeyer et al. 2012, Ratajczak et al. 2017). ThreshEx responses occur against a background of ambient climate variability (Fig. 6). Heavy grazing alone, even in the presence of shrubs, did not recreate the persistent loss of perennial grasses documented in long-term observational datasets. Late in JRN-7, we initiated ThreshEx2 to test the notion that the frequency and duration of yearly, heavy defoliation pulses (simulated grazing) interact with increasing drought intensity and duration to produce abrupt and persistent loss of grasses and other plant community changes.

Hypotheses: A) Effects of defoliation are additive to effects of drought intensity, and there will be no evidence of interactions on grass or shrub productivity. B) Drought reduces the effects of defoliation because reduction of leaf area reduces total plant transpiration and counteracts drought impact. C) There will be an interaction between defoliation and drought duration on grass decline, with the effects of drought duration being magnified by defoliation.

Study design. This experiment has 3 treatment levels: control, defoliated 1 time per year, and defoliated 2 times per year. Grass will be clipped to 5 cm height. The drought intensity (precipitation) treatment contains 10 levels: 10% of ambient, 20% of ambient, 30% of ambient, and so on to 100% of ambient. There are 3 levels of drought duration: 2, 4, and 8 years, resulting in a total of 90 2.5 x 2.5 m plots. Vegetation cover and NPP will be measured following CCE protocols (e.g., QA2). Additional explanatory variables include initial (pre-treatment) grass foliar cover and NPP. **Expected outcomes:** ThreshEx2 will increase our ability to predict vegetation responses to land management under a changing climate and explain threshold patterns we have observed in historical observational datasets.

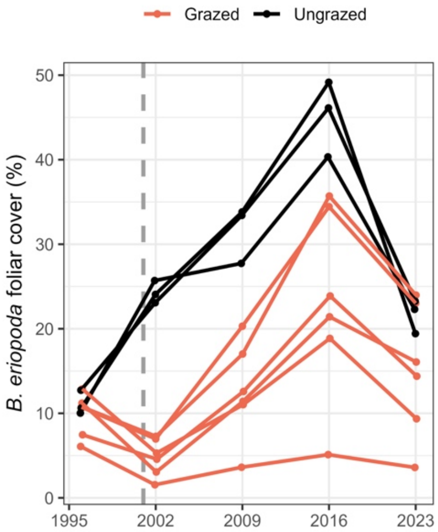

Figure 6. Change in B. eriopoda cover in response to grazing. *Plots subject to heavy summer and winter defoliation (red lines) during the 1996-2000 period and ungrazed controls (black), with varying post-treatment recovery (2001 onwards).*

3.3.B. Biogeochemical interactions and pulse reserve feedbacks (Core areas: Inorganic/Nutrient Cycles, Organic Matter Dynamics, Primary Production)

The purpose of these studies is to assess how carbon and nutrient cycling, and nutrient co-limitations, respond to and control dryland vegetation states **(Objective B)**.

QB1: How do ecosystem states and edaphic heterogeneity control carbon and water flux responses to rainfall pulses across ecosystems? (new and continuing long-term observations)

Background: Ecosystem state change interacting with relatively static edaphic and topographic heterogeneity (Wilcox et al. 2022, Wojcikiewicz et al. 2024) is likely to have profound effects on carbon and water balance at broad scales, but these effects are poorly understood. For example, while shrub encroachment can increase carbon in woody biomass at annual-to-decadal time-scales (Petrie et al. 2015), increasing bare soil, reduced grass roots, and loss of soil organic matter can offset these gains, leading to net losses in stored carbon (Browning et al. 2017). Vegetation state and soil heterogeneity mediate how rainfall pulses interact with surface processes (infiltration, runoff, erosion; Schreiner-McGraw et al. 2020) to determine the physiological responses of microbial, herbaceous, and woody primary producers (Scott et al. 2015, Biederman et al. 2017, MacBean et al. 2021, Barnes et al. 2021). Recent additions to the network of eddy covariance (EC) sites across the Jornada Basin (with 14 sites in different landscapes; Fig. 7) provide an unprecedented opportunity to examine how pulses, soils, vegetation states, and related spatial interactions (e.g., connectivity) affect carbon and water fluxes during and between rain events, at seasonal and inter-annual time scales, and at local to basin spatial scales.

Hypothesis: The magnitude and duration of carbon and water pulse responses reflect the contributions of rapidly responding microbial communities (heterotrophs and biocrust autotrophs) and more slowly responding herbaceous and woody autotrophs. Thus, we expect that soil, biocrust, and plant community density and composition, and the extent of runoff controlled by vegetation cover/connectivity, landscape position, and soil type, will explain site-to-site variability and temporal heterogeneity in water and carbon dynamics across JRN.

Study design: (i) Cross-site standardization: The JRN EC network includes: two Ameriflux towers (US-Jo1 and US-Jo2) with measurements since 2010 in upland shrublands, the JORN NEON tower in a *B. eriopoda* grassland since 2017, four tower sites installed since 2022 by USDA-ARS, representing distinct states across a grassland to *P. glandulosa* shrubland ecotone, five *P. glandulosa* and two *L. tridentata* sites installed by collaborators from the Army Research Laboratory, and two playa sites (ephemeral wetland; CZO and Perez Ruiz 2023). Common processing workflows will include comparison of open- and closed-path gas analyzers using a designated reference analyzer co-located for one month at each site (Scott et al. 2015), standardized ONEFlux pipeline for u* filtering, coordinate and spectral corrections, data gap-filling, and flux partitioning into gross primary productivity (GPP) and ecosystem respiration (Pastorello et al. 2020). Standardized seasonal and annual EC footprints will be calculated for each site using the method of Kljun et al. (2015) and we will compare standard flux-partitioning with methods that accommodate rain-pulse features (Moran et al. 2009). **(ii) Carbon pools:** We will estimate current aboveground biomass and soil carbon pools to quantify the long-term impact of vegetation state changes on carbon storage and exchange with the atmosphere. Aboveground biomass will be estimated using UAS image collections and the structure-from-motion (SfM) approach, with established allometric relationships (Cunliffe et al. 2021), augmented with a field campaign to characterize plant and biocrust community composition and plant and soil samples to estimate organic and inorganic soil carbon pools. **(iii) Carbon and water pulse responses:** Standardized 30-minute fluxes at the 14 JRN towers will be used to quantify carbon and water fluxes to represent sink and source dynamics in response to rainfall events, as well as seasonal and interannual rainfall variability. We will explore functional relationships to identify how precipitation and evapotranspiration (ET) control GPP and R_{eco} across sites differing in species dominance and phenological profile (Fan et al. 2015, Browning et al. 2018). **(iv) Phenology:** We will evaluate the degree to which camera-derived greenness correlates with daily GPP contingent on PFT and time since rainfall pulse. We anticipate that the strength of the relationship will vary with vegetation state characteristics, such as amplitude of GPP, contributions of biocrusts, and plant community composition. **(v) Basin scale modeling:** We will use Random Forest modeling with our EC time series to characterize spatial and temporal variability in fluxes (NEE, ET, R_{eco}, GPP) as functions of rainfall pulse characteristics, PFT and biocrust cover, vegetation state (e.g. greenness), soil type, and landscape position. Application of the fitted model at the basin scale (on a 30 m grid) will use spatial data on soils and landforms, interpolated weather data from our meteorological station network, phenocam- or satellite-derived vegetation indices, a map of biocrust cover in development, and PFT cover estimates from the Rangeland Analysis Platform (Jones et al. 2018). **Expected outcomes:** The proposed efforts will be a first step toward understanding landscape-level carbon and water dynamics at the JRN. We will develop new insight into how pulse-responses following rain events stimulate activity in bare soil, biocrust, herbaceous and woody plant communities, and how these scale in time and space. **Cross-site activities:** The JRN EC network will complement similar data collected at other dryland and southwestern North America regional eddy covariance sites in the LTER network, *Ameriflux* and the *FluxNet* communities.

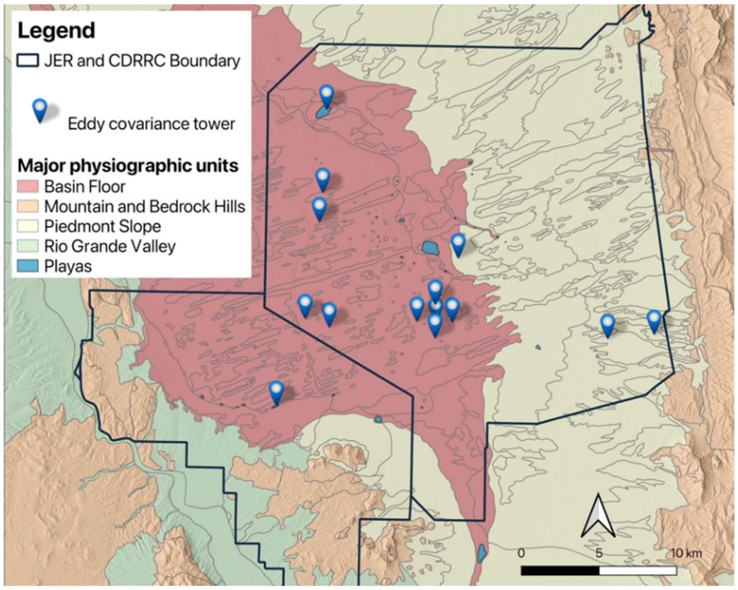

***Figure 7. Distribution of eddy covariance sites in two spatially dominant landforms of the Jornada Basin**, including sites on shallow gravelly soils of the piedmont slope, and deep sandy soils of the basin floor (Monger et al., 2006). The northernmost and southernmost sites are on sandy soils in seasonally flooded depressions (playas).*

QB2: How do biocrust and bare soil contribute to rapid rainfall pulse responses and are these responses determined by ecosystem state? (augmentation of long-term experiments)

Background: Understanding of dryland ecosystem function has been limited by the fact that biological activity responds rapidly to rainfall pulses (even small ones) in ways that can be short-lived and spatially heterogeneous (Huxman et al. 2004, Cable et al. 2008). Thus, the timing of measurement is enormously important in determining the magnitude, variability, and controls over core ecosystem processes such as photosynthesis, respiration, NPP, and nitrogen fixation (Fig. 8). While our EC network (QB1) will capture pulse-responses at the ecosystem scale, the network cannot easily assess rapid CO_2 production following rainfall pulses (Huxman et al. 2004, Cable et al. 2008, Munson et al. 2010) or the specific role of soil and biocrust in photosynthetic uptake and respiratory release. We also expect that the roles of biocrusts and soil microbes might vary with ecosystem state as a function of vegetation production, open ground cover, and erosion-related degradation of soil communities mediated by connectivity (Hansen et al. 2023). Recent advances in high frequency chamber-based gas exchange technology offer new opportunities to quantify high temporal resolution pulse responses (Fig. 8), particularly for biocrust relative to bare soil, such that we can now more fully evaluate the drivers, patterns, and consequences of pulse-reserve dynamics in alternative states (Darrouzet-Nardi et al. 2015, 2018).

Hypotheses: Dryland mineral soil and biocrust exchange of CO_2 with the atmosphere is controlled by rainfall pulses such that discontinuous assessments with arbitrary timelines miss the majority of activity and control. The amplitude and duration of responses to pulse events will be positively but non-linearly related to the size of the pulse and will depend heavily on the cover and type of biocrust. Biocrust CO_2 uptake will be highest in mixed grass-shrub states, where there is higher open ground than in grasslands but where erosion potential is reduced compared to shrubland. Mineral soil CO_2 efflux will also be highest in this state due to its relatively high vegetation productivity.

Study design: In the *pulsed carbon and nitrogen analysis study* (PCNAS), we will use automated flux chambers (Li-Cor 7810, with clear chambers, already available at JRN) to measure hourly (24 h/day) bare soil and biocrusted soil CO_2 and CH_4 exchange (Fig. 8). Biocrusted soil will be intact soil (present at each site) with autochamber collars, and the bare soil treatment will have the autotrophic topsoil component gently removed prior to placing the collars (Chamizo et al. 2022). Auto-chamber collars will be placed in the footprint of three EC towers across a vegetation state gradient, including a *B. eriopoda* grassland, grass-shrub mix, and *P. glandulosa* shrubland (preliminary EC data indicate that the grass-shrub mix has highest NPP). Measurements will be rotated annually over the 6-year project, capturing two full years, and myriad rainfall and dry-down events, at each site. These measurements will allow estimation of biocrust contributions to ecosystem CO_2 and CH_4 fluxes (QB1) and benchmark GPP and R_{eco} partitioning methods typically used by the EC community. The autochamber access ports will also allow us to sample N_2O fluxes in different seasons. We will join this data collection with assessments of weather, soil microclimate, leaf-level photosynthesis, and plant and biocrust community composition and cover. Outside of, but adjacent to, the EC footprints, we will conduct complementary in situ experiments using manual soil respiration chambers, to measure mineral soil and biocrusted soil CO_2 responses to combinations of resources (i.e., by adding water and dissolved carbon, nitrogen, and/or phosphorus) to assess how changes to the availability of individual and multiple resources affect the photosynthetic uptake and respiratory loss of soil CO_2, as well as the transfer of CH_4, N_2O, and the concentration of dissolved organic carbon, total dissolved nitrogen, inorganic nitrogen, and phosphate. **Expected outcomes:** This experiment will build a holistic understanding of how precipitation pulse events stimulate rapid responses in soil microbial communities and biocrust in the context of different ecosystem states. These fine scale measurements will be coupled with coincident EC flux measurements, lending insight into the multi-temporal and -spatial scale (bare soil, biocrust, vascular plant) controls over fundamental ecosystem functions following resource pulses and critical information on the coupled dryland biogeochemical cycles of carbon, nitrogen, and phosphorus.

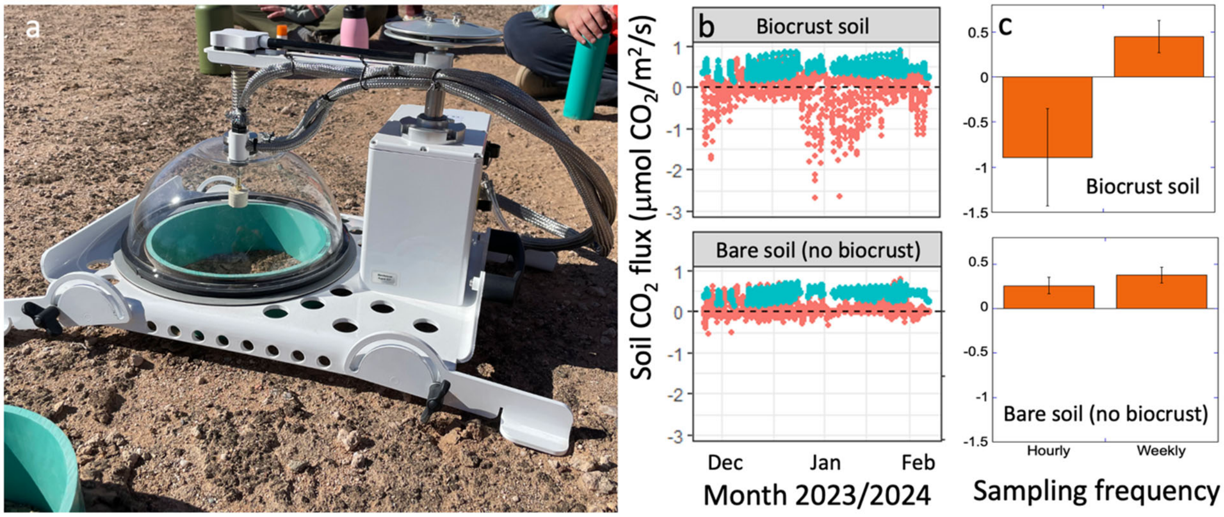

Figure 8. Impact of sampling interval on estimates of soil respiration. *a) Automated soil CO_2 flux analyzer with clear chamber to allow measurement of biocrust and soil net carbon exchange; b) hourly soil CO_2 flux measurements using this system for 2.5 months in soils with (red points) and without (blue points) biocrusts (positive fluxes show net respiratory loss to atmosphere, negative fluxes show net uptake); c) demonstration of sampling errors in estimating long-term fluxes comparing interpolated hourly measurements to interpolated weekly midday measurements (a common measurement frequency with manual chambers). Higher resolution measurements change not only the magnitude of flux estimates, but also the sign of the net flux for biocrusted soils. These data underscore the dynamic nature of dryland carbon cycling and the need for the high-resolution CO_2 assessments proposed in JRN 8.*

QB3: Do dryland carbon and nutrient cycling reflect patterns of nutrient limitation associated with vegetation state change? (new observations and experiments)

Background: Our understanding of nutrient limitation in drylands remains poor and hinders our ability to explain and predict variations in NPP associated with state change. Annual precipitation, for example, only explains a fraction of the variability in plant productivity, indicating the importance of controls other than water availability (Biederman et al. 2016, Peters and Savoy 2023). It is also well known that state change can alter the spatial heterogeneity of nutrients (Schlesinger et al. 1996, Li et al. 2008, 2017, Okin et al. 2015, 2018), yet the implications for resource limitation are unknown. Studies from other drylands suggest an important role for multiple resource limitation in regulating soil heterotrophs, such that concurrent changes in the availability of multiple resources (e.g., water *and* nutrients) have effects orders of magnitude larger than the effects of changing water availability alone (Choi et al. 2022). It has been suggested that nitrogen is the second most important regulator of dryland NPP after water (Hooper and Johnson 1999), and dryland systems have been proposed as exceptionally vulnerable to changes in nutrient inputs, such as through nitrogen deposition (Pardo et al. 2011). Yet recent dryland studies are divided on the extent to which dryland productivity is strongly (Ettershank et al. 1978, Gutierrez et al. 1988, Hooper and Johnson 1999) or weakly (Phillips et al. 2021, Osborne et al. 2022, Brown and Collins 2024) controlled by nutrients. This work points to the role of ecosystem state, spatial heterogeneity, and interacting resources in determining dryland ecosystem function. Long-term experimental plots at JRN, specifically the *Ecotone* experiment and a rainfall×N fertilization experiment (Reichmann et al. 2013b), will be used to address how ecosystem state and resource limitation interact to regulate fundamental ecosystem processes in plants (assessed as NPP) and soils (assessed as soil respiration).

Hypotheses: Plants and soil heterotrophs in grassland states will exhibit co-limitation among resources (e.g., water, nitrogen, phosphorus) because background availability of resources is relatively low and spatially homogeneous, making organisms less able to respond to changes in the availability of a single resource, but highly responsive to concurrent change in multiple resources. By contrast, in shrubland states where plant traits and water/wind connectivity lead to "islands of fertility", nutrient availability and limitation will vary by microsite (i.e., shrub canopy vs. interspace). Shrubs, grasses, and soil heterotrophs associated with shrub canopies will be limited by a single resource (water), but heterotrophs in the interspace will be co-limited by multiple resources.

Study design. We will use the *Ecotone* experiment (see QD3) to determine how plant and soil carbon, nitrogen, and phosphorus vary across a gradient of grass to shrub dominance, which will significantly increase the resolution of our understanding for how transitions from grassland to shrubland states affect nutrient cycling and coupled biogeochemistry. We will collect shrub and grass foliar tissue from 10 individuals each of *B. eriopoda* grass and *P. glandulosa* shrubs within grassland, mixed, and shrub-dominated areas located in five blocks of *Ecotone* (15 sites = 300 plants). We will link these data to assessments of NPP for the same individuals. We will collect soils (0-10 cm) from under the canopy and from adjacent interspace for each plant and will use elemental analysis to quantify carbon, nitrogen, and phosphorus (Reed et al. 2007), as well as use these soils in the soil nutrient limitation incubation described below. The *Ecotone* portion of the study will assess spatial patterns in nutrient availability. To directly assess resource limitation to NPP, we will use a precipitation×N fertilization experiment where the availability of water and nitrogen have been modified since 2006 (Reichmann et al. 2013b). Plots are 2.5 x 2.5m and are co-dominated by *B. eriopoda* and *P. glandulosa*. There are 6 treatments with 6 plot replicates each: 80% rainfall reduction with and without nitrogen fertilization, 80% rainfall increase with and without nitrogen fertilization, and no precipitation change with and without nitrogen fertilization (Reichmann et al. 2013b). Fertilization treatments are 100 kg N/ha/y applied as 2 mm precipitation events to whole plots twice during each growing season, with the same amount of water applied to unfertilized plots. We will measure the NPP of all shrubs and grasses (i.e., those growing in shrub canopies and in interspaces among shrubs) to determine water and nutrient limitation (assessed by comparing NPP in treatment plants compared with controls (Vitousek and Howarth 1991). We will analyze carbon, nitrogen, and phosphorus concentrations of plant tissue for shrubs, grasses in the interspace, and grasses under shrub canopies (n = 5 per type; 15 plants/plot) and of soils (0-10 cm depth) under shrub canopies and in the interspace, which we will also use to assess nutrient limitation of soil respiration. We will then perform a soil incubation experiment using soils collected from *Ecotone* and from the N×rainfall manipulation and will add the following resources in a full-factorial design (water, C, N, P) using the methods described in Choi et al. 2022. Our predictions are that soil respiration will show co-limitation in *Ecotone* grassland soils and interspaces, and single resource limitation (likely water) from soils under shrubs. We further predict that the addition of nitrogen in fertilization plots will result in interspace soils that have shifted from co-limitation (control plots) to single resource limitation (+N plots). **Expected outcomes**: This work will allow 1) assessment of nutrient cycling and limitation in contrasting ecosystem states and 2) improved quantification of carbon and nutrient distribution in plants and soils and its variation among states. The results will advance our fundamental understanding of dryland nutrient limitation and coupled biogeochemical cycles in drylands, and improve our parameterization and evaluation of models of dryland function.

3.3.C. Spatial interactions and connectivity feedbacks (Core areas: Inorganic/Nutrient Cycles, Disturbance, Population/Trophic Dynamics)

The purpose of these studies is to quantify how spatial connectivity with respect to wind and water transport can reinforce or reverse ecosystem state change **(Objective C)**.

QC1: How does hydrological connectivity on dryland hillslopes impact runoff, with potential feedback on vegetation dynamics? (augmentation to long-term observations)

Background: Hydrological connectivity is central to processes underlying shrub encroachment in arid landscapes (Okin et al. 2015, Iwaniec et al. 2021, Wilcox et al. 2022) where intense rainfall pulses may overcome soil infiltration capacity, leading to local redistribution of water and losses via drainage channels (Schreiner-McGraw and Vivoni 2017, Keller et al. 2023). At the JRN, hydrological connectivity is prevalent on the shallow soils of the piedmont slopes, but is also important during large events on the basin floor (McKenna and Sala 2018). Shrub encroachment on hillslopes promotes the expansion of bare soil areas, the production of hillslope runoff and infiltration in sandy channels (Keller et al. 2023), and the storage and delayed use of subsurface water by deep rooted shrubs (Pérez-Ruiz et al. 2022). The simultaneous loss of grass cover, increase in runoff, and deep soil recharge might explain shrub expansion and persistence on piedmont slopes (Schreiner-McGraw et al. 2020), while channel runoff during larger storms transmits water to downslope ephemeral playas (Kimsal 2023). In JRN-8, we will (i) model hillslope pulse processes that generate runoff at the plot-scale and (ii) link this with basin-scale dynamics of downstream playas and stock ponds. At both scales, vegetation state changes mediate, and are influenced by, the hydrologic connectivity across a landscape.

Hypothesis: Vegetation state changes on the JRN piedmont are mediated by hydrological connectivity feedbacks that inhibit grass and favor shrubs at plot scales and link hillslope vegetation state to downslope playa dynamics.

Study design: (i) Experimental watershed: Continuous data collection in our piedmont experimental watershed began in 2010 (Templeton et al. 2014) and now includes extensive measurements of hydrological parameters including four hillslope runoff plots, first and second order streamflow observations, extensive soil moisture monitoring, meteorological data collection (including a disdrometer for rain drop size and intensity measurements), EC flux measurements, and vegetation characterization using phenocams and UAS imagery (see QB1). These watershed-scale measurements allow us to observe how rainfall pulses at plot scales are propagated and attenuated at the landscape (watershed) and basin scale in response to vegetation (inc. plot-scale connectivity) and edaphic interactions. **(ii) Ephemeral playas and stock ponds:** To integrate our understanding of hydrological connectivity at watershed and basin scales we now monitor water levels in 18 ephemeral playas and five stock ponds (Fig. 9). We have characterized catchments for these playas/stock ponds using 1-m LiDAR elevation data, covering ~12% of JRN, and use bias-corrected radar rainfall to derive hourly rainfall intensity thresholds required for inundation events (Kimsal 2023). In JRN-8, we will expand this analysis to determine differential site responses to precipitation and flooding events across sites and in relation to upland watersheds, providing large-scale quantification of how small-watershed factors (soil properties, vegetation states, topography) interact with rainfall pulses to control inundation in downslope ephemeral playas and stock ponds. **Expected outcomes:** The proposed hydrological monitoring activities will augment our understanding of hydrological pulse-responses at plot and watershed scale and the role of hydrologic connectivity to downstream sites. These data will enhance our ecohydrological understanding of dryland landscapes and contribute to process-based modeling of how rainfall pulses are modulated by vegetation state to control partitioning between vertical and horizontal flows and evapotranspiration (see Section 3.4).

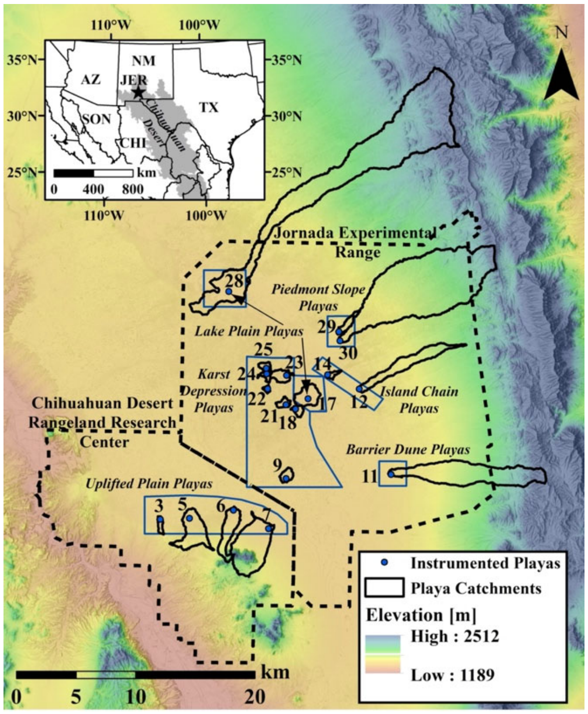

Figure 9. Location of instrumented ephemeral playas *(numbered blue circles) and their upstream catchments in the JER and CDRRC. Blue polygons surrounding playas/catchments link playas to common geomorphologies. Inset: location of JRN in the larger Chihuahuan Desert.*

QC2: How does aeolian connectivity interact with competition for water in controlling grass recovery in degraded drylands? (continuing long-term experiments)

Background: Aeolian connectivity has been identified as a critical positive feedback amplifying shrub encroachment in the Chihuahuan Desert (Peters et al. 2020, Payne et al. 2023), particularly on sandy soils where sediment redistribution by wind and sand-blasting of seedlings can suppress grass reestablishment (Fick et al. 2016, Niu et al. 2023). The *cross-scale interactions experiment* (CSIE, Rachal et al. 2015, Peters et al. 2020) has demonstrated strong interactions between aeolian connectivity (reduced using "connectivity modifiers", ConMods, Fig. 10a-b) and competition with shrubs (killed with herbicide; Fig. 10c). In particular, grass recovery was promoted synergistically by both factors combined, with little or no response to either factor in isolation (Peters et al. 2020, in review). The CSIE will continue as part of JRN-8 to determine if grass recovery in the ConMods will propagate spatially beyond the immediate ConMod footprint, as expected when biomass reserves cross critical thresholds (Fig. 2). More recently, we have extended the CSIE experiment to examine interactions between aeolian connectivity and rainfall. The *threshold responses in grass growth, establishment and recovery* (TRIGGER) experiment tests the proposition that grass establishment on flat, sandy soils depends on interactions between precipitation and aeolian connectivity. In this context, enhanced precipitation has been shown to support grass recovery (Sala et al. 2012, Gherardi and Sala 2015a) while decreased precipitation enhances shrub encroachment (e.g., Christensen et al. 2023). The spatially-mediated interactions between precipitation pulses and aeolian connectivity are unknown, but wind's ability to redistribute seeds, soil, and nutrients likely modulates spatial patterning of response to precipitation pulses.

Hypothesis: CSIE: spatial propagation of grass recovery will be greatest where shrub mortality has reduced belowground competition for water. TRIGGER: A) There is a lower level of precipitation below which reduced connectivity is ineffective in triggering grass recovery because too little water is available for germination and recruitment. B) There is an intermediate threshold of precipitation below which connectivity controls grass establishment and above which connectivity has little effect on grass recovery, because water is sufficient for recruitment and growth in most microsites. C) Effects of precipitation and connectivity are modulated by initial grass cover where the ConMod threshold effect increases with decreasing initial grass cover.

Study design: TRIGGER was established in 2019 and consists of 64 individual treatments on sandy soils. Plots were stratified into low, medium, and high initial grass cover, with precipitation treatments representing 100-y and 10-y wet or dry sequences (-80%, -50%, ambient, +50%, and +80%; per (Gherardi and Sala 2013), with paired ConMod/no ConMod treatments. Annual measurements of plant cover by functional type and measurements of litter cover using structure-from-motion techniques are made. Precipitation data are collected at nearby weather stations within 0.8 km. Soils collected near ConMods (initial and every 3y) will be analyzed for organic matter. **Expected outcomes:** CSIE and TRIGGER evaluate the importance of interactions between precipitation pulses and above- and belowground spatial interactions in grass recruitment, with implications for successful grassland restoration.

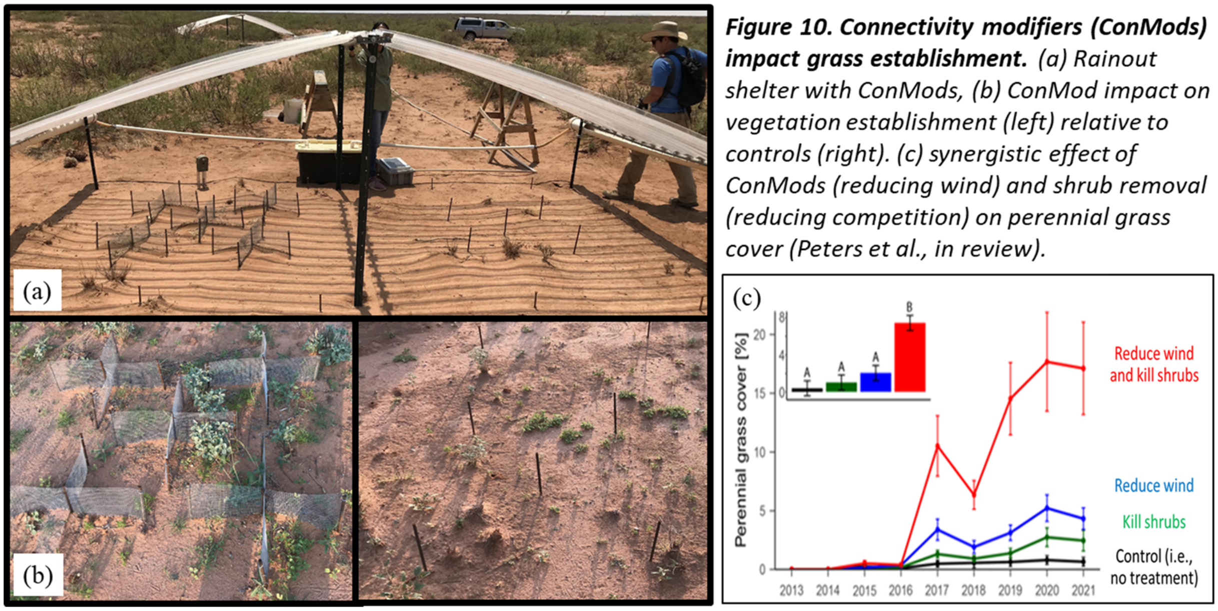

Figure 10. Connectivity modifiers (ConMods) impact grass establishment. *(a) Rainout shelter with ConMods, (b) ConMod impact on vegetation establishment (left) relative to controls (right). (c) synergistic effect of ConMods (reducing wind) and shrub removal (reducing competition) on perennial grass cover (Peters et al., in review).*

QC3: How do vascular plant and biocrust cover impact and respond to aeolian transport of sediments in drylands? (augmentation to a long-term experiment)

Background: The *nutrient effects of aeolian transport* (NEAT) experiment was established in 2004 to study how disturbances simulating progressive removal of grass cover upwind of an undisturbed location may initiate aeolian feedbacks suppressing grass cover and favoring shrub dominance (see Li et al. 2007, 2008, 2009a, 2009b, Alvarez et al. 2011, 2012, Niu et al. 2021). More recently, sediment deposited in downwind plots has unexpectedly begun to erode as scouring fronts advance downwind, and winnowing of soils by wind causes depletion of soil organic matter, nitrogen, and soil fines (e.g., Neupane 2019, Niu et al. 2021). In JRN-8, NEAT will continue to allow monitoring of the effects of progressive deposition and erosion on spatial patterns of state change, but biocrust augmentations to NEAT (experimental biocrust establishment and monitoring biocrust on treatments without inoculation) will allow investigation of interactions between biocrust, connectivity-mediated aeolian transport, and state change. Biocrust and soil stability loss with increasing wind erosion may have contributed to grassland-shrubland transitions during earlier grazing and drought episodes, and biocrust establishment could contribute to grass recovery when conditions are favorable.

Hypothesis: Biocrust inoculation will allow us to test new hypotheses: A) Survival of biocrust inoculum and establishment of mature biocrusts is inversely related to total horizontal aeolian flux; B) The threshold wind speed for erosion increases nonlinearly with crust development (measured as chlorophyll concentration). Monitoring on treatments without inoculation will supplement and expand the space in which we can test these hypotheses.

Study design: NEAT consists of three blocks on sandy soils, with each block having five treatments: 100% grass removal, 75% grass removal, 50% grass removal, 25% grass removal, and a control. Treatments consist of an upwind area (50 x 25 m) with vegetation removal and an adjacent downwind 50 x 25 m area where no direct manipulation was undertaken but which is expected to experience vegetation change due to the impact of aeolian connectivity and sediment delivery from upwind. Vegetation cover is recorded annually, and recent work has used UASs to characterize soil surface height (changing due to aeolian transport) and vegetation cover (Zhang et al. 2021b, 2021a). During JRN-7, we surveyed microbial community composition and phototrophic biomass, isolating >20 strains of pedigreed local cyanobacteria for culture and reinoculation, and identified pathogenic agents (Bethany et al. 2019, 2022) that could inhibit inoculation success. We then applied cultured, pathogen-free inoculum to sites within one of the blocks. Crust cover is monitored annually and new spectroscopic techniques to estimate crust cover are being developed. **Expected outcomes:** NEAT quantifies the effects of aeolian processes and connectivity of bare soil areas on survival of different PFTs which thus changes connectivity. It thus evaluates the feedback between transport and state change. The crust additions to NEAT will elucidate how spatial context and connectivity influence biocrust regeneration and impacts of biocrust cover on sediment transport (Garcia-Pichel and Sala 2022).

3.3.D. Biotic interactions and trophic feedbacks (Core area: Population Dynamics/Trophic Interactions)

The purpose of these studies is to characterize biotic interactions underlying vegetation state change, including demographic processes, plant-microbe interactions, and trophic feedbacks **(Objective D)**.

QD1: How are the critical demographic rates underlying long-term changes in shrub communities impacted by varying climatic and edaphic interactions? (new long-term observations)

Background: There are three main shrub communities/states at JRN dominated by *F. cernua* (tarbush), *L. tridentata* (creosotebush) and *P. glandulosa* (mesquite). However, little is known about processes underlying dominance by different shrub species, or the relative importance of climatic and edaphic bottlenecks in controlling shrub establishment and species dominance. We also know very little about sub-seasonal scale germination and seedling turnover due to drought, herbivory or other causes (James et al. 2011). Vegetation state change in response to climate, land use, and vegetation-resource feedbacks is ultimately controlled by demographic processes, but these processes have seldom been measured at JRN or for long-lived dryland plants more generally (Salguero-Gómez et al. 2012). Variability in rainfall pulses, competition by grasses on juvenile shrubs, and both insect and small mammal granivory/herbivory can all influence seedling survival and shrub recruitment (Fig. 11; Bestelmeyer et al. 2007, Pierce et al. 2019, Weber-Grullon et al. 2022, Toth et al. in prep). Furthermore, while shrub-shrub competition reduces shrub growth in dense stands (Ji et al. 2019, Wojcikiewicz et al. 2024), basin-scale shrub densities are generally too low for shrub-shrub interactions to have a strong effect (Fig. 11; Wojcikiewicz et al. 2024). In JRN-7, master's student Caroline Toth examined shrub seed germination and seedling survival responses to soil microbial communities, soil type, and rainfall (Toth et al., in prep). Tarbush is currently severely limited by seed viability, linked elsewhere to lack of cross-pollination and proximity to climate limits (Valencia-Díaz and Montaña 2005). Post-germination mesquite and creosote seedlings (<24 days) favored average or above-average rainfall, but neither was impacted by soil type or soil sterilization, while older seedlings (<75 days) of mesquite prefer higher rainfall than creosote. The lack of soil type effects on seedling survival during early growth suggests that filtering in shrub dominance across the JRN landscape must emerge via differential seedling survival in subsequent dry and cool seasons, motivating the observations and experiments proposed here.

Hypothesis: Patterns in shrub dominance across the basin are governed by differential survival of seedlings and saplings in the dry/cool seasons following seedling establishment related to species-specific shrub traits, temporal variability in rainfall and temperature, and interactions with soil characteristics.

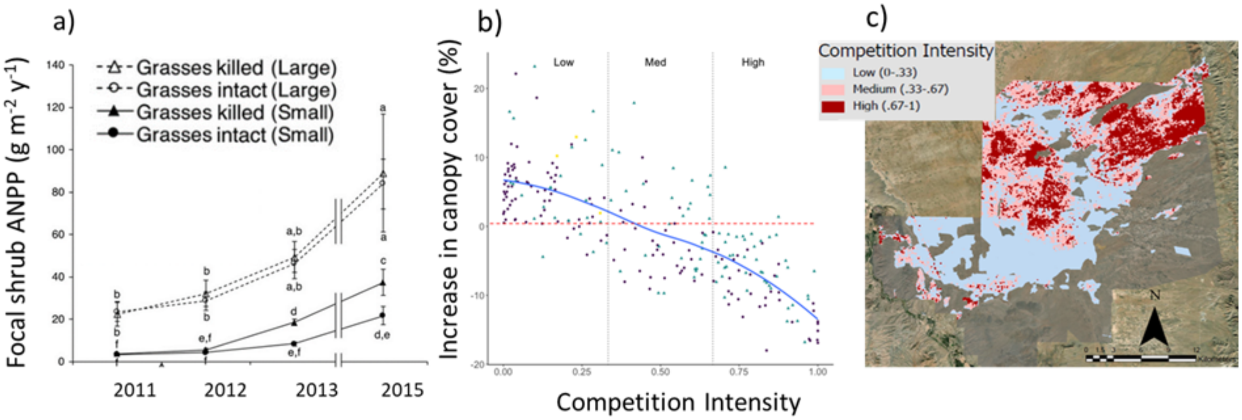

Figure 11. Biotic interactions limiting shrub recruitment and growth at JRN. *(a) shrub seedling growth is reduced in competition with grasses (solid lines), while adult shrub growth is not affected (dotted lines; Pierce et al., 2019), (b) growth in P. glandulosa canopy cover is positive in low density sites, but becomes negative when competition is high (Wojcikiewicz et al., 2024), and (c) at Basin scale, shrub competition is high in some areas, but relatively low in most P. glandulosa-dominated landscapes (Wojcikiewicz et al., 2024).*

Study design: (i) Permanent Inventory Plots (PIP): In JRN-7, we deployed four 70x70 m permanent inventory plots (PIP), adjacent to long-term NPP sites, and representing communities dominated by three shrubs and one grass (*L. tridentata*, *P. glandulosa*, *F. cernua*, and *B. eriopoda*, respectively). We will add 4 additional plots during JRN-8. PIPs are surveyed annually using UAS imagery and structure from motion to derive 3-dimensional mm-scale data for shrub growth/dimensional analysis, and assessment of herbaceous, biocrust, and bare soil cover. Complementary field measurements will provide precise identification and geolocation of individual woody plants, including seedlings, assessments of recruitment and mortality events, and correlation with climate variability. To place short-term shrub growth and survival into long-term perspective, we will analyze historic aerial imagery to quantify long-term recruitment and mortality rates. **(ii) Reciprocal transplants:** We will conduct reciprocal seedling transplants in plots adjacent to the PIP sites. Using seed scarification protocols established in JRN-7 (Toth et al. in prep), we will plant mesquite and creosote seeds and establish seedlings in paired plots (with/without exclosures to test impacts of small mammal & ant granivory/herbivory), with/without initial watering to mimic wet monsoon years and promote initial establishment. Subsequent, cool season measurements (biweekly) will record canopy dimensions, height, and survival. **(iii) QuadCams:** Germination events after rainfall are central to pulse-reserve processes but may go undetected in annual or seasonal field measurements. In JRN-7, we developed an automated approach (QuadCams) using 8 MP digital NIR/RGB cameras (daily frequency, sub-mm resolution) to record vascular plant germination events in imagery suitable for deep-learning identification of seedlings to PFT and, potentially, species. We will deploy QuadCams at the PIPs to quantify this neglected plant demographic process. **Expected outcomes:** Data will enable mechanistic explanations of variability in rates of grassland-shrubland transitions, current shrub dominance, and plant community composition. Demographic rates will provide key inputs to the new dryland model. Reciprocal transplants will provide data on shrub recruitment and mortality processes behind observed spatial patterns in shrub dominance. QuadCams will allow us to quantify vital plant demographic rates at a temporal scale not previously possible in the field. **Cross-site activities:** JRN PIP data will contribute to the network of long-term forest inventory plots from LTER and other sites, allowing JRN to participate as a dryland end-member in analysis of global forest, woodland and shrubland dynamics.

QD2: Are patterns in grass recovery controlled by plant-microbe interactions impacting establishment and survival probabilities? (a new experiment)

Background: Plants develop in a tight relationship with soil microorganisms, with beneficial and antagonistic interactions. There is potential for suppression of plant establishment by non-native ("away") soil microorganisms or facilitation by "home" soil microorganisms (Lekberg et al. 2018, Bardgett and Caruso 2020, Coban et al. 2022). Here, we propose a systematic study of the soil microbiomes associated with *B. eriopoda* grass and *P. glandulosa* shrubs to establish if there is specificity in rhizosphere and bulk soil microbiomes associated with these plants, and test for potential microbiome feedbacks underlying shrub encroachment using controlled microbiome transplants.

Hypotheses. Soil microbiomes and soil-plant interactions determine the probability of grass establishment and may reinforce or dampen state change. We hypothesize that either i) *B. eriopoda* establishment depends on the presence of its home microbiome, ii) the microbiome of *P. glandulosa* inhibits establishment of grasses, or both i) and ii) act in unison. Thus, *B. eriopoda* microbiomes will enhance *B. eriopoda* survival, and/or *P. glandulosa* specific microbes will inhibit *B. eriopoda* establishment.

Study design. We will first define the core microbiome of *B. eriopoda* and *P. glandulosa*, and the extent of variability in those microbial communities in space and between seasons (experiment 1), then conduct microbiome reciprocal transfer experiments (experiment 2; Chase et al. 2021). Standard microbiome analyses for bacteria and fungi using molecular techniques will be used. Measured experimental variables will include germination, establishment, and survival success of *B. eriopoda* from seeds or seedlings, planted in grassland or shrubland states, amended (or not) with microbiome preparation extracted from healthy stands of each plant (Fig. 12). **Expected outcomes.** This research will test the role of plant-microbe interactions in creating establishment bottlenecks, representing a new feedback controlling state change, and that could potentially be manipulated for restoration of grassland states.

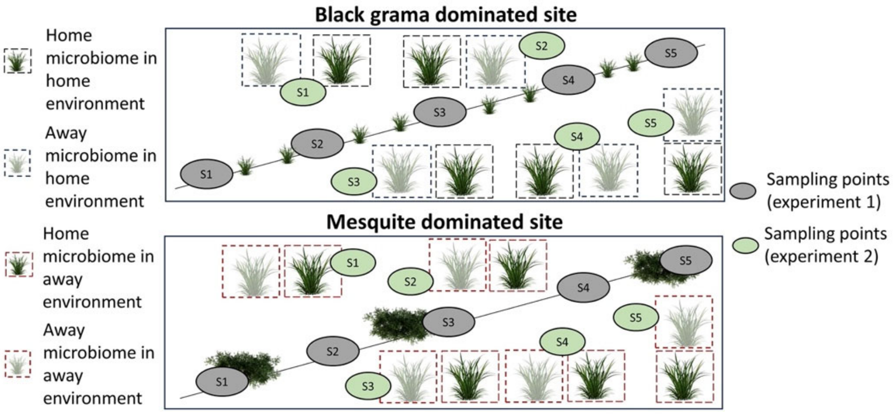

Figure 12. Experimental design for plant-microbe interactions experiment, *to quantify the influence of plant microbiomes on establishment and growth of black grama using reciprocal transplants with home (black grama) and away (mesquite) microbiomes in home and away environments.*

QD3: How do changes in vegetation state impact higher trophic levels, and are there feedbacks on vegetation dynamics that amplify or suppress state changes? (new and long-term observations and experiments)

Background: Consumer populations may respond to productivity pulses mediated by ecological states (Schooley et al. 2018), with feedbacks that reinforce state changes (Bestelmeyer et al. 2007). At JRN, our 25-year *small mammal exclosure study* (SMES) experiment that hierarchically excluded mammalian herbivores showed that perennial grass cover depends on herbivory-climate interactions. During wet periods, small native mammals (rodents and lagomorphs) had stronger effects on grass recovery than domestic and exotic large mammals (Fig. 13; Andreoni et al. in review). Furthermore, lagomorph behavior reflects the "landscape of fear" as they perceive shrubland states to be safer than grasslands (Wagnon et al. 2020). Thermal loading and heat stress may also be reduced for small mammals in shrublands because of increased shading by shrubs, allowing longer foraging periods during the heat of the summer (Kronfeld-Schor and Dayan 2013, Milling et al. 2017, Cunningham et al. 2021). Meanwhile, populations of both desert rodents (Schooley et al. 2018) and lagomorphs (Wagnon 2023) respond most strongly to rainfall pulses in shrubland states. In combination, therefore, herbivore pressure is high in shrublands when conditions for grass establishment are favorable, constituting positive feedbacks that could suppress grass recovery. Other interactions between vegetation state change, consumers, and a broader range of predator-prey interactions are unexplored. Changes in herbivore foraging behavior, altered bat-insect defoliator interactions, and modified biocrust dynamics and soil nutrients associated with small mammal foraging disturbance are likely to exhibit important feedbacks with state change (Eldridge and Whitford 2009, Whitford and Steinberger 2011, Davis et al. 2016).

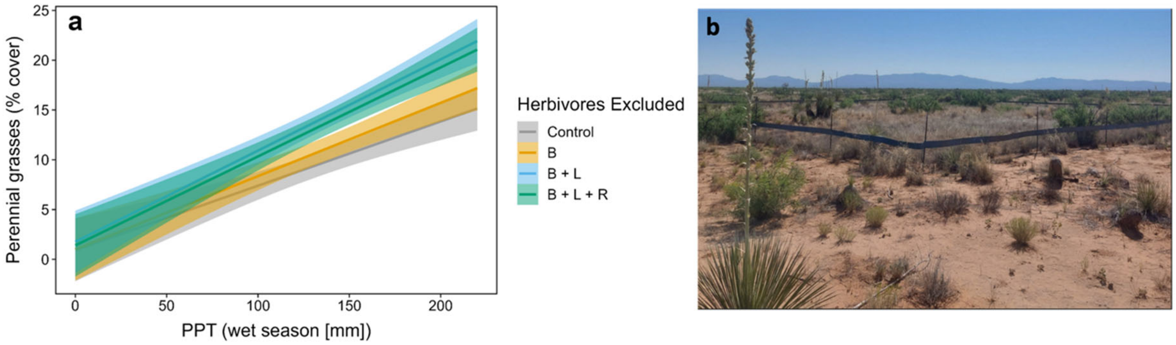

Figure 13. Small herbivores impact grass establishment. *(a) Predictive plots for perennial grasses at the 25-y herbivore exclosure experiment (SMES). Perennial grass cover responded to herbivore-climate interactions with wet season precipitation most strongly affecting grass cover in plots excluding bovids and lagomorphs/rodents (B + L and B + L + R treatments). (b) Example of a plot that excluded all mammal groups showing surrounding area in foreground with open access to all mammalian herbivores.*

Hypotheses: A) Shrub encroachment reduces thermal constraints for lagomorphs by providing shaded foraging microhabitats. Lagomorphs will respond to this altered thermal landscape by increasing activity, thus elevating herbivory pressure in shrubland states. B) Shrub encroachment reduces habitat diversity and potential arthropod species richness and abundance, with cascading impacts on bat species richness, foraging activity, and diet diversity. However, playas are expected to buffer these impacts on bat communities. C) Soil surface disturbances by small mammals produce species-poor biocrusts dominated by early successional cyanobacteria, increasing spatial heterogeneity in soil nutrients, and decreasing favorable sites for grass establishment.

Study design: (i) *Ecotone*: Five spatial blocks in the *Ecotone* study include *B. eriopoda* grassland, grass-shrub mix, and *P. glandulosa* shrubland sites (3 ha each). We monitor canids and lagomorphs annually (July-October) with 2 cameras on each site on all 5 blocks plus at 9 additional sites (24 sites total) to assess abundance and diel activity of predator and prey species and examine how spatio-temporal niches (Kohl et al. 2019) change with shrub encroachment. We will test whether shrub cover extends windows of opportunity for increased herbivory when thermal constraints and predation risk are relaxed. For the insectivore trophic interactions, we will determine bat species richness and foraging activity using acoustic recorders co-located with cameras on the 5 spatial blocks. We will measure connectivity to playa habitats to examine the role of ephemeral water sources on bat activity. By metabarcoding arthropod samples and bat fecal pellets collected during mist net surveys, we will also quantify insect diversity and predation across shrub gradients to infer how bat activity relates to vegetation state, arthropod abundance, and defoliation potential. **(ii) Small Mammal Exclosure Study (SMES):** We established an herbivore exclusion study in 1995 in a *B. eriopoda* grassland being invaded by *P. glandulosa* shrubs, with 4 blocks each receiving three herbivore exclosure treatments and an unfenced control. Treatments exclude only bovids (cattle and exotic oryx, B), bovids and lagomorphs (B + L), or all mammalian herbivores including rodents (B + L + R). We measure plant cover and soil disturbance every 5 years with the next measurement scheduled for 2025. After 25 years, exclusion of all mammalian herbivores resulted in a 3-fold increase in perennial grass cover compared to controls (Fig. 13; Andreoni et al. in review). We will expand this study beyond vascular plant responses by adding assessment of biocrust cover and soil sampling to examine how abundances and spatial heterogeneity of biocrusts and nutrients (nitrogen and phosphorus) respond to herbivore removal. **Expected outcomes:** The set of integrated studies will clarify mechanisms for how shrub encroachment alters trophic interactions and feedbacks to state change. They also will link our long-term studies of consumer dynamics with soil microbial communities and nutrient cycles.

3.4. Numerical Modeling

Background: Dryland ecosystems are characterized by levels of temporal variability (e.g., rainfall and grazing pulses at sub-daily to inter-annual time scales), spatial variability (e.g., varying PFT, biocrust and bare soil cover at patch, landscape and basin scales), and connectivity feedbacks not experienced by most other biomes (Figs. 2-3). Indeed, global drylands are the primary source of uncertainty in atmospheric CO_2 fluxes (Ahlström et al. 2015), fire emissions (Poulter et al. 2015, van der Werf et al. 2017), and future responses to global change (Maestre et al. 2012, Fawcett et al. 2022). However, current generation land surface models (LSM) and dynamic global vegetation models (DGVM) are optimized for more mesic ecosystems and generally not well suited to simulating vegetation, carbon, and nutrient cycles in temporally and spatially heterogeneous drylands (Dahlin et al. 2015, Biederman et al. 2017, Smith et al. 2019, MacBean et al. 2021). JRN-8 will address these issues through a new focus on process-based dryland modeling, informed by our field-based research (Section 3.3) and previous JRN modeling efforts (Peters et al. 2010) and linked directly to the PIRFCT framework (Section 2).

Our modeling emphasis will build on prior development of process-based models describing dryland ecosystem processes, including plant demographic and growth models (e.g., Peters 2002, Tredennick and Hanan 2015), hydrological/biogeochemical models (e.g., Ivanov et al. 2008, Turnbull et al. 2010, Pierini et al. 2014, Schreiner-McGraw et al. 2020), and wind and water connectivity-mediated feedbacks models (e.g., Stewart et al. 2014, Zhang 2020). We will leverage JRN's historical emphasis on landscape connectivity to develop process models that center on spatial interactions, which work at JRN has shown is fundamental to understanding dryland state change. Our goal for these models is to enable simulation of ecosystem state change and its consequences in drylands globally under varying climatic and land use drivers. Our work can then inform development of model parameterizations suitable for regional and global LSM and DGVM models. Our JRN-8 modeling thus represents a plan for the next six years and a vision for how JRN science can be better integrated with the important regional and global scale efforts to understand complex dryland interactions within the Earth System.

(A) Dryland process modeling: The "JRN-Drylands Model," based on Stewart et al. (2014) simulates spatial connectivity (movement of water, water- and wind-borne sediments, nutrients, and propagules) and competitive interactions (within and between shrubs and grasses; Fig. 14). This model is a natural fit with the PIRFCT framework because it already incorporates a) vegetation responses to pulsed rainfall and management, b) aeolian and hydrological transport processes in response to connectivity-mediated spatial interactions, c) simple biogeochemical accounting, and d) predictions of state change. It also provides an excellent foundation for additional model components now considered critical for global drylands and for which we will develop new data in JRN-8 (e.g., biocrust impacts on nutrients and erosion, herbivore-predator feedbacks, plant-microbe interactions, and grass and shrub bottlenecks for establishment). While fire is now rare at JRN, it is a key component in adjacent landscapes and drylands worldwide. Thus, we will implement subroutines for fire connectivity and impacts on vegetation (e.g., Hanan et al. 2008, Beckage et al. 2011), allowing the model to be relevant in drylands where fire is important, including the historical JRN.

(B) Hydrologic connectivity modeling: In JRN-7, we applied the Real-time Integrated Basin Simulator (tRIBS) model to an experimental watershed to determine the relative roles of woody plant encroachment and climate change on subsurface water losses (Schreiner-McGraw et al. 2020). This detailed, physicallybased ecohydrological model provides mechanistic insights on the role of precipitation characteristics, soil and landscape properties, vegetation phenology, and rooting strategies on hydrologic connectivity vertically within the soil and laterally from hillslopes to downstream channel sites. In JRN-8, we will use the model to simulate the hydrologic connectivity from piedmont slope watersheds to stock ponds and ephemeral playas, as an initial step towards landscape-level implementation. We will include additional model processes: (1) prognostic vegetation and root dynamics (Ivanov et al. 2008), (2) multi-layered soils with deep percolation, and (3) soil carbon pools and fluxes (Verduzco et al. 2018) in order to collectively improve the representation of feedbacks between subsurface water storage and shrub persistence and its effect on the watershed carbon budget. Model testing will include novel plant-level phenological and water quality observations at the experimental watershed as well as water level observations at stock ponds and ephemeral playas and remotely-sensed flood imagery from their upstream areas.

(C) Process-inspired machine learning model: We will initiate a new effort to build process-inspired surrogate Machine Learning (ML) models (trained using the JRN-Drylands model) with lower computational demands (compared to the process-based model), thus enabling more ambitious scenario testing. Initial explorations of this approach demonstrate that a neural network model, trained on the process-based model, is able to reproduce the dynamics of the process-model based on climate and management drivers and edaphic context (Fig. 14). During JRN-8, we will refine our ML models in parallel with JRN-Drylands Model development, providing a tool for efficient modeling of dryland processes.

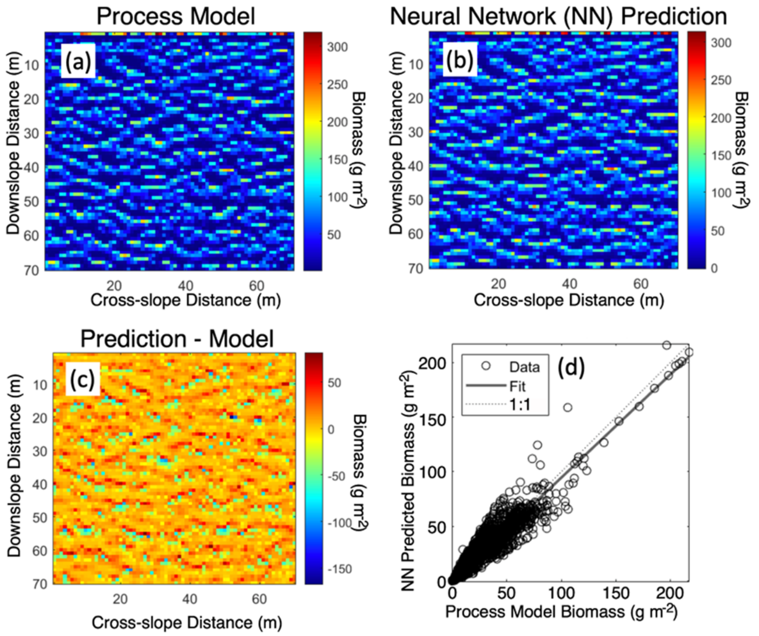

Figure 14: Numerical and machine learning models for L. tridentata shrubs and B. eriopoda grass at the Jornada *using (a) the Stewart et al. (2014) model and (b) a neural network model trained on Stewart et al. (2014) results. Panel (c) shows the difference between the detailed process model in (a) and the ML model in (b), with (d) plotting the comparison between process and ML models.*

Expected outcomes: The JRN-Drylands Model (A) will integrate current and historical JRN insights into a process-based model capable of simulating the feedbacks underlying ecosystem state change (shrub encroachment or grass restoration). Improved ecohydrological modeling (B) will enable exploration of feedbacks between hydraulic conductivity and state change. The tRIBS model will capture the bi-directional feedbacks between hydrologic mechanisms that lead to groundwater recharge and the hydrological processes favoring dominance by woody or herbaceous PFT. The combination of an improved process-based model for drylands, that incorporates the critical effects of spatial connectivity and pulse-responses not well represented in other dryland models, with a process-inspired ML model (C) will allow us to develop model-based experiments and predictive scenarios over much larger domains and longer time-periods than a detailed process-based model would allow. This will provide opportunities to evaluate implications of climate and management at places/times that cannot be investigated in the field at present-day JRN. The enhanced tRIBS application for the piedmont slope will also provide benchmarking hydrological data for the relatively simpler JRN-Drylands Model and derived machine learning model described above.

3.5. Synthesis

Proposed research in JRN-8 is grounded in a new conceptual framework (PIRFCT; Section 2), describing how the effects of weather, long-term climate, and land management pulses are modulated in drylands by the combination of spatial, biogeochemical, and biotic interactions and feedbacks that control growth and survival of different PFT and biocrust communities, thus controlling ecological change (Fig. 2). The PIRFCT framework motivates our planned field based research (Section 3.3, Table 1), with observations and experiments proposed to characterize and quantify mechanisms under four primary research themes (Climate and Land Management, Biogeochemical Interactions, Spatial Interactions, Biotic Interactions). We will then use PIRFCT-relevant process-based and machine learning models to synthesize field data for spatially explicit dryland ecosystem modeling (Section 3.4).

JRN-8 field-based research will traverse spatial scales (Fig. 3), including (i) plot-scale responses of dryland communities to climate change, grazing, and plant-microbe interactions, (ii) landscape-scale differences in nutrient and carbon dynamics, connectivity and herbivore-carnivore / insectivore interactions associated with different vegetation states, and (iii) basin-scale variability in vegetation dynamics, carbon and water fluxes, and shrub demographic processes associated with soil and geomorphological heterogeneity (Fig. 3). JRN-8 research will also traverse temporal scales, from hourly-scale exploration of ecosystem rainfall pulse-responses (e.g., chamber and eddy covariance CO_2 fluxes), to seasonal-scale vegetation, herbivore and predator dynamics, to multi-annual, decadal and centennial-scale analysis of long-term ecosystem changes with varying climate and land use stressors. A new spatially-explicit, process-inspired modeling framework will integrate research results across scales to enable forecasts of state change under different driver scenarios and heterogeneous initial conditions.

The research proposed in JRN-8 will resolve key questions for our overarching goal to identify the mechanisms and consequences of abrupt and persistent state changes in drylands, and advance our ability to model and predict dryland futures under global change. We anticipate that the empirical and theoretical advances in understanding state change in drylands will also provide new insight into the occurrence of abrupt state changes, tipping points, and hysteresis in other ecological systems, marking a significant step towards a broader understanding of alternative stable states and hysteresis in ecosystem ecology.

Section 4: Results from Prior Support

1. Hanan, B. Bestelmeyer, S. Bestelmeyer, Garcia-Pichel, Okin, Pietrasiak, Sala, Schooley, Vivoni
Award: #2025166, **Total:** $6,762,000, **Performance Period:** 12/1/18-11/30/24

Title: "LTER: Long-Term Research at the Jornada Basin (JRN-7)"

Intellectual Merit: The long-term contributions of JRN in the study of drylands and development of key dryland concepts is outlined in Section 2. In the previous grant cycle (JRN-7), we continued to expand our understanding of state transitions in drylands via new studies on the intensifying role of climate change, feedbacks involving biological soil crusts and trophic cascades, the roles of spatial heterogeneity and connectivity at multiple scales, and detailed studies of population and community interactions underlying dryland ecosystem state changes. In the 5 years since December 2018, we have published 116 peer reviewed journal articles in leading ecological journals (see References Cited), including a special collection, *Dynamic Deserts*, in Ecosphere focused on Jornada and southwestern drylands. JRN also made 291 new data packages publicly available through the Environmental Data Initiative repository (EDI; see Supplementary Table A1), and over 330 unique EDI data packages were updated with data from recent field seasons and improved metadata.

Among JRN-7 publications, we have selected 10 papers (below) that represent major advances in (i) our understanding of dryland processes at microbial to regional scale (7 papers), and (ii) notable advances in dryland ecological theory (3 papers). These papers also lay the foundation for the development and testing of the PIRFCT framework within the four thematic areas of JRN-8. They demonstrate the importance of climate (Currier and Sala 2022, Christensen et al. 2023) and land management (Peters et al. 2020) as interacting drivers of ecosystem processes and state change in drylands, and synthesize that knowledge into conceptual models that can be investigated at multiple scales (Bestelmeyer et al. 2018a). They elucidate the role of resource pulses in triggering state change (Schooley et al. 2018, Garcia-Pichel and Sala 2022), and of connectivity and feedbacks at multiple scales during transitions (Peters et al. 2020, Schreiner-McGraw et al. 2020, Payne et al. 2023). They highlight critical biotic interactions, such as competition, predation, and consumer dynamics, and their impact on dryland processes (Schooley et al. 2018, Bethany et al. 2022, Wojcikiewicz et al. 2024). And finally, several of these papers address biogeochemical cycling and the central role of microbial communities (Peters et al. 2020, Garcia-Pichel and Sala 2022, Bethany et al. 2022), helping to frame our expanding research on these topics in JRN-8.

Ten Most Significant Publications of JRN-7

Group (i): Significant site-based results supporting JRN-8 innovations

- Bethany, J., Johnson, S. L. and Garcia-Pichel, F., 2022. High Impact of Bacterial Predation on Cyanobacteria in Soil Biocrusts. *Nature Communications* 13: 4835 (DOI: 10.1038/s41467-022-32427-5).
- Christensen, E. M., James, D. K., Randall, R. M., and Bestelmeyer, B. T., 2023. Abrupt Transitions in a Southwest USA Desert Grassland Related to the Pacific Decadal Oscillation. *Ecology* 104 (7): e4065. (DOI: 10.1002/ecy.4065).
- Currier, C. M., and Sala, O. E., 2022. Precipitation versus Temperature as Phenology Controls in Drylands. *Ecology* 103 (11): e3793. (DOI: 10.1002/ecy.3793).
- Peters, D. P. C., Okin, G. S., Herrick, J. E., Savoy, H. M., Anderson, J. P., Scroggs, S. L. P. and Zhang, J., 2020. Modifying Connectivity to Promote State Change Reversal: The Importance of Geomorphic Context and Plant–Soil Feedbacks. *Ecology* 101 (9): e03069. (DOI: 10.1002/ecy.3069).
- Schooley, R. L., Bestelmeyer, B. T. and Campanella, A., 2018. Shrub Encroachment, Productivity Pulses, and Core-Transient Dynamics of Chihuahuan Desert Rodents. *Ecosphere* 9 (7): e02330. (DOI: 10.1002/ecs2.2330).
- Schreiner-McGraw, A. P., Vivoni, E. R., Ajami, H., Sala, O. E., Throop, H. L. and Peters, D. P. C., 2020. Woody Plant Encroachment Has a Larger Impact than Climate Change on Dryland Water Budgets. *Scientific Reports* 10 (1): 8112. (DOI: 10.1038/s41598-020-65094-x).
- Wojcikiewicz, R., Wenjie, J. and Hanan, N. P., 2024. Quantifying Shrub–Shrub Competition in Drylands Using Aerial Imagery and a Novel Landscape Competition Index. *New Phytologist* 241 (5): 1973–84. (DOI: 10.1111/nph.19505).

Group (ii): Major contributions to dryland theory supporting JRN-8 innovations

- Bestelmeyer, B. T., Peters, D. P. C., Archer, S. R., Browning, D. M., Okin, G. S., Schooley, R. L. and Webb, N. P., 2018. The Grassland–Shrubland Regime Shift in the Southwestern United States: Misconceptions and Their Implications for Management. *BioScience* 68 (9): 678–90. (DOI: 10.1093/biosci/biy065).
- Garcia-Pichel, F. and Sala, O. E., 2022. Expanding the Pulse–Reserve Paradigm to Microorganisms on the Basis of Differential Reserve Management Strategies. *BioScience* 72 (7): 638–50. (DOI: 10.1093/biosci/biac036).
- Payne, S. A. R., Okin, G. S., Bhattachan, A. and Fischella, M. R., 2023. The Two Faces of Janus: Processes Can Be Both Exogenous Forcings and Endogenous Feedbacks with Wind as a Case Study. *Ecology* 104 (4): e3998. (DOI: 10.1002/ecy.3998).

Broader Impacts: Since 2019, JRN has supported 11 successful PhD dissertations, 16 MS theses, and >19 undergraduate research experiences (both formal REU students and investigator-led mentoring). JRN science also forms the basis for the award-winning science education programs of our K-12 education partner, the Asombro Institute for Science Education. Asombro educational programs based on JRN science are aligned with Next Generation Science and Common Core Standards, reaching over 107,000 K-12 students and 4,000 teachers in the last five years, in a region that is largely Hispanic (69%), disadvantaged (74%), and where more than one third of children live in poverty.

2. Romero-Olivares Award: #2312226, **Total**: $467,999, **Performance period**: 7/1/23-6/30/26.
Title: A trait-based approach to determine fungal responses to global change drivers
Intellectual merit: The goals are (i) develop a trait-based approach to determine fungal responses to global change, providing essential knowledge on fungal traits behind climate change responses at the community level, with ecosystem-scale implications, (ii) improve understanding of microbial trait ecology and insight for microbial trait-based approaches in climate change models. No products yet.
Broader impacts: 1) mentoring undergraduate researchers (five minority undergraduate students engaged); 2) mentor graduate students; 3) benefit society and impact science by contributing to the growing body of studies on trait-based microbial ecology.

Section 5: Response to Previous Midterm Review

Our 2022 Midterm Review (MTR) provided feedback that was generally positive regarding our ongoing contributions to dryland and ecological theory. The panel made four recommendations during this review that we immediately addressed and have integrated into this JRN-8 proposal.

Recommendation 1: **Focus collaborative efforts on the development of a predictive model that will move the JRN towards its stated goal of forecasting dryland state transitions.** We viewed Recommendation 1 as an opportunity to renew and expand JRN's focus on dryland modeling, integrating JRN perspectives with those from global drylands under the PIRFCT umbrella to develop an integrated modeling framework with utility and predictive power beyond the confines of JRN. In April 2023, the JRN Drylands Modeling Team met at Arizona State University to develop this framework, building on the Stewart et al. (2014) model and forming the basis for modeling plans described in Section 3.4.

Recommendation 2: **Clearly define what the JRN considers to be its core long-term datasets and make sure those are clearly described and accessible via the website.** To respond to this recommendation, the Information Management Team gathered input from JRN investigators and made changes to the website. The JRN data catalog is extensive and diverse, and therefore not always easy to search. Within a few months of receiving the MTR recommendations, a new facet of the website data catalog was created and populated with a manageable list of "Featured Datasets." This serves to highlight the long-term, high-impact datasets emblematic of JRN's research strengths and history.

Recommendation 3: **JRN should actively work to diversify the team, including cover page PIs, Executive Committee, Investigators/Senior Personnel, students, with emphasis on NMSU faculty recruitment.** We are taking a community building approach to steadily enhance the diversity of the JRN team, including greater representation across gender, career stage and LGBTQ+ identity. In this proposal, JRN has added two cover-page PIs - Dr. Stephanie Bestelmeyer who leads our education and outreach programs and Dr. Sasha Reed to enhance the dryland biogeochemical interactions group. We also diversified the Investigator team by adding three new NMSU investigators (Laverty, Maurer, Romero-Olivares), two of whom are female assistant professors. We also added a new assistant professor at our partner institution UTEP (Mauritz-Tozer), and seven new collaborators (4 women, 3 men) at NMSU and UTEP. The JRN Team includes multiple LGBTQ members. At the same time, we have expanded efforts to recruit a broad range of students and undergraduates into the program, recognizing that recruiting and retaining diverse researchers and students in ecology and STEM subjects requires ongoing efforts. We are building those efforts into our programs. See "Broader Impacts" (Broadening Participation) and Project Management Plan for more details.

Recommendation 4: **Complete a thorough review of JRN field safety policies and work to update policies to reflect current best practices for biological field stations and other field sites.** In response to Recommendation 4, the JRN DEIJ committee drafted the *Jornada Field Safety Manual and Code of Conduct*. This document, developed in coordination with NMSU, the USDA-ARS Jornada Experimental Range, and JRN researchers, contains a range of critical safety and conduct resources for students, staff, and investigators, is available at Jornada field locations and on the JRN website, and has now been field-tested and further refined during two field seasons. More details are provided in the Safe and Inclusive Work Environment Plan attachment to the proposal.

Section 6: Related Research Projects

Complementary infrastructure providing key resources to this research include the field infrastructure provided by the USDA-ARS Jornada Experimental Range (JER) and the NMSU Chihuahuan Desert Rangeland Research Center (CDRRC; see "**Facilities, equipment and other resources' supplement).** JER is the only site in the US to host an LTER, National Ecological Observatory Network, Critical Zone Collaborative Network, and USDA Long-Term Agroecosystem Research (LTAR) Network that together provide a wealth of complementary data. Related research projects supporting this research include an NSF LTREB to Investigator Sala (NSF #1754106; LTREB: Long-term ecosystem responses to directional changes in precipitation amount and variability in an arid grassland), which provides baseline data on how changes in rainfall mean and variability will impact shrub-grass productivity and dominance, and the recent LTAR-funded Duneland Restoration Project (DuRP), which is exploring carbon flux responses to grassland-shrubland and shrubland-grassland state changes. In particular, DuRP has added 3 eddy covariance flux towers to the JRN EC network that will contribute to JRN-8 basin-scale carbon and water flux analysis. In addition, the Meteorological Sensor Array was established on JER by the Army Research Laboratory under a data-sharing cooperative agreement with USDA, contributing an additional five eddy covariance flux towers and 62 precipitation/soil moisture monitoring sites. At the regional scale, the USDA-funded Restore NM project (Investigators Schooley and B. Bestelmeyer) provides a broader perspective across contrasting climates and soil types on the cascading impacts of shrub removal in arid grasslands.

The JRN also participates in numerous regional, national and global networks including (NSF networks in bold): 1) International Biological Program/Grassland Biome (1970-72); 2) World Network of Biosphere Reserves (1976-), 3) **NSF Long Term Ecological Research Network** (1982-); 4) UV-B Monitoring Climatological and Research Network (1994-); 5) U.S. Climate Reference Network (2007-); 6) NRCS Soil Climate Analysis Network (2009-); 7) AmeriFlux (2010-); 8) **National Ecological Observatory Network** (2012-); 9) USA National Phenology Network (2013-); 10) Nutrient Network (NutNet; 2013-); 11) USDA Climate Hubs (Southwest is at JER; 2014-); 12) USDA Long Term Agroecosystem Research Network (2014-); 13) National Wind Erosion Research Network (2015-); 14) Drought Net (2015-); 15 Grazing Exclosure Network (2017-); 16) **Critical Zone Collaborative Network** (2020-); 17) RestoreNet (2020-).

Broader Impacts

JRN's long history has allowed the development of collaborations supporting extensive and effective programs that broaden the impact of JRN science and reach multiple audiences: K-12 students and teachers, undergraduate students, graduate students, the general public, and land managers. For example, our K-12 program is run through a 25-year-old collaboration with the nonprofit Asombro Institute for Science Education. This partnership results in one of the largest K-12 education and outreach programs in the LTER network; in the last five years, these programs reached more than 107,000 K-12 students and 4,000 K-12 teachers, with demand growing each year. In JRN-8, we will continue these collaborations and expand our successful programs, working toward the **five outcomes** detailed below.

Outcome 1: Broadening Participation

JRN is located in Doña Ana County, a southern New Mexico county on the US-Mexico border. The county's population includes groups traditionally underrepresented in STEM; 69% of the population is Hispanic, and 25% of the total population and 36% of children are in poverty. Therefore, JRN has a unique opportunity and responsibility to continue providing programs that broaden participation for underrepresented groups.

Figure 15: *Middle school students collecting data near rainout shelters at Asombro's nature park, which is adjacent to the JRN.*

<u>Broadening Participation through K-12 Student Programs (Fig. 15)</u> – The pipeline for expanding STEM opportunities for underrepresented groups begins with children in the K-12 education system. In particular, K-12 schools are pivotal in STEM literacy, and this is where students make decisions about their future in STEM (Elliott 2015, Sungur Gül et al. 2023). JRN began developing K-12 programs 25 years ago (see Outcome 2 below). We use anonymous teacher evaluations to assess our accomplishments towards two broadening participation goals: (a) increasing K-12 student ecological literacy and excitement about science, and (b) encouraging students to consider science careers by reducing stereotypes about how scientists should look and what they do. Program quality and teacher word-of-mouth recommendations to colleagues have resulted in JRN-Asombro programs that now serve more than 21,000 K-12 students and 800 teachers each year. We target schools serving some of the most underserved students in the region, and the demographics of our K-12 participants reflect our dedication to broadening participation: 80% of K-12 participants are Hispanic, 2% are black, and 70% are economically disadvantaged. Our suite of K-12 programs involves entire classes and sometimes schools, rather than only self-selected students with the resources to sign up for optional science programs, stimulating interest among students who hadn't previously considered science careers. We also focus on broadening participation in all lesson plans, using a Diversity, Equity, and Inclusion screener we developed in 2020. Each lesson must show evidence for nine criteria that honor the languages and cultures of our region while including features to assist English learners and students with disabilities. We shared this screening tool with other LTER Education and Outreach coordinators.

<u>Broadening Participation through Undergraduate Internships</u> – Participating in research increases undergraduate consideration of graduate school and participation in STEM (Hrabowski 2012, Eagan et al. 2013). In JRN-8, we have designed a new undergraduate internship program targeting extended research and mentoring experiences for local (NMSU and UTEP) students, the majority of whom are minority students (Hispanic and Native American) from New Mexico and the borderlands region. Students will be recruited each fall semester for 6-8 month internships (spring and summer), providing extended engagement with research and mentoring (by JRN investigators, collaborators, graduate students), and financial support to make this program possible for low-income students. The intern selection process will emphasize holistic selection criteria that account for factors beyond academic achievement, including non-traditional skills, family background, work and life experience, and community involvement. We budgeted for small equipment and supplies to support student research projects. Additional initiatives to broaden undergraduate participation are outlined in the Safe and Inclusive Fieldwork Plan, including a gear fund to ensure that no student is precluded from field research due to a lack of essential field gear.

<u>Broadening Participation of Graduate Students</u> – Working toward broader participation in STEM by underrepresented groups requires that we train, mentor, and support graduate students from these groups. In JRN-8, we aim to increase the number and diversity of graduate students supported by the project, with support for students from three HSIs: 4 graduate students/y at NMSU (each funded 50% by this grant, and

50% by their mentor), 2-3 graduate students/y at ASU, and one each at UTEP and U. Illinois. In addition, as a tool for recruiting future investigators and leaders for JRN, we will continue our successful Graduate Research Fellowship Program (GRFP) with 4 summer fellowships each year, primarily for students of new JRN investigators and collaborators. JRN promotes a sense of community and inclusivity for graduate students through the summer Desert Ecology Short-Course, featuring field excursions, guest speakers, student talks, posters, professional development, networking, and team-building elements. In the last three years, the short course has attracted 30-60 participants each year from NMSU, UTEP, ASU, UCLA, U. Illinois, and regional universities. Broadening participation is also supported through a unique component of the graduate student fellowship; fellowship recipients assist with JRN K-12 education, including helping with K-12 programs and discussing their research in teacher workshops and at public events. These experiences help graduate students practice science communication with diverse audiences while serving as science role models for the underrepresented K-12 students served by the project.

Broadening Engagement with Native American Communities – In recent years, JRN has increased collaboration with local and regional Native American communities (Piro-Manso-Tiwa community, Santa Ana Pueblo, and Mescalero Apache). These collaborations have included an educator training in spring 2024 and discussions of potential education and research opportunities, recognizing deeply rooted indigenous knowledge of the Chihuahuan Desert and southwestern drylands. Our agenda for this engagement is not predetermined. Instead we will work with existing indigenous collaborators to explore areas of mutual interest, allowing us to listen and learn about indigenous ways of knowing southwestern ecosystems. We include funds in the budget to engage with key partners (recognizing their time and expertise) to explore opportunities for partnerships.

Broadening Participation of Early Career Scientists – JRN-8 greatly expands involvement of early career, diverse *Investigators* (Senior Personnel, with core support for students and research), and *Collaborators* (JRN scientific team members, with access to financial support through graduate fellowships and seed-grants). The expanded team brings new and diverse perspectives on dryland ecology, and a group of early career researchers who are excited to develop dryland ecology research and who show great potential for future leadership of JRN research (see PM Plan). These include NMSU (Garbowski, Laverty, Romero-Olivares) and UTEP (Maurtiz-Tozer, Darrouzet-Nardi, La Rue, Ramirez) Assistant Professors.

Outcome 2: Improved STEM Education and Educator Development

The JRN is located in a state with significant K-12 educational challenges; New Mexico ranked 50th in education in the Annie E. Casey Foundation's 2023 Kids Count Data Book. Therefore, the JRN's K-12 program has tremendous opportunity to improve STEM literacy for a population of mostly underrepresented students. All programs feature (1) direct connection to JRN themes and data, (2) focus on long-term data, (3) alignment with state and national education standards, (4) expansive reach due to leveraged funds, and (5) intentional focus on DEI in the design and delivery of lessons. We evaluate progress toward our goals of increasing student and teacher STEM literacy and excitement about science through anonymous evaluations filled out by teachers.

1) Field trips – K-12 students attend field trips to the JRN and Asombro's adjacent Chihuahuan Desert Nature Park to learn about habitats (K/1st grade), erosion (2nd/3rd grades), using science to protect natural resources (4th/5th grades), and shrub encroachment (6th-8th grades). On teacher evaluations using a scale from 0 (strongly disagree) to 10 (strongly agree), the average scores were 9.8 for increasing students' content knowledge, 9.5 for enhancing their ability to use science practices, and 9.4 for exciting students about science. In JRN-8, activity stations for each field trip will be revised to include updated data and themes (e.g., the role of soil crusts in reducing wind erosion in the 2nd/3rd-grade field trip).

2) Classroom/schoolyard lessons – The JRN K-12 team visits classrooms to guide students in hands-on science lessons. Between 2019 and 2023, we delivered 4,258 one-hour lessons for 97,238 K-12 students, an average of 95 lessons every month of the school year. In anonymous evaluations for the 2022/23 school year, teachers gave an average score of 9.7 out of 10 for the program's ability to increase students' science content knowledge, 9.5 for increasing their practice skills, and 9.5 for exciting their students about science. In JRN-8, we will continue these effective lessons and expand the Schoolyard Field Trip

model developed in 2023. In these two-hour, hands-on schoolyard ecology projects, students collect and analyze data to answer questions in their schoolyards, thus getting the benefits of outdoor learning (Solomonian et al. 2022) with reduced logistical issues (e.g., bus costs, guardian permission slips) that can prevent teachers from taking off-campus field trips.

3) Desert Data Jam – The JRN team conceived the "data jam" in 2012, and it is now used by multiple other LTERs (Bestelmeyer et al. 2018b, Forster et al. 2018). Seventh-grade students choose a JRN dataset, identify a trend, and communicate the trend with creative projects like poems, physical models, videos, and games. Since 2018, 1,067 students have participated, and survey results indicate increased student knowledge and interest in the local environment and confidence working with data. 51% of students said the Data Jam increased their interest in pursuing college studies and/or a career in science. We will continue hosting the Desert Data Jam in JRN-8.

4) One Day in the Desert – JRN's contribution to the LTER children's book series was published in 2017. We incorporated the book in 5th-grade in-person lessons and also created an online lesson module that includes three interactive video lessons with two data interpretation activities. In JRN-8, we will continue to support these lessons.

5) Teacher workshops – JRN hosts five annual teacher workshops on desert ecology and data interpretation, with in-person and video options to enable participation of teachers in remote parts of the state or with family obligations that preclude travel. Half of each workshop involves guest speakers and field trips to increase teachers' content knowledge. The other half includes teacher practice with JRN-created lesson materials. Teachers report significant increases in content knowledge and confidence following JRN workshops. In JRN-8, we will continue delivering five in-person and videoconference workshops per year.

6) Undergraduate internships in education and outreach – These paid internships allow undergraduate STEM students to work with the JRN K-12 team on outreach, inspiring them to engage in STEM education and providing near-peer educational interactions for K-12 students. Undergraduates are recruited and mentored by Asombro staff. They assist in classroom lessons and on field trips, help develop new materials, and create materials for teacher workshops. We pilot-tested the internship in the 2022/23 school year and will expand it in JRN-8 with two interns annually.

Outcome 3: Increased Public Science Literacy and Public Engagement

JRN investigators work toward increased public science literacy and engagement through three projects.

1) Family-friendly public education events: JRN and Asombro collaborate to host several family-friendly public education programs each year at Asombro's nature park, located just south of the JRN research sites. Programs include guided hikes and hands-on activity stations to engage the general public in JRN research, data, and discoveries. We will host an average of three events each year throughout JRN-8.

2) Jornada Symposium: The annual Jornada Symposium, organized in collaboration with the USDA-ARS, draws over 100 participants/y from research, agency, tribal, and ranching communities as well as local congressional staffers. The Symposium integrates research from various programs and networks, providing opportunities to link JRN ecosystem science with programs emphasizing, for example, sustainable livestock production, vegetation and soil management, wildlife conservation, and climate adaptation. In JRN-8, we will continue this popular annual event.

3) Interpretive signs and public art: Asombro's nature park is open to the public, free of charge, six days per week. The site features interpretive signs about JRN research, including rainfall manipulation experiments, and public art displays like the Desert Ecology and Ecología del Desierto murals that are used during student field trips and public education events to highlight JRN research.

Outcome 4: Increased Partnerships Between Academia, Industry, and Others

JRN, in cooperation with USDA-ARS and other NMSU programs, supports regional and global efforts to monitor and manage ecosystem change in drylands. JRN-USDA's cooperation in developing rangeland monitoring methods and interpretive tools underpins standard protocols adopted by the Bureau of Land

Management (BLM), USDA Natural Resources Conservation Service (NRCS), other agencies, NGOs, and international partners, such as the Mongolian government (Dashbal et al. 2023). Widespread adoption has resulted in a massive and growing dataset across US rangelands (over 85,000 field locations) available in a new tool, the Landscape Data Commons (McCord et al. 2023) that has been used in collaboration with NRCS and BLM to develop satellite-based, continuous fractional vegetation cover products across the rangelands of the entire US and to identify broad-scale state change (Jones et al. 2018, Allred et al. 2021). Most notably, JRN has contributed to the development of publicly available data on land cover and vegetation structure through the Rangeland Analysis Platform (RAP) and the Landscape Cover and Analysis Reporting Tool (LandCART), both of which are managed by JRN PIs and collaborators constituting an important component of JRN outreach to public and private land managers. Furthermore, the Land Potential Knowledge System (LandPKS) mobile application, based on concepts developed by JRN-USDA, enables data collection on agroecosystems worldwide using a simplified system (Quandt et al. 2020). These tools are interpreted with respect to vegetation state and transition models, implemented by NRCS based on JRN's frameworks (Bestelmeyer et al. 2017). Ground and remotely-sensed monitoring data, in turn, are being used by agencies and ranching groups (e.g., Malpai Borderlands Group) with JRN guidance to implement management based on an understanding of the spatio-temporal heterogeneity in state transitions (Bestelmeyer et al. 2021).

Data collected in JRN-8 will contribute to additional datasets, such as the North American Bat Monitoring Program (NABat), dedicated to understanding the status and population trends of North America's bats. Given bat biodiversity peaks within the United States in the arid Southwest (Morgan et al. 2019), data from the JRN may provide insights on broader community-level trends that may be harder to document in less speciose environments.

JRN also collaborates with BLM in the Restore New Mexico Collaborative Monitoring Program, where we are testing the effects of shrub removal on grassland restoration and biodiversity responses across 2.4 million ha of public lands (Bestelmeyer et al. 2019, Schooley et al. 2021), and helping managers predict how changes in climate, grazing, and shrub removal resist or direct vegetation state change. Current efforts are directed at understanding how bird and lizard communities are affected by landscape mosaics created by extensive but patchy restoration efforts. These applied regional studies are extensions of the fundamental research of the JRN, including its work on grass-shrub transitions and the role of multi-scale connectivity.

Outcome 5: Facilitating Advances in Earth System Models used for International Decision Making about Climate Change

Earth system models (ESMs) and the dynamic global vegetation models (DGVMs) that form their land component are critical tools for national and international decisions about anthropogenic responses to climate change. For example, these models are foundational to the scenarios and decisions considered by the Intergovernmental Panel on Climate Change (IPCC; 2023) and for U.S. national policy priorities and reports, such as the National Climate Assessment (USGCRP 2023). However, many studies show that the model representation of drylands and their contribution to carbon cycling and climate change is particularly poor (Hartley et al. 2017, Renwick et al. 2019, MacBean et al. 2021). The modeling community has made clear they need improved quantitative understanding and datasets of dryland processes and responses to change, with long-term data representing a particularly valuable resource to parameterize and validate models and inform DGVM representation of critical dryland processes (MacBean et al. 2022). Due to the societal use of modeling tools for prediction and to inform decision-making, the JRN-8 contribution of data and modeling that can directly inform ESMs can have a societal impact through its utility to modelers and the myriad users of model outputs.

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