

Timetable with Yearly Goals and Deliverables

Table 10. Project Management Schedule. Project Description Sections are in purple.																		
Semester: Year:	Fa 17	Sp 18	Sm 18	Fa 18	Sp 19	Sm 19	Fa 19	Sp 20	Sm 20	Fa 20	Sp 21	Sm 21	Fa 21	Sp 22	Sm 22	Fa 22	Sp 23	Sm 23
RESEARCH DESIGN																		
8.1. Piñon-Juniper Baseline - Legacy Data (Fig. 3: a)																		
Analyses	X	X	X	X	X	X	X											
8.2. Die-off and Extreme Wildfire Climate Soil Moisture Conditions - Legacy Data (Fig. 3: b & g)																		
Analyses	X	X	X	X	X	X	X											
8.3. Post-disturbance Initial Divergences - Trajectories Tracking (Fig. 3: c vs. c' & h vs. h')																		
Installations		X	X	X	*	*												
Field Data Collection			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Analyses				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
8.4. Post-die-off Piñon Re-establishment - Field & Controlled Climate Experiments (Fig. 3: c vs. c')																		
Piñon field expt				X	X	X	X	X	X	X	X	X	X	X	X			
Piñon chamber expt							X	X	X	X								
8.5. Post-extreme Wildfire: Shrubs vs. Invasive Grass – Field & Chamber Expts. (Fig. 3: h vs. h')																		
Shrub chamber expt												X	X	X	X	X		
Grass field expt									X	X	X	X	X	X	X	X		
Grass chamber expt									X	X	X	X	X					
8.6. Additional Tree Die-off under Hotter Drought - Leveraged Experiment (Fig. 3: d vs. d'; e vs. e')																		
Complete expt	X	*	*	*	*	*												
8.7. Post-disturbance Dynamics – Projections Modeling (Fig. 3: all, including f vs. f' and i vs. i')																		
Develop SHIFT							X	X	X									
Link to Core Areas									X	X	X							
Apply and refine											X	X	X	X	X	X	X	X
8.8 Syntheses across Sites and Systems																		
Scaling up #		1	1	1	1	1							1	1	1	2	2	2
Cross systems #				1	1	1	2	2	2	3	3	3	4	4	4	5	5	5
INFORMATION MANAGEMENT																		
Add Legacy data		X	X	X	X													
Web Site & Storage	X	X	X	X	X	X	X	*	*	X	*	*	X	*	*	X	*	X
Data Management		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
BROADER IMPACTS																		
9.1 Education	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9.2 Partnership			X	*	X	X	*	X	X	*	X	X	*	X	X	*	X	X
9.3 Co-Production	X	X	X	*	X	X	*	X	X	*	X	X	*	X	X	*	X	X
9.4 Public Access			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Publications			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Meetings		S	A		S	A		S	A		S	A		S	A		S	A
Sp = Spring; Sm = Summer; Fa = Fall; expt = experiment; * = as needed; # = corresponds to 8.8 subsection #; S = All PJP Team Site Meeting; A = All LTER Meeting or Cross-LTER Collaboration Meeting.																		

PROJECT SUMMARY

ILTER: Pajarito Plateau Semiarid Woodland (PJP) – Ecological Trajectories following Hotter-Drought-Driven Tree Die-off and Extreme Wildfire

Univ. Arizona with USGS, NPS, LANL, Columbia, UW, UCSB, UID, UNM & UAntioquia

Overview

Global change disturbances driven by drought under ever hotter conditions are increasingly triggering widespread plant die-offs and extreme wildfires in piñon-juniper woodlands of the western US and in semiarid systems globally. These transformations are iconic of climate change consequences for arid and semiarid ecosystems worldwide. The biggest opportunity for the LTER Program to simultaneously advance ecological science and societal relevance regarding climate change is to consider ecosystems already undergoing the most rapid, disturbance-triggered transformations—those of sufficient magnitude and geographic extent as to be of imminent concern to both the public and land managers.

The importance of how extreme climate events translate into ecological impacts and how novel climate conditions can lead to novel ecological responses is increasingly recognized, but the ability to predict both state change and novel trajectories under climate change and associated extreme events remains poor. Moreover the mechanisms that stabilize or amplify the effects of extreme event perturbations remain a major science frontier in an era of climate change. Thus, there is a critical need to build on recent conceptual frameworks that consider the ecological consequences of extreme events and the potential for novel ecological trajectories. Emphasis should be on ascertaining the nature of underlying mechanisms that determine ecological trajectories, while also accounting for legacy effects, current ecological conditions, and protracted climate conditions [i.e., decadal-to-multidecadal variability] that constrain potential ecological responses. Although all LTER sites consider “disturbance patterns” as one of the five core areas for long-term data and research, the proposed Pajarito Plateau (PJP) LTER would be the first to target, from the onset, an ecosystem undergoing rapid, climate-driven transformation.

Intellectual Merit

The PJP LTER would explicitly focus on rapid, pronounced, and extensive disturbances directly tied to climate that have potential to trigger transformational state changes and novel trajectories of pronounced public concern and impact. The PJP LTER long-term goal is to advance integrated assessment of extreme events, state change, novel trajectories—and the stabilizing and amplifying feedbacks that drive them—to improve understanding, prediction, and management of arid and semiarid ecosystems in the face of global change. The PJP LTER overall objective is to use semiarid woodlands as a model for systems undergoing rapid climate-driven transformation exemplified by hotter-drought driven plant die-off and extreme wildfire. The central hypothesis is that amplifying feedbacks associated with plant–biocrust–brown-food-web–soil feedbacks in the near soil-surface sliver mediate disturbance-initiated state change and novel trajectories in rapidly transforming ecosystems (the specifics of which must account for timing of unfavorable climate and punctuated extreme events—hotter droughts in this case). This hypothesis will be evaluated through a combination of extensive legacy data, new field time-series measurements and experiments, modeling, and scaling and cross-site synthesis activities.

Broader Impacts

The Broader Impacts leverage the PJP LTER location, particularly the proximity to Native Pueblos and federal lands, to provide significant societal benefits. The proposed approach recognizes that changes in personal and societal values necessary to meet the challenges of climate change cannot be addressed by science alone. This proposal addresses four Broader Impacts goals: i) provide a strong education pipeline for Native students; ii) nurture a strong Native community-researcher partnership model; iii) encourage knowledge transfer between scientists, land managers, and local communities; and iv) provide public access to the PJP LTER work through the arts, humanities, and social media. The expected outcomes for Broader Impacts include a fostered vibrant education and engagement program that affect the education pipeline, co-produces knowledge (rather than the typical one-way transfer of information via outreach), and reaches broad national and international audiences regarding our results.

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

PROJECT DESCRIPTION

LTER: Pajarito Plateau Semiarid Woodland (PJP)

- Ecological Trajectories Following Hotter-Drought–Driven Tree Die-off and Extreme Wildfire

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Organizational Abbreviations

BNM: Bandelier National Monument. **CCASS:** Center for Climate Adaptation Science and Solutions. **Columbia:** Columbia Univ. **CZO:** Critical Zone Observatory. **LANL:** Los Alamos National Laboratory. **NEON:** National Ecological Observatory Network. **NPS:** National Park Service. **UAntioquia:** Univ. Antioquia (Medellin, Colombia). **UCSB:** Univ. California Santa Barbara. **UI:** Univ. Idaho. **UNM:** Univ. New Mexico. **UW:** Univ. Washington. **USGS:** U.S. Geological Survey. **US NPN:** U.S. National Phenology Network.

Note: Citations with an asterisk (*) denote publications co-authored by PJP LTER Team members.

1. Overview

Global change disturbances driven by drought under increasingly hotter conditions are triggering plant die-offs and extreme wildfires in piñon-juniper woodlands of the western US, emblematic of climate change impacts on arid and semiarid ecosystems worldwide (IPCC 2014*). Disturbances, such as these, are abrupt, regionally extensive, and globally distributed—and they can trigger state changes and initiate novel trajectories. The outcomes are profoundly, immediately, and societally relevant, and pose daunting management challenges (Millar & Stephanson 2015). ***An emerging opportunity for the LTER Program, in which to simultaneously advance ecological science and societal relevance regarding climate change, is to evaluate ecosystems already undergoing the most rapid, disturbance-triggered transformations—those of sufficient magnitude and geographic extent as to be of imminent concern to the public as well as to ecologists and land managers.*** The tree die-off events and extreme wildfires in western US epitomize this target of opportunity for the LTER Program.

Conceptual frameworks in ecology have progressed from *i)* assessing how ecosystems vary in response to climate variation within a range of nominal conditions, to *ii)* incorporating periodic disturbances, to *iii)* considering multiple alternate stable states and rangelands state-and-transition models (e.g., Law & Morton 1993, Beisner *et al.* 2003, Suding *et al.* 2004, Briske *et al.* 2005). Now, the importance of how extreme climate events translate into ecological impacts (Smith 2011) and how novel climate conditions can lead to novel ecological responses (Williams & Jackson 2007*, Hobbs *et al.* 2009) is increasingly recognized (IPCC 2012, 2014*), but the ability to predict both state change and novel trajectories under climate change and associated extreme events remains poor. Moreover the mechanisms that stabilize or amplify the effects of extreme event perturbations remain a major science frontier in an era of climate change. *Thus, there is a critical need to build on recent conceptual frameworks that consider the ecological consequences of extreme events (e.g., Smith 2011) and the potential for novel ecological trajectories. Emphasis should be on ascertaining the nature of underlying mechanisms that determine ecological trajectories, while also accounting for legacy effects, current ecological conditions, and protracted climate conditions [i.e., decadal-to-multidecadal variability] that constrain potential ecological responses.* Although all LTER sites consider “disturbance patterns” as one of the five core areas for long-term data and research, the proposed Pajarito Plateau (PJP) LTER would be the first to target, from the onset, an ecosystem undergoing rapid, climate-driven transformation.

Our long-term goal is to advance integrated assessment of extreme events, state changes, novel trajectories—and the stabilizing and amplifying feedbacks that drive them—to improve understanding, prediction, and management of arid and semiarid ecosystems in the face of global change. Our overall objective is to use semiarid woodlands as a model for systems undergoing rapid climate-driven transformation exemplified by hotter-drought driven plant die-off and extreme wildfire. Our central hypothesis is that ***amplifying feedbacks associated with plant–biocrust–brown-food-web–soil feedbacks in the near soil-surface sliver mediate disturbance-initiated state change and novel trajectories in rapidly transforming ecosystems*** (the specifics of which must account for the timing of favorable or unfavorable climate and punctuated extreme events—hotter droughts in this case).

Our rationale is that the refinement and integration of conceptual frameworks on extreme events and mechanisms driving state changes and novel ecological trajectories under climate change *i)* will help address unprecedented land management challenges for one of the most extensive vegetation types in the US (piñon-juniper woodlands; Huang *et al.* 2009), and *ii)* will provide a prototype to assess and mitigate impacts in other arid and semiarid ecosystems undergoing rapid transformation driven mostly by climate change. Focusing on a site that is already undergoing major transformation, and for which there are extensive relevant data already available (published and unpublished) that quantify an array of pre-disturbance conditions, is critical for addressing our overall objective.

Our research team (Tables 3 & 4) collectively has >100 person-years of research experience in our site on the Pajarito Plateau, has generated more than 35 papers with >100 citations each that together total >13,000 citations (Google Scholar), has integrated results into the most recent national and international assessments (NAC 2014*, IPCC 2014*), and has garnered extensive media coverage. Our team expertise is critical to the success of the proposed PJP LTER: it includes *i)* transformational hotter-drought research on tree die-off (e.g., Breshears *et al.* 2005*) and wildfire (e.g. Williams *et al.* 2013*); *ii)* observational data sets spanning > 25 years; *iii)* 15 years’ prior LTER experience (Co-PI Monson); *iv)* expertise in all five LTER core areas; *v)* a demonstrated record of operating a long-term study site from a

remote campus (Jemez Mountains CZO by Univ. of Arizona); and *vi*) a compelling track record of broader impacts reaching underrepresented groups with novel engagement approaches

As a result, we have developed a conceptual framework applicable not just to PJP, but also to other comparable ecosystems. Recognizing the limitations of what can realistically be accomplished during the first cycle of LTER funding, we will focus on critical splits in ecological trajectories likely to occur during initiation of PJP LTER: a *post die-off* split between whether or not piñons re-establish after die-off, and a *post-extreme-wildfire* split between whether resprouting shrubs or invasive grasses will become dominant. For these two critical splits, we apply time-series measurements at contrasting sites, field experiments and chamber experiments. We test hypotheses in one or more ways for each trajectory segment of our conceptual model using a suite of approaches ranging from analysis of legacy data sets to field and controlled experiments to cross-site syntheses of data from other forest ecosystems. We couple our intellectual goals with a carefully integrated set of strategies for **Broader Impacts** to leverage the PJP LTER location, particularly its proximity to Native nations and federal lands, and emphasize linkages to Native American communities. The PJP LTER will have an innovative focus on fostering the educational pipeline, building strong community-researcher partnerships producing two-way knowledge development.

Increasingly, managers of protected and other natural areas are faced with novel ecological change and conditions and conflicting objectives to preserve the past while fostering resilience for an uncertain future. Historically, management of protected areas (and to a large degree most LTER sites) has been predicated on the assumption that ecosystems develop predictably along a single successional pathway. Confronted with the specter of having to manage novel ecosystem change under their stewardship, protected-area managers will have to consider the influence of external ecological phenomena and trends, relying on a better and evolving understanding of the local dynamics and history of novel ecosystem development. The costs and technical knowledge required to manage a moving and uncertain target will often exceed capacity, necessitating either a change in objectives away from historical fidelity, or a much more focused management strategy that utilizes triage, prioritization, and constant monitoring and updating to guide highly targeted actions ([Powell et al. 2013*](#)). Managers also will need to rely on an unprecedented degree of coordination across other protected areas in the region. Numerous national parks, reserves, monuments, and forests in the western and southwestern US encompass piñon-juniper woodlands, ranging from south-central Idaho to west Texas. In a fast-changing world, the PJP LTER aims to be the trailblazer for research and management of this region's protected areas.

Our expected outcomes of an initial cycle of LTER funding for PJP include observational, experimental, and educational outcomes that link to LTER Core Areas 1-4, including characterization of key ecological drivers that determine post-disturbance trajectories of semiarid ecosystems and creation of a vibrant education and engagement program that reaches broad audiences of regional stakeholders and widespread classrooms. We expect to evaluate, in a variety of ways, our overarching hypothesis on the role of abiotic-biotic stabilizing and amplifying feedbacks in differentiating ecosystem recovery, state change, and novel trajectories. Additionally, we will develop widely accessible PJP data sets through transfer of PJP legacy data sets that are locally available and via new data sets to LTER portals. The PJP LTER would explicitly focus on rapid, pronounced, and extensive disturbances directly tied to climate that have potential to trigger transformational state changes and novel trajectories of pronounced public concern and impact. Therefore, we believe PJP provides the best opportunity for the LTER Program to advance ecological science and societal relevance under the duress of climate change.

2. Expanded Grand Vision for LTER

During the last few decades, longer and hotter growing seasons, exacerbated by severe drought, are synchronizing wildfires, pine-beetle outbreaks, and tree die-offs over large areas of western North America. Given the prospects for further warming and drying, successional trajectories are mostly conjectural in the evolving climatic and ecological space. The mutual challenge for science and management is to predict ecological change and prescribe near- and long-term management actions calling for strategic monitoring, opportunistic and timely experiments, and unprecedented coordination between researchers and resource managers. While we aim to add a critical arid-semiarid site to the LTER Network, we also will build upon the LTER Program's accomplishments to date to promote an expanded grand vision for LTERs, given the growing demand of "*climate change, land use, fire and shifting biotic interactions*" (NSF 16-509). We identify key ways in which LTER guiding principles ([LTER Network 2015](#))

can be expanded to more directly address the pressing demands of ecological change in the 21st century (**Table 1**). For semiarid woodland and forested ecosystems (with relevance to many other ecosystems as well), without rapid greenhouse gas emissions reductions, we may be entering a “last favorable window” in which the LTER Program could advance understanding that can be applied to better address a looming “protracted unfavorable” set of climatological drivers impacting ecosystems.

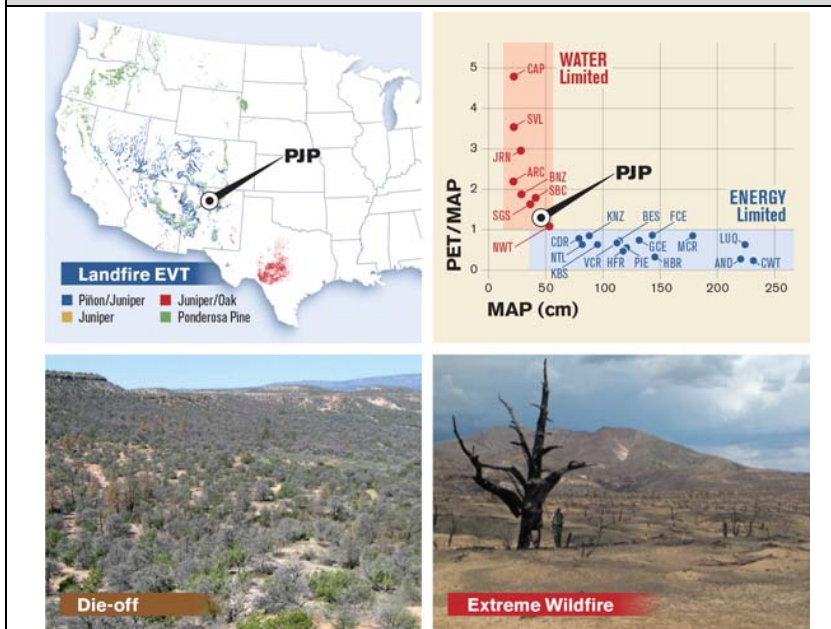
Table 1. How PJP will contribute to expanding LTER guiding principles (LTER Network 2015).

1. Understanding: <i>To understand an array of ecosystems at multiple spatial and temporal scales</i> LTER can build on strengths (e.g., primary productivity) and increased focus on population dynamics and food webs to explicitly account for how those relationships will respond to extreme climate events. Additionally, population-through-ecosystem responses can more fully embrace trait-based community ecology and the complexities and knowledge frontiers associated with soil microbial dynamics. We advocate that “plant-soil feedbacks” need to consider more explicitly both stabilizing and amplifying “plant–biocrust–brown-food-web–soils” complexes and their responses to extreme climatic events. And while there has been progress on thresholds, there is little LTER progress that specifically enables ongoing prediction of rapid extreme event changes that force management strategies to confront acute ecological change and address the “death of stationarity” (Milly <i>et al.</i> 2008) in an ecological context.
2. Synthesis: <i>To create general knowledge through long-term, interdisciplinary research, synthesis of information, and development of theory</i> We advocate building on approaches that complement long-term data collection and field experiments, but with less emphasis on studies that fit only into a traditional experimental, hypothesis-driven framework and more emphasis on methods to advance science sufficiently and promptly so as to be useful relative to rapid changes underway. This includes additional emphasis on off-site controlled climate experiments, more development of predictive tools drawing on empirical data, more cross-site syntheses, more use of large digital data sets (e.g. LiDAR) to conduct model simulations, and a focus on models specifically for abrupt transformative changes.
3. Information: <i>To inform the LTER and broader scientific community by creating well-designed and well-documented databases</i> LTER can extend broad-scale data management and integration across other networks, including NEON and CZO. We will help lead in developing virtual simulations whereby high-resolution digital-elevation models of topography are integrated with details of ecosystem structure enabling unparalleled responses in user-friendly formats for management and public outreach.
4. Legacies: <i>To create a legacy of well-designed and well-documented long-term observations, experiments, and archives of samples and specimens for future generations</i> We envision a key leadership role in developing data legacies through increased synergies to build on the substantial data management practices LTER has developed to date; create emergent data management opportunities with NEON, and leverage synergies with leadership in data management through the CZO Network.
5. Education: <i>To promote training, teaching, and learning about long-term ecological research and the Earth’s ecosystems, and to educate a new generation of scientists</i> We think LTER can dig even deeper to reach underrepresented groups, making needed investments to do so. We will work closely with regional Native American communities and develop novel education venues and program assessment tools. Also, we seek to work with other programs to transform the ethnic diversity of land managers through creation of a new K-12 career pipeline.
6. Outreach: <i>To connect with the broader scientific community, natural resource managers, policymakers, and the general public by providing decision support, information, recommendations, and the knowledge and capability to address complex environmental challenges</i> We seek expansion beyond “outreach,” implying one directional knowledge transfer, to engagement in “co-production” of knowledge between scientists and stakeholders. We seek to be the “go to” program for participatory production of knowledge and approaches to semiarid land management.

3. Biome Domain and Climate Space

PJP represents semiarid woodland dominated pre-die-off by piñon and juniper species (primarily represented at PJP by *Pinus edulis* and *Juniperus monosperma*) and associated herbaceous species (predominantly *Bouteloua gracilis* at PJP). Semiarid piñon-juniper woodland (**Fig. 1 upper left**) spans ~20 million ha (Gottfried *et al.* 1995*, Romme *et al.* 2009*), not counting juniper-oak. The upper ecotones merge with ponderosa pine forest, which covers an additional 16 million ha (Arno *et al.* 1995). PJP receives approximately 400 mm of mean annual precipitation (MAP), split roughly evenly between winter snow-dominated and summer rain-dominated periods; mean annual temperature is approximately 9°C. Within the context of the LTER Network, PJP represents an important inflection point at the intersection between water-limited ecosystems (where potential evapotranspiration, PET/MAP >1.0) vs. energy-limited ecosystems (where PET/MAP <1.0; **Fig. 1 upper right**; Jones *et al.* 2012). Numerous PJP long-term data sets, several spanning >25 years, are available, along with high-resolution mapping of local geology, soils, and vegetation. These woodlands are experiencing two major types of large-scale disturbance associated with hotter drought: tree die-off driven directly by drought and/or in association with pests and pathogens (**Fig. 1 lower left**) and extreme wildfire that consumes nearly all above-ground biomass (**Fig. 1 lower right**).

Fig 1. Upper left: Domain of the piñon-juniper semiarid woodland biome and associated juniper and ponderosa pine systems (data: Landfire EVT). Upper right: The climate domain of the PJP site plotted as Potential Evapotranspiration (PET) / Mean Annual Precipitation (MAP) vs. MAP; highlighting it as in inflection point between water- and energy-limited ecosystems (modified Jones *et al.* 2012, lists LTER sites). Lower left: Tree die-off in piñon-juniper semiarid woodland, with dead grey trees still standing (most trees fall within three years). Lower right: Extreme wildfire in piñon-juniper semiarid woodland, with nearly all above-ground biomass consumed.



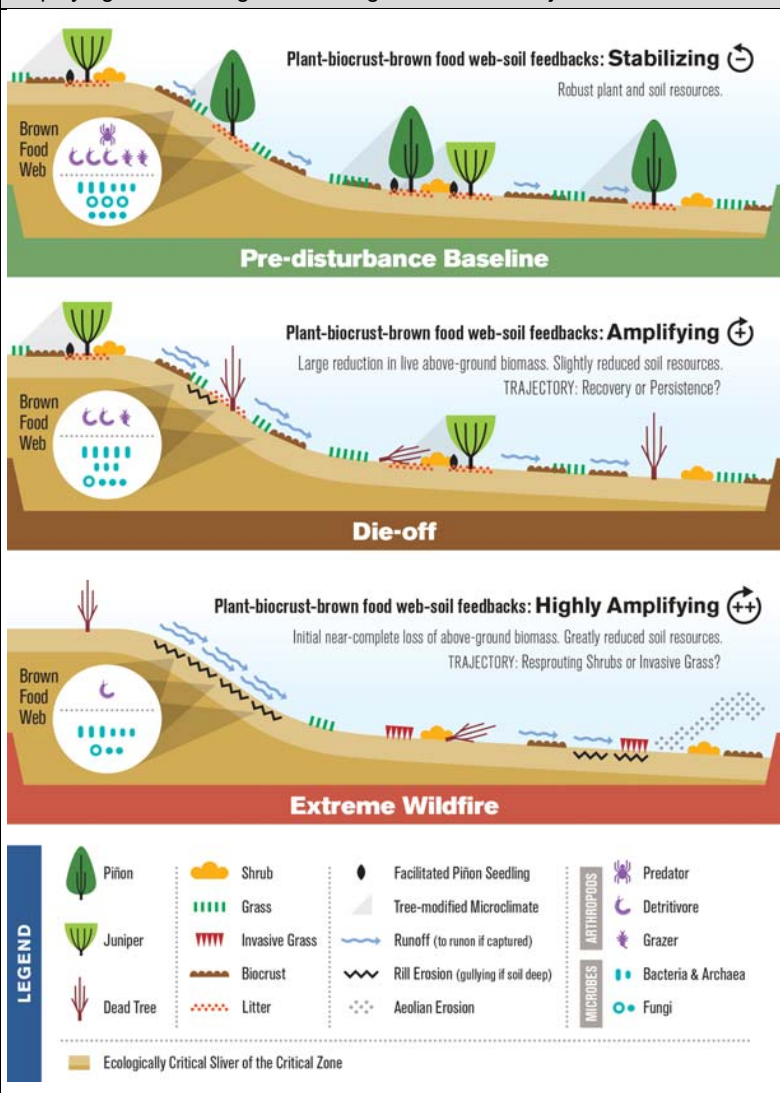
4. Intellectual Merit: Conceptual Framework

Existing conceptual frameworks in ecology in general and LTER in particular have progressed from i) focused on assessing how ecosystems vary in response to climate variation within a range of nominal conditions, to ii) inclusion of periodically considering disturbances, to iii) considering multiple alternate stable states and, within the rangelands literature, similar state and transition models. However, the critical challenge that has not yet been addressed is of the forces of change that will occur at the nexus of extreme events and their potential to drive novel ecological trajectories. Current ecological theory has poor predictive capability to address abrupt ecosystem transformation. Such predictive capability will be inherently site- and time-dependent, based on ecosystem characteristics and disturbance event type and characteristics, posing challenges for broad generalization. Yet, the LTER Program can hardly afford to overlook such large-scale and broad transformations (as those underway for semiarid woodlands and forests) as a critical testbed for advancing theory on ecosystem change in response to extreme events. The conceptual framework proposed by Smith (2011) draws on prior ecological literature in related areas such as alternate ecological states and state and transition models (e.g., Briske *et al.* 2005, Bowman *et al.* 2015). To advance this framework, we propose that it should be expanded to explicitly include the concept of novel ecosystem trajectory conditions as described by Williams & Jackson (2007*) and that it

include specifics about the mechanisms that differentiate ecological trajectories between recovery, a state change, or to novel ecosystems. Building on related concepts (e.g., [Scheffer et al. 2001](#), [Connell & Ghedini 2015](#), [Ryer et al. 2015](#)), we propose that **the primary mechanism that differentiates between ecological trajectories is the nature of biotic and abiotic feedbacks**: when these feedbacks are negative, they provide a stabilizing force that prevents post-disturbance state change or novel trajectories from occurring; when these feedbacks are positive, they enable amplifications of change that enable state change, and under novel climate and associated extreme events such as hotter drought, even novel ecological trajectories. Although these concepts exist separately in the literature, they have not been sufficiently integrated to test their robustness relative to changing climate and extreme events.

For semiarid ecosystems, especially in a post-disturbance context, the key biotic-abiotic feedbacks occur in a shallow section of the soil: the interface between plants, *biocrusts* (biological soil crusts), and the *brown food web* (soil biota, including bacteria, archaea and fungi components of the microbial community and key functional groups of arthropods [e.g., grazers, detritivores, predators]; [Fig. 2](#)). This very thin zone can be viewed as *the ecologically critical sliver* of the “critical zone” (tree canopy to groundwater), where the key action occurs in semiarid ecosystems following disturbances such as die-off and extreme wildfire. The response of biotic-abiotic interactions also has an important geomorphic context, in which small variations in topography influence such processes as redistribution of runoff water as re-concentrated water flow to other locations, or determinations of soil microbial locations of differential enzyme activity related to C, N, and P. Leaching is limited primarily to the critical sliver. Erosion, as driven by both water and by wind, is also a key part of these systems. To test our central hypothesis that *amplifying feedbacks associated with plant–biocrust–brown-food-web–soil feedbacks in the “near soil-surface sliver” mediate disturbance-initiated state change and novel trajectories in rapidly transforming ecosystems (influenced by the timing of favorable/unfavorable climate conditions and punctuated by extreme events)*, we propose a conceptual framework for semiarid woodlands undergoing transformation by die-off and extreme wildfire ([Box 1](#)).

Fig. 2. The *ecologically critical sliver* (top few cm at soil surface) as the driver of key processes: C, nutrient, and hydrologic cycles; weathering; dust capture; decomposition; and soil stability ([Pointing & Belnap 2012*](#)). Soil surface organisms mediate inputs and outputs of water, gases, and nutrients from soils ([Belnap et al. 2003*](#)); nutrients accumulate at the surface due to limited leaching, dust input, and organism activity ([Belnap 2003*](#)). Plants obtain soil interspace C and N via this sliver ([Green et al. 2008](#)). Semiarid woodland baseline and post die-off and extreme wildfire are hypothesized to differ in stabilizing biotic-abiotic feedbacks vs. amplifying ones driving state changes and novel trajectories.



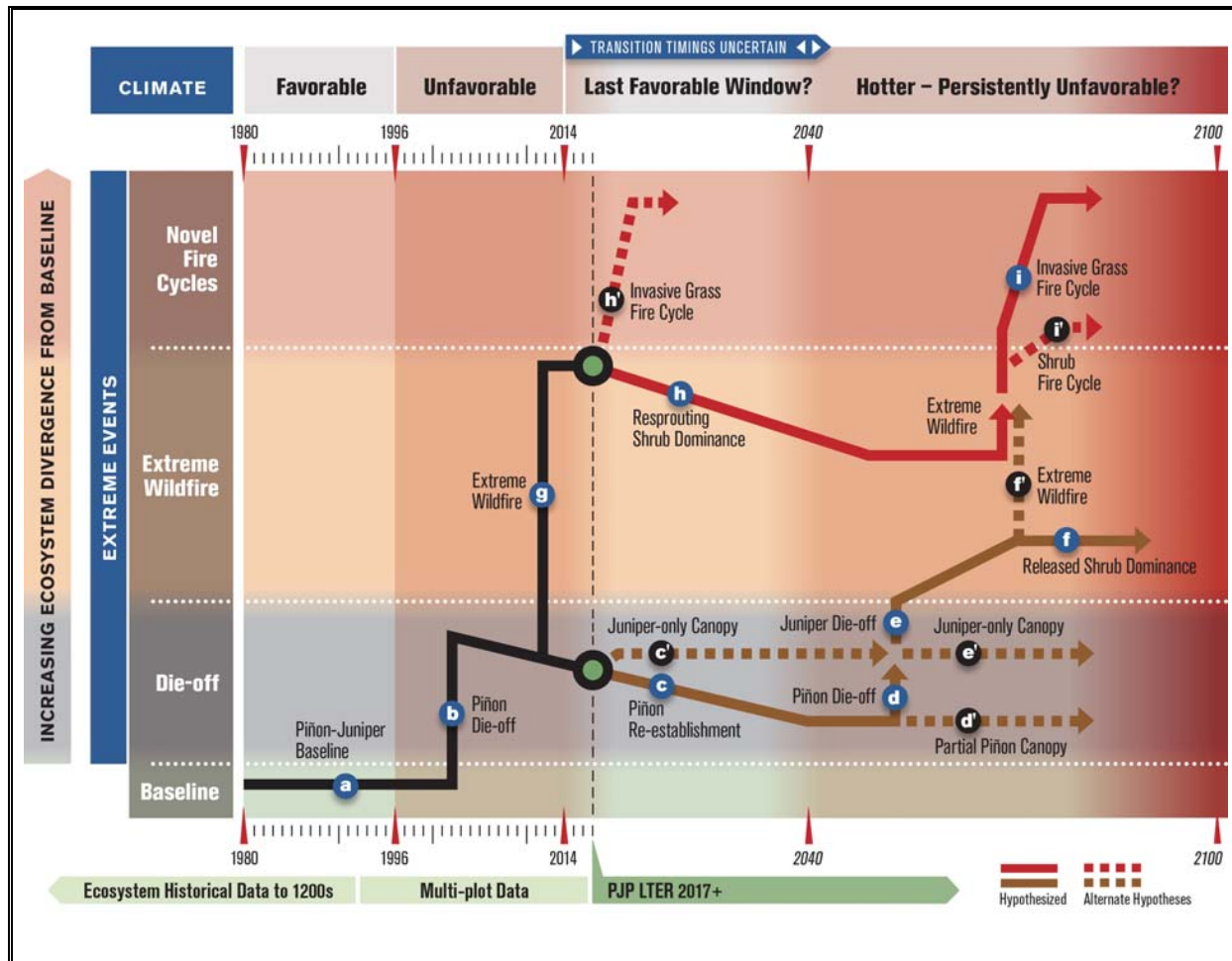


Fig. 3. Conceptual framework for Die-off (brown) and Extreme Wildfire (red) trajectories, as detailed in **Box 1**. Solid lines are hypothesized trajectories for lettered segments; dashed lines are alternate hypotheses.

Box 1. Conceptual framework for semiarid woodland trajectories after hotter-drought-driven tree die-off and extreme wildfire (shown graphically in **Fig. 3**): climate drivers, hypothesized die-off trajectory (**Fig. 3 brown lines**), hypothesized extreme wildfire trajectories (**Fig. 3 red lines**), and context and generality. PJP research focuses on lettered segments of **Fig. 3**.

Climate Drivers. The Southwest exhibits decadal-to-multidecadal variability in moisture conditions favorable or unfavorable (Swetnam & Betancourt 1998*) for plant germination, growth, and establishment (**Fig. 3 upper band**). For PJP and much of the Southwest, 1976–1995 was warm and wet, particularly favorable for establishment. Unfavorable conditions, due to continued warming and reduced precipitation, have prevailed since 1996. The Pacific Decadal Oscillation (PDO) shifted positively in 2014, potentially indicating a return to favorable conditions. If so, wetter conditions could persist for the next two decades. The Forest Drought Severity Index (FDSI; Williams *et al.* 2013*), composed of antecedent precipitation and current temperature, also exhibits decadal-to-multidecadal variability. FDSI is very sensitive to warmer temperatures that drive increased atmospheric moisture demand; by ~2050, average years may exceed the 2002–2003 drought and late 16th-century megadrought. Rising temperatures could offset relief from individual wet years and even pluvials (e.g., broadscale tree die-off in California just occurred despite the shift in the PDO; Asner *et al.* 2016). Regardless, the next occurrence of favorable conditions could be the last for Southwest semiarid woodlands and forests unless greenhouse gas emissions are sharply curtailed (Williams *et al.* 2013*).

Box 1. Conceptual framework (continued).

Die-off Trajectory (Fig. 3 brown lines). Southwest woodland and forest dynamics will track these decadal variations in conditions, exacerbated now by unprecedented warming and hotter droughts (Fig. 1 lower left). **a:** Except at their northern, migrating edges on the Colorado Plateau and Great Basin, distributions of piñon-juniper woodlands have been relatively stable over the Holocene. The main response to climate have been temporary shifts in composition and structure in response to past megadroughts and megapluvials (Swetnam & Betancourt 1998*, Betancourt *et al.* 1993*), or prehistoric clearing and fuelwood harvesting, which likely left a lasting ecological legacy on contemporary piñon-juniper woodlands (Samuels & Betancourt 1982*, Allen 2004*). **b:** ~1996, conditions became unfavorable, particularly west of PJP and then subsequently in 2002–2003, where drought associated with warmer temperatures triggered large-scale die-offs at PJP and across the Southwest (Breshears *et al.* 2005*, Shaw *et al.* 2005). Precipitation following the 2002–2003 drought and piñon die-off resulted in a release of understory vegetation (Rich *et al.* 2008*). The hypothesized trajectory following die-off is that upon entering the “last favorable window.” **c:** piñon seedlings will establish, the precursor needed to recover the overstory, and as opposed to **c'**, a lack of piñon re-establishment resulting in persistence of juniper-only canopy. **d** and **e:** However, given the increasing severity of drought due to continued warming, after the persistently and increasingly unfavorable period is entered, re-established piñons, as well as many remaining juniper, are expected to undergo further die-off due to hotter drought (Adams *et al.* 2009*, McDowell *et al.* 2016*), consistent with unpublished observations of initial juniper mortality already in our legacy data, and as opposed to piñons or juniper persisting (**d'** and **e'**, respectively). **f:** Under these hotter conditions with complete piñon and juniper die-off, we expect shrubs to be released and persist, given the existing stabilizing plant–biocrust–brown-food-web–soil feedbacks, although eventually with reduced shrub canopy cover as hotter-drought stresses further increase (as opposed to an alternative extreme wildfire trajectory in shrubland, **f'**, leading to **i** or **i'** [below]).

Extreme Wildfire Trajectory (Fig. 3 red lines). **g:** The unfavorable period from 1996–2013 resulted in major wildfires across the Southwest and at PJP, including the Las Conchas extreme wildfire during particularly extreme fire weather in 2011 (Williams *et al.* 2014*), which resulted in near-consumption of all above-ground biomass at our PJP wildfire site (Fig. 1 lower right). **h:** Resprouting shrubs are expected to eventually become dominant after the fire, based on initial observations and responses from other local fires (Allen *et al.* 2016*), precluding takeover by invasive grasses (or, **h'**, these resprouting shrubs will slow their spread as the persistently unfavorable period is entered). **i:** Due to the increasingly severe climate, in combination with unstable, exposed soil conditions and amplifying plant–biocrust–brown-food-web–soil feedbacks, we expect invasive grasses to increasingly take over and establish an invasive grass fire cycle of fuel buildup, frequent fire, an erosional pulse, declining shrub viability, and repeat of the cycle (as opposed to shrubs persisting in a shrub fire cycle, **i'**).

Context and Generality. Our conceptual framework also includes an explicit embedded geomorphic context that considers the redistribution of runoff as runoff; potential for amplified erosion, and stabilizing vs. amplifying effects of plant–soil microbial–biocrust–soil feedbacks (Fig. 1). **Our conceptual framework is not site-specific to PJP but rather presents the likely major trajectories for semiarid woodlands of the western US, and also has high relevance to semiarid western US forests, as well as general relevance to semiarid woodlands and forests globally.**

5. Key Ecological Questions

Our conceptual framework (Box 1) yields hypotheses by segment for LTER Core Areas (Table 2). Our approach will be to conduct assessments specific to each segment in Box 1. For each segment, we hypothesize corresponding responses to each of the four LTER Core Areas. With this approach, we first determine the relevant segment in Box 1 and then map directly to hypotheses in Table 2 to test additional hypotheses specific to the Core Areas.

Table 2. Predicted responses for trajectory-lettered segments from conceptual framework (Fig. 3).

LTER Core Areas (1–4) (responses for segments a and b)	LTER Core Area 5. Patterns and Frequency of Disturbances	
	<i>DIE-OFF (a-b-c-d-e-f)</i>	<i>EXTREME WILDFIRE (a-b-g-h-i)</i>
1. Patterns and Controls of Primary Production. Above-ground primary productivity (AGPP) is limited by precipitation. a: Prior to die-off, woody component fluctuates with prior winter precipitation; herbaceous fluctuates with annual precipitation. b: AGPP initially drops greatly with live biomass loss.	c: Herbaceous release results in small AGPP increase. d, e: Die-off of most remaining tree biomass under unfavorable conditions, leaving AGPP linked to remaining understory. f: Gradual release of shrubs following tree die-off results in further AGPP decrease.	g: Near-complete loss of above-ground biomass results in near-zero AGPP. h: AGPP slowly increases with resprouting shrubs under favorable conditions, leveling under unfavorable conditions, and resetting to near-zero after extreme wildfire. i: AGPP increases as invasive grass progresses with precipitation to peak biomass and then drops to near zero, after which the fire cycle repeats.
2. Spatial and Temporal Population Dynamics & Food Web Interactions. Arthropod types, bacteria:fungi ratio, and stable biocrust vary spatially and temporally with vegetation structure change. a: Prior to die-off, taxa-specific arthropod community dynamics reflect variation in precipitation seasonally, annually, with prior year lag effects, and with multi-decadal phases. b: Abundance reductions in all components of brown food web; increased bacteria:fungi ratios.	c: Biocrust and microbial biomass increases, with a decrease in bacteria:fungi ratios, leading to slow increase in arthropod detritivore and grazer abundances, lagged by increased arthropod predator abundance. d, e: Reductions in components of brown food web and increased bacteria:fungi ratios. f: Biocrust and microbial biomass decreases, with an increase in bacteria:fungi ratios, leading to a decrease in arthropod detritivore and grazer abundances, lagged by decreased arthropod predator abundance.	g: Extreme reduction in microbial biomass with large increase in bacteria:fungi ratio; near-complete loss of biocrust and arthropods. h: Biocrust and microbial biomass increases, with decrease in bacteria:fungi ratios; slow increase in arthropod detritivore and grazer abundances, lagged by increased predator abundance. i: With extreme wildfire, extreme reduction in biocrust and microbial biomass with large increase in bacteria:fungi ratio; near-complete loss of arthropods; with subsequent invasive grass, biocrust, microbial biomass and arthropod diversity all increase mildly with decrease in bacteria:fungi ratio, all pulsing with fire cycles.
3. Patterns and Controls of Organic Matter Accumulation and Decomposition. Under trees organic matter is greater, with more lignin; slower decomposition is driven by UV photo-degradation and microbial activity that is limited by soil-litter mixing and precipitation, not temperature. a: Prior to die-off, organic matter accumulation is dominated by tree litter production; decomposition is most rapid for herbaceous litter buried via soil litter mixing. b: Piñon die-off creates huge pulse of litter; coarse woody debris increases as trees lose branches and fall in next years.	c: Ratio of high-to-low lignin litter decreases due to post-die-off herbaceous pulse of litter; some biocrust loss; downed woody debris increases sediment capture, soil-litter mixing, and decomposition. d, e: With die-off of both juniper and any recovered piñons, additional large input and accumulation of litter; dead junipers remain standing longer so coarse woody debris input is less than for initial dead piñon input. f: Gradual litter production increases with shrub cover, then organic matter is stable.	g: Extreme loss of organic matter via depletion of much of the labile or active carbon, with a significant recalcitrant fraction remaining. h: With increase in released shrubs; increased soil pH. i: With extreme wildfire, near-complete loss of above-ground organic matter; with subsequent invasive grass, small pulsed increments of organic matter inputs before being lost each fire cycle.
4. Patterns of Inorganic Inputs and Movement of Nutrients. a: Atmospheric deposition and fixation inputs are stable; biocrust cover, high; erosion, low. b: Following die-off, there are small initial changes in inorganic elemental phases in both standing dead and decomposing trees; and within mineral soil, increased biocycling rates due to increased energy and moisture inputs to soil.	c: Increased loss of inorganics with higher erosion rates on steeper geomorphic positions. d, e: Biocrust decrease reduces inputs; some increase in wind and water erosion with plant loss reduces contrasts between former canopy and intercanopy. f: Reduced inorganic movement as shrub cover increases.	g: Following extreme wildfire substantial initial loss of mobile inorganic phases due to wind and water erosion; leaching nutrients out of profile. h: Change in nutrient distribution in space and with depth and nutrient capture via water and dust transport. i: First with extreme wildfire, near-complete loss of above-ground organic matter, then with invasive grass small pulsed increments of organic matter inputs before being lost each fire cycle.

6. Project Personnel

Table 3. PI and Co-PIs

Name	LTER Core Area Expertise Lead Section Leads [Sections contributing to]	Institution
David D. Breshears	PI ; Core Area 5: Disturbance: Die-off & Extreme Wildfire Overall Coordination; Lead 8.3, 8.4 [all 8, 9.1, 9.4]	Univ. Arizona
Wendy Moore Brusca (W. Moore hereafter)	Co-PI ; Core Area 2: Population Dynamics and Food Webs Lead 8.1 [8.3, 8.7, 8.8, 9.3]	Univ. Arizona
Russell K. Monson	Co-PI ; Core Area 1: Primary Productivity Lead 8.8 [8.1, 8.3, 8.7, 9.3]	Univ. Arizona
Rachel E. Gallery	Co-PI ; Core Area 3: Organic Matter Dynamics Lead 8.5 [8.3, 8.4, 8.7, 8.8, 9.2]	Univ. Arizona
Craig Rasmussen	Co-PI ; Core Area 4: Inorganic Inputs Lead 8.7 [8.3, 8.8, 9.1]	Univ. Arizona

Table 4. Senior Personnel

Name	Expertise, Section Leads [Sections contributing to]	Institution
Lead Collaborating Researchers		
Craig D. Allen	BNM Science Legacy: Die-off and wildfire Lead 8.2 [7, 8.1, 8.3, 8.4, 8.5, 8.8]	USGS
Nate G. McDowell	LANL Science Legacy: Die-off ecophysiology Lead 8.6 [7, 8.1, 8.2, 8.8]	LANL
Information Management		
Matej Durcik ^a	Information Management Director Lead Data Management Plan [7, all 8]	Univ. Arizona
^a Oversees 1.0 FTE* Data Manager and data management efforts of onsite Sr. Research Specialist		
Broader Impacts		
Sara Chavarria ^b	Education Pipeline - Coordinate 9, Lead 9.1 [9.2, 9.3]	Univ. Arizona
Jeremy Garcia ^b	Community-Research Partnership Model - Lead 9.2	Univ. Arizona
Bruce Johnson ^b	Education Evaluation - Lead Evaluation on 9.1 & 9.2	Univ. Arizona
Katharine L. Jacobs ^b	Co-produced Knowledge Transfer - Lead 9.3	Univ. Arizona
Ellen McMahon ^b	Art-Humanities-Environment Network - Lead 9.4 [9.1]	Univ. Arizona
Thomas W Swetnam ^b	Iconic Trees and Groves Initiative [9.1, 9.2, 9.3]	Univ. Arizona
Juan C. Villegas ^b	International Ecosystem Services Coordination [9.1]	UAntioquia
^b In collaboration with identified UA onsite tribal and engagement/education coordinator		
Logistics Coordination		
Darin J. Law ^c	Program Coordination from UA [all 8]	Univ. Arizona
Collin Haffey ^c	USGS Field Station Coordination [7, all 8]	USGS
Jeremy Sweat ^c	BNM Resources Approvals [8.3, 8.4, 8.5]	NPS
^c In coordination with onsite Sr. Research Specialist (UA-supported; 0.75 FTE data collection)		
* FTE: Full-Time Equivalent		

Table 4. Senior Personnel (continued)

<i>Name</i>	<i>Expertise [Sections contributing to]</i>	<i>Institution</i>
<u>Network Synergies</u>		
Jon Chorover	Jemez River Basin Critical Zone Observatory [8.8]	Univ. Arizona
Lisa Thomas	NPS Inventory and Monitoring Program [8.8]	NPS
Jake F. Weltzin	U.S. National Phenology Network [8.8]	USGS
Carolyn Enquist	SW Climate Science Center [8.8, 9.3]	USGS
<u>Additional Technical Expertise</u>		
Jayne Belnap	Biological soil crust, cheatgrass [8.3, 8.4, 8.5, 8.8]	USGS
Julio L. Betancourt	Paleoecology, invasive grasses [8.1, 8.5, 8.8]	USGS
Greg A. Barron-Gafford	Ecosystem fluxes – carbon [8.1, 8.3]	Univ. Arizona
Yves Carrière	Insect ecology and biostatistics [8.1, 8.3]	Univ. Arizona
Dave Christianson	Large mammal population dynamics [8.8]	Univ. Arizona
Michael A. Crimmins	Climatology [8.1, 8.2, 9.3]	Univ. Arizona
Brian J. Enquist	Tree biogeography projections [8.7, 9.3]	Univ. Arizona
Margaret E.K. Evans	Tree demography projections [8.1, 8.2, 8.7]	Univ. Arizona
Jason P. Field	Ecohydrology and sediment [8.1, 8.3, 8.4, 8.5]	Univ. Arizona
Donald A. Falk	Fire histories and forest management [8.1, 8.2, 9.3]	Univ. Arizona
Laura López-Hoffman	Ecosystem services [8.8, 9.1, 9.3]	Univ. Arizona
Stephen T. Jackson	Novel ecosystems [8.8, 9.3]	USGS
Ellis Margolis	Tree-ring reconstructions [8.1, 8.2, 8.8]	USGS
David J.P. Moore	Ecosystem modeling, data assimilation [8.3, 8.7]	Univ. Arizona
Guo-Yue Niu	Coupled modeling [8.7, 8.8]	Univ. Arizona
Jonathan T. Overpeck	Paleoclimatology and drought [8.2, 8.8]	Univ. Arizona
Robert R. Parmenter	Fauna population/community ecology [8.1, 8.3, 8.8]	NPS
Tyson L. Swetnam	LiDAR vegetation-topography analyses [8.1, 8.3, 8.7]	Univ. Arizona
Willem van Leeuwen	Remote sensing applications [8.1, 8.3, 8.8]	Univ. Arizona
James Walworth	Soils and seedling germination [8.4, 8.5]	Univ. Arizona
Jeffrey J. Whicker	Wind erosion [8.3, 8.7]	LANL
<u>Collaborating Sr. Personnel with Existing PJP Products for Additional Technical Synergies</u>		
Jeffrey A. Hicke	Beetle and wildfire remote sensing [8.1, 8.3, 8.8]	UI
Matthew D. Hurteau	Post-fire seedlings, fire modeling [8.4, 8.7, 8.8]	UNM
Abigail L.S. Swann	Eco-climate modeling (CESM-ED) [8.3, 8.7, 8.8]	UW
Christina Tague	Ecohydrological modeling (RHYESS) [8.3, 8.7, 8.8]	UCSB
A. Park Williams	Forest Drought Severity Index [8.1, 8.2, 8.8]	Columbia

7. PJP Research and Data Legacies

We will leverage numerous available ongoing long-term PJP data sets ([Table 5](#)) to characterize pre-disturbance conditions and scale up to the landscape ([Fig. 4](#)), including tree-ring fire history and woodland demography; >40 long-term woodland vegetation plots; >100 NPS permanent fire monitoring research plots; >25 years of dendrometer tree growth (e.g., [Allen 2007*](#), [McDowell et al. 2010*](#)); 25 years of cm-resolution surface cover and microtopography from 10 300-m permanent transects; 20 years of runoff & erosion from a 1-ha watershed ([Wilcox et al. 2003*](#)); 20 years of surface cover and microtopography from paired 40-ha treatment/control watersheds ([Jacobs 2015](#)); and 25 years of continuous terrestrial arthropod pitfall trap censuses ([Lightfoot et al. 2008*](#)). LANL data include 24 years of soil moisture and plant water potential ([Breshears et al. 2009a*](#), [2009b*](#), [McDowell et al. 2016*](#)) and the in-progress DOE SURvival-MORTality (SUMO) experiment lead by McDowell at LANL. SUMO stresses piñon and juniper trees through individual and combined drought and heat treatments (initiated June 2012, with 5°C increase above ambient and precipitation reduction of 45%, increased to 85% May 2016).

To date, the scientific impact of research on PJP includes more than 35 papers each with >100 citations, totaling >13,000 citations (Google Scholar). This includes the first high spatio-temporal resolution documentation of rapid

drought-induced ecotone shift ([Allen & Breshears 1998*](#)); the first documentation of regional-scale vegetation die-off posited to be driven by hotter drought (or “global-change-type drought”, [Breshears et al. 2005*](#)); the longest continuous plant water potential field data-set spanning a die-off event ([Breshears et al. 2009a*](#); [McDowell et al. 2016*](#)); development of new theory and evaluation of results based on Darcy’s Law revealing greater vulnerability of larger trees ([McDowell & Allen 2015*](#)); development of a powerful new Forest Drought Severity Index that predicts tree growth, NDVI change, and die-off and wildfire events ([Williams et al. 2013*](#)); seminal fire history ([Touchan et al. 1996*](#), [Swetnam et al. 2016*](#)) and diverse post-fire ecology research ([Barclay et al. 2004](#), [Foxx 2013](#)); the first quantification of post-wildfire runoff and erosion from standard rainfall simulation ([Johansen et al. 2001*](#)); and a runoff redistribution and erosion threshold framework ([Wilcox et al. 2003*](#)).

Fig 4. Primary research areas of the proposed PJP LTER and key available data sets. Our research design draws on these research and data legacies, focusing on a DIE-OFF site in BNM (using long term soil moisture and plant water potential data from LANL as a supplementary DIE-OFF site), EXTREME WILDFIRE on BNM where high-severity wildfire initiated within and consumed piñon-juniper woodland (*Pinus edulis* and *Juniperus monosperma*), and a supplementary REMNANT FRAGMENT site on LANL (Veg: Vegetation).

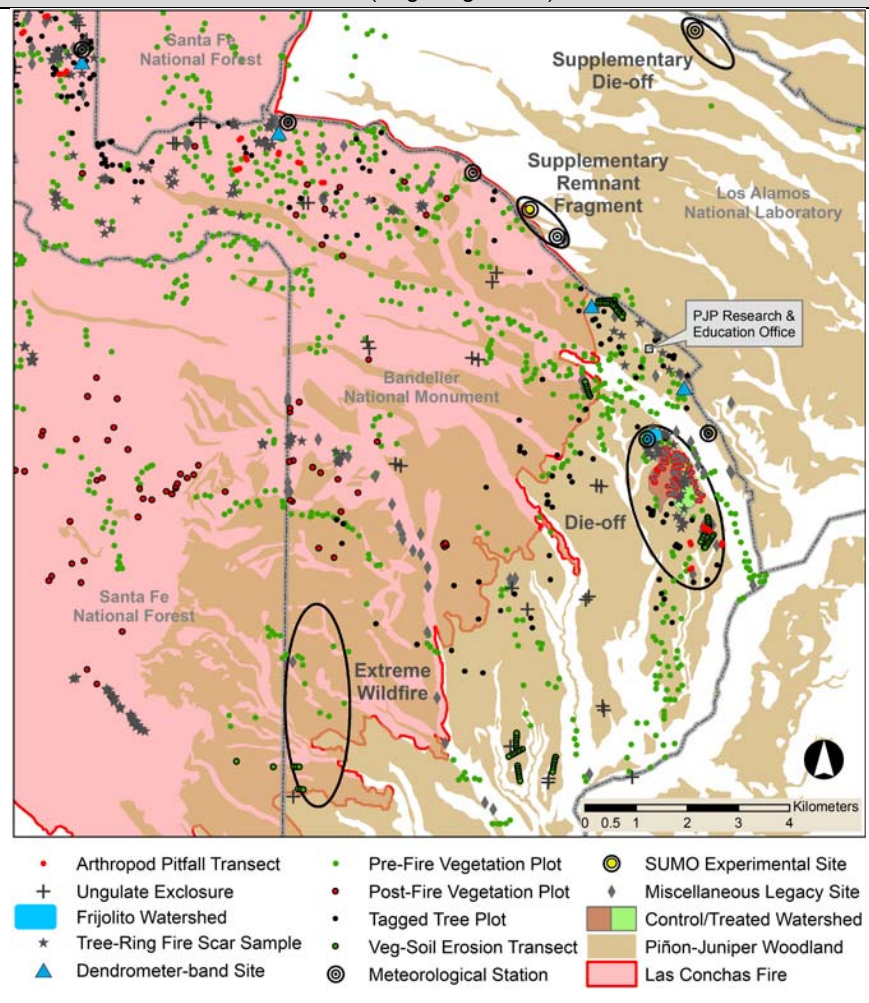


Table 5. PJP data sets available for assessing pre-disturbance conditions, disturbance responses, and scaling from plot to landscape, all detailed in [Section 8](#), as well as for additional synthesis activities. These data will be added from current servers to the LTER Network data portal (Supp.: Supplementary). Numbers in bold refer to LTER Core Areas (as in listed in [Table 2](#)).

Location	Data
DIE-OFF Core Site [BNM]	Vegetation-soil surface transects at 1-cm resolution (300 m) (3 transects, started 1991; re-reads up to annually), with 15 associated “erosion bridges” (soil surface microtopography transects, 30 points/bridge) [1,2,3,4,5]; Paired Control/Treated large watersheds (40 ha each) with 40 vegetation transects (100 m at 1-cm resolution) [established 1996; re-reads up to 7X] and 90 erosion bridges [1,3,4,5]; Frijolito watershed (1.09 ha) with 3 vegetation transects (~60 m each at 1-cm resolution, started 1993, re-read annually), 53 erosion bridges, multi-scaled sediment traps (1-m ² X 12, 0.1 ha X 4, whole watershed X 1) and 2 flumes operated 1995–2013, high-resolution DEM generated in 2005, soil carbon characterized watershed wide in 2002 [1,2,3,4,5]; Landscape-function-analysis transects (~25 - ~75 m at 1 cm resolution) [6 transects, started 2005; re-read 2X] [1,3,4,5]; Large vegetation plots (20 x 50 m) 10 plots; started late 2000s; all trees tagged; re-read 2X [1,3,4,5]; Small vegetation plots (400m ²) 20 plots, established in 2000s, some re-read once [1,3,4,5]; Temporary (5 yrs) elk enclosure [1,3,4,5]; All previously listed vegetation transects span 1 or more die-off events; Close-up ground-surface repeat photos (Green Meadow) [5]; Detailed soil maps (2001); Range trend and soil condition map from 1974 [1,3,4,5]; Butterfly data [2]; Bird data [2]; Surface-dwelling arthropod pitfall traps (5 30-m transects X 6 traps each) collected 4X/year since 1991 [2]; Biocrust studies [3]; historical ground-based photos at all plots (time series 1991 - present) [1,3,4,5]; High-resolution air photo veg mapping (1935, '54, '58, '63 '81, 2005) [5]; Aerial detection survey insect and disease impact mapping [5]; Dendroecology tree-ring studies back to AD 1600 on: complete demographic history from two 0.5 ha plots (started 2001) and 1.09 ha Frijolito watershed (estab.1998) with all trees & deadwood aged, mapped, tagged, and all shrubs tagged [2,5]; climate:tree-ring growth/resin-defense/mortality piñon studies [1,5]; and dendro-fire history [5]; meteorological station (1993–present).
Supp. DIE-OFF Site [LANL]	Predawn plant water potential biweekly-monthly since 1992 [1,5], including pre- and post die-off; Soil moisture with depth and by canopy-intercanopy biweekly-monthly since 1988 [1, 3, 4, 5] including pre- and post-die-off; Vegetation transect at 1 cm resolution (100 m) established 1988, soils map [3,4], soil characterization [3,4], pre-disturbance woody plant demography by size and canopy cover [1]; multi-scale runoff, redistributed runoff and erosion data [1,3,4]; nearby meteorological station (TA-54).
EXTREME WILDFIRE [BNM]	Vegetation transects at 1-cm resolution (50 m, 3 transects, established 1995 re-read annually [1,3,4,5]; 1 elk enclosure with 3 treatments (2 levels of fencing and control) each with basal line-intercept transects, read repeatedly since 1975; [1,3,4,5]; Small vegetation plots (400m ²) 10 plots, established in 2000s, some re-read once [1,3,4,5]; Vegetation transects at 1 cm resolution (50 m) [3 transects, started 2011 post wildfire; re-read annually) [1,3,4,5]; post-fire site erosion rating [3, 4]; erosion bridges[3,4].
Supp. REMNANT FRAGMENT Site [LANL]	Soil moisture [1,2,3,4,5], predawn plant water potential, conductance, photosynthesis; SUMO mortality experiment [1,2,3,5]; nearby meteorological station (TA-49); includes trees with supplemental water (downslope of SUMO).
<i>Other PJP data sets extending beyond lower and upper ecotones or in adjacent ecosystems</i>	Elk enclosure and control plots (piñon-juniper: 5 established 1999, 2 in 1975; ponderosa:11 established 1999), with vegetation-soil transects and shrub browsing data [1,3,4,5]; Numerous diverse vegetation plots/transects spanning 1 or more die-off and/or wildfire events, many with tagged trees[1,3,4,5]; Surface-dwelling arthropod pitfall traps in ponderosa pine (five 30 m transects X 6 traps each) collected 4X/year since 1991 [2,5]; Dendrometer-banded sites (piñon site: 8 trees, 1995–2003) ponderosa: 2 sites, 12 trees/site measured weekly, 1991-present) [1,5]; tree-ring fire history to AD 1500 [5]; meteorological stations (multiple BNM and LANL).

8. Proposed Research

Our Research Design focuses on addressing the segments of our conceptual framework ([Fig. 3](#)) and testing our central hypothesis: *amplifying feedbacks associated with plant–biocrust–brown-food-web–soil feedbacks in the near soil-surface sliver mediate disturbance-initiated state change and novel trajectories in rapidly transforming ecosystems (influenced by the timing of favorable/unfavorable climate conditions and punctuated by extreme events)*. Our primary study sites ([Fig. 4](#)) focus on contrasts between **DIE-OFF** and **EXTREME WILDFIRE** and variations within each. Our **DIE-OFF CORE SITE** in BNM will be supplemented with existing long-term soil moisture and plant water potential data from our **SUPPLEMENTARY DIE-OFF SITE** at LANL. The die-off event was so extreme that there are only a few small remnant fragments with mature piñon trees on the landscape. We have extensive pre-die-off data ([Table 5](#)) but as needed we will use a **SUPPLEMENTARY REMNANT FRAGMENT SITE** at LANL (adjacent to the SUMO experiment). Much other existing data ([Table 5](#)) will be used to scale from plots to landscape. Recognizing an initial LTER ramp is substantial—even with our team experience and extensive legacy data—we will put the most emphasis on installing equipment to initiate a full suite of measurements at our two core sites (**DIE-OFF** and **EXTREME WILDFIRE**), along with field and controlled-chamber experiments targeted for trajectory changes currently underway (**c vs. c'** and **h vs. h'** in [Fig. 3](#)). Our research design has eight subsections (8.1–8.8), each of which relates to one or more segments of our conceptual framework ([Fig. 3](#)).

8.1. Piñon-Juniper Baseline - Legacy Data ([Fig. 3: a](#))

We will use several legacy data sets (Section 7) to test three hypotheses related to pre-disturbance baseline conditions ([Table 6](#)). These will be complemented with extensive publications on pre-disturbance conditions (partially summarized in [Breshears 2006*](#)). In addition, we will obtain data from the **REMNANT FRAGMENT** site as part of our Trajectories Tracking (Section 8.3) that will provide data not available in the legacy data sets (e.g., microbial community, detailed soil biogeochemistry).

Table 6. Predictions of key ecological conditions to assess Piñon-Juniper Baseline (segment a of the conceptual figure (Fig. 3) that can be tested with existing legacy data (Section 7).	
Soil moisture and vegetation cover: <i>Prediction:</i> Soil moisture dynamics drive vegetation cover dynamics as a function of canopy, canopy-intercanopy edge, and intercanopy locations detected by vegetation greenness (NDVI).	Data: Vegetation cover transects for DIE-OFF and other PJP sites evaluated pre-die-off as related to soil moisture using higher resolution LANDSAT TM (rather than the lower resolution AVHRR used in Rich et al. 2008*) in combination with time-series vegetation cover data.
Piñon masting conditions: <i>Prediction:</i> Piñon pine nut masting depends on climate sequences reflected in current year temperature, precipitation lagged 1 year (affecting cone production) and FDSI or soil moisture—both integrators of climate—lagged 2 years (affecting <i>primordiea</i>) (Forcella 1981 , Parmenter et al. in prep*).	Data: Climate, FDSI and soil moisture data and regional data on harvest documentation (e.g., New Mexico Piñon Nut Company) and observational research (Parmenter et al. in prep*).
Arthropod community climate: <i>Prediction:</i> Taxa-specific arthropod community dynamics (total and relative abundances of grazers, detritivores and predators) pre-die-off reflect multi-scale temporal variation (seasonal, annual, prior year lag effects, multi-decadal), which are disrupted with vegetation change following the die-off.	Data: Climate data, vegetation transect data, and arthropod pitfall trap data at DIE-OFF site and other PJP piñon-juniper sites from 1991–2001 (pre-die-off; building from non-temporal analysis of Lightfoot et al. 2008*).

8.2. Die-off and Extreme Wildfire Climate and Soil Moisture Conditions - Legacy Data ([Fig. 3: b & g](#))

We will develop modifications of FDSI to produce PJP-specific time series to improve linkages with climate and soil moisture conditions driving die-off and extreme wildfire. First, we will apply the FDSI equation from [Williams et al. \(2013*\)](#) to the local climate record. Second, we will capitalize on the rich collection of tree-ring and biophysical datasets available for the PJP region to develop region-, species-, and elevation-specific estimates of how climate variability affects tree growth, considering piñon pine and one-seed juniper, as well as ponderosa pine and Douglas-fir. This will advance [Williams et al. \(2013*\)](#) by considering climate variables in addition to precipitation and vapor pressure deficit (VPD) such as minimum daily temperatures and more comprehensive representations of the water balance such as

potential evapotranspiration (PET; calculated using the physically-based Penman-Monteith formulation [Monteith 1965]), the Palmer Drought Severity Index (Palmer 1965), the Standardized Precipitation-Evaporation Index (Vicente-Serrano *et al.* 2010), and Climatic Water Deficit (Stephenson 1998). These indices will be calculated from gridded climate data as well as from the 15-minute weather station records that have been collected at LANL since the 1980s. We will also use the land-surface model records of soil moisture and snowpack produced by the NLDAS2 (Xia *et al.* 2012) and GLDAS (Rodell *et al.* 2004) land-data assimilation projects. We will also take advantage of the Legacy long-term soil-moisture data from the DIE-OFF SUPPLEMENTARY SITE to compare the moisture-balance indices listed above to the observational soil-moisture records. This will enable us to identify the indices' relative abilities to represent observed variations at timescales spanning from monthly to decadal. We will calibrate a combination of the above moisture-balance indices to the observed soil-moisture record to reconstruct PJP soil moisture variability as far back as 1895. This reconstructed soil-moisture record will then be used as a potential predictor of tree growth and drought stress in our localized FDSI construction and analysis. These analyses will be carried out using the multi-product climate database compiled by Williams (e.g., Williams *et al.* 2015*). Data products will include PRISM (Daly *et al.* 2008), CLIMGRID (Vose *et al.* 2014), TopoWx (Oyler *et al.* 2015), Berkeley Earth (Rohde *et al.* 2013), NLDAS2 (Xia *et al.* 2012), Princeton Global Forcing (Sheffield *et al.* 2006), MERRA2 (Molod *et al.* 2015), and CRU (Harris *et al.* 2014).

8.3. Post-disturbance Initial Divergences - Trajectories Tracking (Fig. 3: *c* vs. *c'* & *h* vs. *h'*)

This section covers the long-term data collection for the LTER Core Areas (Table 2) that is central to the LTER Program. We will focus our measurements on the DIE-OFF CORE site and EXTREME WILDFIRE site. Using existing transects at both sites (Table 5; and extending length or adding new transects where needed) we will expand measurements for three 300-m vegetation transects at each site to include a series of meteorological, physiological, and biogeochemical measurements (planned primary infrastructure is detailed in Table 7). These data will enable us to track if the DIE-OFF CORE site progresses via *c* or *c'*, and if the EXTREME WILDFIRE site progresses along *h* or *h'*. Given that extensive pre-disturbance data exist, that much relevant data is being collected by the SUMO experiment, and that the REMNANT FRAGMENT site is not large enough to accommodate the full design, only a targeted set of subset of measurements will be obtained in the REMNANT FRAGMENT site—the only site with live adult piñons. *Meteorological* measurements (precipitation, temperature, relative humidity, wind speed and direction, and albedo) will be continuously at the DIE-OFF (CORE), EXTREME WILDFIRE, and REMNANT FRAGMENT sites.

LTER Core Area 1: Primary production. To capture patterns and controls of above-ground primary production and the divergence of ecosystem function after extreme events, we propose to link instantaneous measures of carbon and water flux at the leaf and ecosystem scale with integrated measures of net primary production from vegetation transects that include biocrusts (historic data), allometry (e.g., Schuler & Smith 1988, Grier *et al.* 1992), dendrometry for annual biomass increment, clip plots (herbaceous species), and remote sensing (e.g., Huang *et al.* 2012), such as structure from motion (where photos from multiple angles enable reconstruction of vegetation structure, Eltner *et al.* 2016). Primary production will be evaluated within a complete carbon balance framework, including assessment of biomass increment, litter production, total below-ground carbon allocation, and allometric allocation to needles using previously developed approaches for post-fire pine forests (Litton *et al.* 2004). Data-model assimilation approaches will be developed using the tower flux data and existing ecosystem process models (e.g., SiPnET, see Braswell *et al.* 2005, Sacks *et al.* 2006) to estimate gross primary productivity and ecosystem respiration for the DIE-OFF (CORE), EXTREME WILDFIRE, and REMNANT FRAGMENT sites. Multiple PJP team members have coupled such data assimilation approaches with remote sensing products to reduce uncertainty in modeled values (e.g., Zobitz *et al.* 2014*). We will deploy portable flux masts at the three sites for a targeted range of conditions (i.e., three 2-week periods spanning the growing season for an average moisture year, a wet year and a dry year, based on antecedent moisture from winter snowfall; Breshears *et al.* 2009b*) to obtain estimates of CO₂ flux and primary productive for each site. For each of three 300-m vegetation transects at the DIE-OFF (core) and EXTREME WILDFIRE sites, we will monitor physiological conditions (including sapflow where feasible) of nine seedlings and nine saplings of both piñon and juniper (if available) and nine adult junipers (a subset of these measurements will be obtained at the REMNANT FRAGMENT and/or as part of the SUMO experiment and will also include adult piñons). Repeating these measurements of leaf photosynthesis and leaf water potential (degree of water stress)

Table 7. Primary infrastructure and long-term data collection at DIE-OFF and EXTREME WILDFIRE sites (three transects/site); the size-limited supplementary REMNANT FRAGMENT site has equal sampling density (1/3 of those shown).				
Monitoring Network	Sample Frequency	Number and Location per Site	Standard Method and Instrumentation	Core Area
Meteorological				
<i>precipitation</i> <i>relative humidity</i> <i>air temperature</i> <i>wind speed/direction</i> <i>solar radiation</i>	continuous measurements logging interval range (1 sec to 1 hr)	1 meteorological station	- tipping bucket - humidity sensor - thermometer - anemometer/wind vane - net radiometer [4 component]	1, 2, 3, 4 1, 3 1, 2, 3 1, 2 1, 2, 3, 4
<i>CO₂ flux with portable mast</i>	3–4 X annually for 2 weeks (for a wet, medium and dry yr)	portable mast 1.5x canopy height	- Eddy covariance with sonic anemometer & net radiometer	1
<i>high-resolution wind speed/ direction</i>	3–4 X annually for 2 weeks (for a wet, medium and dry yr)	attached to portable mast	- sonic anemometer	1
Physiological				
<i>sap flow</i>	continuous measurements	12 piñon and juniper seedlings and saplings	- sap flow sensors	1, 2
<i>phenology</i>	continuous	12 cameras	- pheoncams	1, 2, 3
<i>photosynthesis</i>	3–4 X annually	32 piñon and juniper seedlings and saplings	- LiCOR 6400	1, 2
<i>virtual forest</i>	annually	18–24 scans	- LiDAR (TLS)	1, 2, 3, 4
<i>seedling establishment</i>	2–3 X per LTER cycle	24 seedlings of piñon and juniper	- field observations	1, 2, 3, 4
<i>biocrust establishment</i>	2–3 X per LTER cycle	27 plots (0.5 m ²)	- soil inoculum & fertilizer	1, 2, 3, 4
<i>biocrust change; C, N inputs; soil stability</i>	annually	36 locations	- soil samples & soil surface change	1, 2, 3, 4
Biogeochemical				
<i>soil moisture and temperature</i>	continuous measurements	30 for ≤2 cm depth & 54 for ≥ 10 cm depths	- TDR probes	1, 3, 4
<i>soil respiration</i>	continuous	36 probes	- Vaisala probes & CO ₂ chamber	1, 3, 4
<i>soil pit</i>	annually	3 pits (0.5 m ²)	- microbial community analyses	2, 3, 4
<i>bioavailable nutrients</i>	2 mo each spring	24 locations	- cation/anion resin bags	1, 2, 3, 4
Sample collection				
<i>arthropods</i>	seasonally	18	- pitfall traps	1, 2
<i>vegetation clip plot</i>	2–3 X annually	24 (0.5 m ²)	- vegetation clipped at base	1, 2, 3, 4
<i>coarse woody debris</i>	2–3 X annually	24 (0.5 m ²)	- woody debris collected	1, 2, 3, 4
<i>litter decomposition</i>	at 1 mo, then every 6 mo	39 per collection time	- litter bags	2, 3, 4
<i>surface soil</i>	seasonally	24 (0.5 m ²)	- soil collection down to ~10 cm	2, 3, 4
<i>biocrust</i>	annually	24 (0.25 m ²)	- biocrust excavation	3, 4
<i>tree cores</i>	seasonally	36 (~0.64 cm dia.)	- increment borers & extractors	1, 3
<i>soil cores</i>	annually	18 (~0.64 cm dia.)	- soil probe	3, 4

across multiple seasons per year will yield insights into the relative degree to which intra- and inter-annual variation in available moisture, atmospheric temperature, and above-ground water stress influence instantaneous function. These data will be complemented with historic time series data on soil moisture and plant water potential data from LANL (McDowell *et al.* 2016*) to bridge ecosystem structure with physical drivers. New LiDAR approaches (linking allometry to metabolic scaling) will be used to quantify inventory and changes in biomass (Swetnam & Falk 2014*). A recently developed approach will enable multi-site estimation of albedo, a key parameter for land surface interactions with the atmosphere, within a few days per site (Stark *et al.* 2016*). Phenological measurements will be made along each of the vegetation transects to obtain information on the timing and duration of different phenological shifts. Measuring below-ground primary production is not feasible (e.g. tree roots penetrating rock fissures), so we will use model assumptions (e.g., RHYESS, ED) and evaluate other measureable model outputs.

LTER Core Area 2: Population dynamics & food web interactions. In addition to the fundamental population dynamics of plants that we will be tracking, we will focus on the “brown” food web highlighted in the critical sliver (Fig. 2) that includes both ground-dwelling arthropods from a variety of functional groups and the soil microbial community, with emphasis on the bacteria and fungi components. Studies of ground-dwelling arthropods have been part of other LTER efforts to date (Lightfoot *et al.* 2008*), although temporal dynamics of populations have not yet been evaluated. Ground-dwelling arthropods studied via pitfall traps present numerous advantages: taxa are diverse, they can be responsive to vegetation cover variation and disturbance (Delph *et al.* 2014, Higgins *et al.* 2014) or seasonality (Meyer *et al.* 2015*). We will build on prior studies of ground-dwelling arthropods in semiarid woodlands (Steinberger *et al.* 1991, Lightfoot *et al.* 2008*, Delph *et al.* 2014, Higgins *et al.* 2014, Meyer *et al.* 2015*). Ground-dwelling arthropods are sensitive to changes in wildfire (Higgins *et al.* 2014) and changes via tree die-off of as little as a 4% reduction in canopy cover and associated increase in woody debris (Delph *et al.* 2014). PJP offers an incredible resource in having 25 years of baseline data on ground-dwelling arthropods, which has only been initially evaluated (Lightfoot *et al.* 2008*). We propose to monitor changes in food webs and population dynamics by continuing and expanding existing arthropod data collection with new collection of soil microbial communities. Additional information on the possible trajectories for food webs and population dynamics will be obtained from data on micro-invertebrates and microbe sequencing, and soil and litter sampling. To detect change in relative abundance of dominant microbial and fungal taxa in litter and soils, high throughput targeted gene sequencing will follow contemporary methods and focus on bacterial and archaeal (16S rRNA gene) and fungal (nrITS gene) communities. Sequence data will be assembled and quality controlled, and analyses will be run using the NSF-funded QIIME (Caporaso *et al.* 2010) in CyVerse. Metadata will conform to BIOM format (standard for Genomics Standards Consortium) with MIMARKS standards (Yilmaz *et al.* 2011*). These data will also provide insights on the relative roles of arbuscular mycorrhizae associated with juniper and ectomycorrhizae associated with piñon (Haskings & Gehring 2004, Karst *et al.* 2014). These surveys of microbial and fungal communities will be coupled with functional measurements (flux and exoenzyme assays) and soil biogeochemistry (see **LTER Core Areas 3 & 4** below). Combined, these data allow inference of “brown” food web dynamics and tests of the population trajectories of ground-dwelling arthropods, micro-invertebrates, and the bacterial, archaeal, and fungal constituents of biocrusts, litter, and soils. In addition, because pollination is expected to be central to vegetation trajectories following disturbance, we will also measure the two dominant pollinators: bees and butterflies. Butterflies will be counted visually along transects following protocols similar to Kleintjes *et al.* (2004*), a PJP-specific study. Bees will be trapped with unscented colored funnel traps (white, yellow and blue; Stephen & Rao 2005) using four replicates per site (DIE-OFF (CORE), EXTREME WILDFIRE, and REMNANT FRAGMENT) twice per year (late spring and late summer).

LTER Core Areas 3 and 4: Organic matter, inorganic inputs, and movement of nutrients. We will monitor how soil moisture, temperature, and microbial populations diversity and dynamics influence biogeochemical processes (carbon [C], nitrogen [N], and phosphorus [P] cycling) along the vegetation transects to determine how the different observed trajectories of biogeochemical conditions relate to various trajectories for biocrust and vegetative community. Biogeochemical measurements will be co-located with the plant physiological measurements to help observe disturbance thresholds that can influence soil-plant interactions and determine to a large part the potential for the system to recover or undergo state change or novel trajectory. *Organic matter dynamics* will be monitored onsite modified from techniques including LTER (Robertson 1999) and NEON (Hinckley *et al.* 2016) standards. We propose to assess baseline soil total C, N, and P pools (e.g., Davenport *et al.* 1996*, Law *et al.* 2012*) and monitor C

and *nutrient dynamics* using resin bags during the two months of maximal plant growth and soil N isotopes post-spring, as well as new approaches for capturing “burn” chemistry and carbon partitioning from mineral versus non-mineral soil, and determining mass balance elements indexed to parent material (loss/gain). Soil moisture and soil temperature are key factors influencing the rates of biogeochemical processes and play a large role in determining the location and occurrence of biogeochemical hotspots and hot moments. Organic matter decomposition and nutrient dynamics are particularly sensitive to changes in soil moisture and temperature (Warnock *et al.* 2016) and could be a factor forcing systems towards recovery or novel trajectory. Building on baseline data (Breshears *et al.* 1998*, 2009*), we will monitor soil moisture dynamics and changes in temperature using a replicated network of time domain reflectometer (TDR) probes at the DIE-OFF (CORE), EXTREME WILDFIRE, and REMNANT FRAGMENT sites at five depths (2, 10, 25, 50, and 75 cm if soil depth is sufficient) for both canopy and intercanopy locations for, where present, seedlings, saplings, and adults of both juniper and piñon. Changes in soil moisture and temperature will be monitored along the vegetation transects at each site and will be compared to physiological changes in biocrust and vegetation structure to determine relationships and thresholds associated with soil-plant-water feedbacks, including the influence of plant and biocrust C, and biocrust N, inputs. Following protocols for semiarid ecosystems that account for photodegradation and soil-litter mixing (Austin 2011), litter decomposition bags to monitor mass loss and transfer to soil C pools will be installed within the network of TDR probes and subsamples collected 2–3 times annually along with coarse woody debris. Microbial community dynamics are also a key determinant influencing the location and occurrence of biogeochemical hotspots and hot moments. We will characterize microbial relative abundance and community composition using high-throughput DNA-based sequencing from soil samples collected along the vegetation transects. Soil subsamples will be coupled with measures of potential exoenzyme activity to estimate microbial rates of C, N, and P mineralization using 7-9 fluorescently labeled substrates (Sinabaugh *et al.* 2002). We will also estimate rates of microbial activity at the DIE-OFF (CORE), EXTREME WILDFIRE, and REMNANT FRAGMENT sites using a network of Vaisala probes to measure CO₂ (soil respiration) at five depths (2, 10, 25, 50, and 75 cm if soil depth is sufficient) for both canopy and intercanopy locations for, where present, seedlings, saplings, and adults of both juniper and piñon.

8.4. Post-die-off Piñon Re-establishment - Field & Controlled Climate Experiments (Fig. 3: c vs. c')

Piñon re-establishment as a function of climate. We hypothesize that piñon re-establishment depends on *climate*, which can affect seed germination viability and survival of seedlings and saplings. Our **prediction** is that under warmer conditions, a lower proportion of piñon seeds will be viable and piñon seedlings and saplings will die more rapidly during drought, as shown for adults (Adams *et al.* 2009*). To determine piñon re-establishment (Fig. 3 c), we will test this hypothesis in five steps in climate-controlled chambers (similar to those of Vertin *et al.* 2010, 2012) and in the field. 1) To test piñon seed germination viability under ambient and warmer conditions, we will conduct chamber germination trials for seeds that have been stratified (subjected to a series of environmental cues to break seed dormancy) or not. Stratification will follow standard procedures (per Baskin & Baskin 1998: seed soaked in aerated water at 20° C for 24 hours, placed in nylon mesh bags which are in a plastic bag with a loose wet towel allowing air circulation, and then suspended in a refrigerator for 30 days at mean temperature of 5° C). Ambient conditions for piñon will include recommended conditions (~25° C for daylight hours, ~18° C for dark hours; Harrington 1987); the warming treatment will increase temperatures by 4° C. Seeds will be placed in trays with a standard soil from the site and watered daily. Germination will be defined as when the radicle protrudes from the seed coat 1 mm and turns down (Larson & Schubert 1969, Harrington 1977). We will follow germinants through to seedling establishment where it occurs. We will test the point at which photosynthesis begins following germination (LiCOR 6400 gas exchange measurements) and use curves of net CO₂ assimilation rate versus the substomatal CO₂ concentration (*A/Ci curve*) to determine the maximum rate of carboxylation is ($V_{c_{max}}$) and the maximum rate of electron transport is (J_{max}). Growth rates will be estimated from seedling height and stem diameters. 2) To test piñon seed germination viability in the field, non-stratified seed will be placed at the DIE-OFF (CORE) and REMNANT FRAGMENT sites in rodent proof enclosures prior to winter. During the winter, seed temperature will be measured beneath the snow with datalogging temperature sensors (Kestrel). In spring stratified seed will be placed in the enclosures next to non-stratified seed and germination will be monitored weekly. Micro-environmental characteristics (soil surface temperatures, soil moisture, solar radiation, rainfall) will be related to seed germination. 3) To test piñon seedling and sapling survival conditions that include warmer temperatures, we will use commercially available plants in the ambient and warmer chambers and subject them to four

levels of watering spanning biweekly to no watering and with and without inoculation of mycorrhizae (Karst & Gehring 2014). 4) To evaluate the effect of loss of overstory on establishment, we will implement three levels of shade cloth on field-established piñon seedlings, quantifying microclimate at each location with hemispherical photos (Rich 1990). 5) To test the effects of root competition associated with a post-die-off release of herbaceous vegetation (Rich *et al.* 2008*) on piñon pine seedling survival, we will conduct root exclusion experiments at the DIE-OFF (CORE) and REMNANT FRAGMENT sites. Root exclusion tubes (Kolb & Robberecht 1996) will be used to partially (15-cm depth) or nearly-completely (30-cm depth) exclude other plant roots from the root zone of piñon seedlings (along with a control treatment). Seedling survival and establishment will be monitored via growth rates, photosynthesis, and respiration.

Piñon re-establishment as a function of safe sites. We hypothesize that piñon establishment is a function of “safe sites” as well as climate: Landscape-level conversion from a relatively homogenous to a heterogeneous distribution of safe sites, due to their loss through redistribution of resources, controls piñon establishment. Our **prediction** is that in relatively undisturbed sites, biocrusts, and plants provide a highly stable environment where resource retention leads to a high number of fairly homogeneously distributed safe sites for piñon establishment/growth. Extreme drought, resulting in total tree loss and some loss of biocrusts, moderately reduces the number, and alters the distribution, of piñon safe sites by reducing shade and obstacles that retain soils. At the far end of this continuum, extreme wildfire incinerates most trees and litter, resulting in extreme soil loss and almost complete loss of safe sites for piñon establishment. The alteration or loss of near-surface soils will be critical in regulating piñon re-establishment.

We will test this using greenhouse and field trials in five steps. 1) The zones around currently established, but very young, piñons in the REMNANT FRAGMENT, will be characterized for likely safe site characteristics (biocrusts; soil depth, nutrients, surface and sub-surface organic matter; and abundance and activity of brown food web biota) to establish which factor or combination of factors likely creates safe sites. 2) In the greenhouse, we will use full factorial experiments to verify field observations of the most important variables for establishment success. 3) The REMNANT FRAGMENT, DIE-OFF (CORE), and EXTREME WILDFIRE sites will then be randomly sampled to identify the characteristics, number, and distribution of piñon safe sites to understand how perturbations have affected these factors. 4) We will then combine data from all the above efforts to construct piñon safe sites in the field to test our prediction. Within 5-20m x 20m plots in each of the REMNANT FRAGMENT, DIE-OFF (CORE), and EXTREME WILDFIRE sites, 10 piñon safe sites will be constructed to imitate the number, distribution, and characteristics found by field and greenhouse studies to be the controlling drivers of establishment. If biocrusts control the response, seedlings will be inoculated with the amendments found to best stimulate their establishment (projects funded by DOD, NPS, BLM, ending in 2017). If soil depth or chemistry treatments control the response soils and/or amendments will be used to reach desired targets (e.g., sugar can reduce available N). Organic matter will be added as conifer needles. Desired abundance and activity of brown food web biota will be achieved by inoculation with control site soils, with the amount and time needed determined by preceding experiments. If shade treatment controls response, shade cloth will be placed above the safe sites. Safe sites will be large enough (1m x 0.5m) to accommodate planting with two one-year old seedlings (grown from local seeds), as well as the placement of 10 locally obtained seeds. Plants and seeds will be protected by small cages. Having seeds and plants will allow us to distinguish between sites safe for germination versus growth, and will be “insurance” against loss of all data if early die-off of new emergents occurs if weather conditions are too dry. Sites will be watered when established, and if needed, again during the growing season. Piñon establishment happens in average or above-average rainfall years (Floyd *et al.* 1982); thus, if rain is insufficient and the seedlings die, re-planting/seeding will take place the following years until rainfall is sufficient. As controls, two of the 10 safe sites in each plot will not be planted. 5) Safe site construction success will be monitored by yearly measures of biocrust cover by species; soil depth and nutrient availability; surface and sub-surface organic matter, and microbial/fungal abundance and activity. Seed success will be monitored by assessment the following spring for emergents. Yearly, we will assess biomass accumulation.

8.5. Post-extreme Wildfire: Shrubs vs. Invasive Grass – Field & Chamber Expts. (Fig. 3: *h* vs. *h'*)

Post-extreme wildfire shrub resprouting. We hypothesize that shrub (oak) resprouting post extreme wildfire is sensitive to climate. Our **prediction** is that under hotter and drier conditions, oak resprouting will be reduced. Opportunities for field experimentation on post-extreme-wildfire resprouting shrubs are more limited than those associated with less severe controlled burns. We will conduct a controlled chamber experiment to assess *h* of Fig. 3., supplemented with additional landscape observations. We will

test this hypothesis on shrub resprouting (**Fig. 3 h**) by using the controlled climate chambers to house 3-to-5-year-old nursery stock of the dominant shrub: oak (*Quercus undulata*). After applying fire, the plants will be subjected to four levels of plant water availability and two temperature regimes (ambient and +4°C). Propane torches will be used to burn the canopies of the potted shrubs prior to placing them in the chambers. Re-sprouting will be assessed by measuring asymmetric leaves (Fair & Breshears 2005*), leaf growth rate, branching, and photosynthesis and respiration (via LiCor 6400). Re-sprouting ability will be assessed in chambers with ambient and elevated temperature under. These experimental results will be supplemented with landscape observations in the area of the EXTREME WILDFIRE site, currently 5-years post fire and with sufficient time for resprouting to have occurred on surviving shrubs. We will expand sampling beyond the three 300-m transects to target a range of sites varying in soil depth, percent slope, site exposure, and soil hydrophobicity (water drop penetration tests; Doerr 1998). These observational data will reveal shrub resprouting potential following extreme wildfire that is not feasible experimentally.

Post-extreme wildfire invasive grass. We hypothesize that invasive grass establishment depends on a highly heterogeneous distribution of near-surface soil resources. Our **prediction** is that annual plants, in general, require higher nutrients and water for survival than perennial plants (Marschner 1995) and thus will be found in downslope positions or other places where soils and nutrients accumulate. Therefore, upslope areas experiencing loss of near-soil resources are expected to be dominated by perennial plants, whereas downslope depositional zones are expected to favor annual plants. Fire also often releases pulses of nutrients, especially nitrogen and manganese, both which favor annual plants (Miller *et al.* 2006). *Bromus tectorum*, an invasive annual grass, occurs in PJP. Seeds of *Bromus* are seldom limiting, as they are easily dispersed. Rather, nutrients and water appear to mostly control its distribution in favorable climate zones (Belnap *et al.* 2016*). In addition, intact biocrusts are well-documented to protect sites from *Bromus* invasion. Therefore, we predict that control areas, with intact biocrusts and low resource loss, will be very resistant to invasion; die-off areas, with intact biocrusts and moderate resource loss will be intermediate in resistance; and extreme wildfire areas, with no biocrusts, high soil resource loss, and flushes of nitrogen, will have very low resistance. In addition, extreme wildfire areas will be invaded such that they add sufficient fuels to lead to increased fire frequency.

We will test our predictions in the greenhouse and in the field through the following six steps. 1) Drivers of invasion in the field will be determined by characterizing 10 randomly chosen invaded and uninvaded patch pairs in the control (if present), die-off (if present), and extreme wildfire areas for plant canopy/ground and biocrust cover by species, including: biomass of *Bromus*; site topography, including placement on slope and fetch above; small and large ground litter; soil depth, nutrient availability, surface and sub-surface organic matter, and brown-food-web abundance/activity. 2) Using the variables that are statistically different between the invaded and uninvaded field patches, we will establish a full factorial experiment (with 10 replicates) in the greenhouse to determine what factor, or combination of factors, is most important in determining establishment and growth rates. We will also use two watering rates: average and 25% above average for PJP. *Bromus* has a very high germination rate; thus, 10 locally obtained seeds will be planted per pot, and thinned to three plants after emergence. 3) To further verify if soil factors control invasion, and that fire enhances these factors, we will also grow *Bromus* in soils collected from the control and wildfire areas (10 replicates). 4) To further determine the influence of soil factors on *Bromus* invasions, we will use the data obtained from experiments #1–3 to establish a controlled field experiment growing *Bromus*. Using 10 of our adjacent invaded-uninvaded plot pairs in the wildfire zone, and 10 areas of unburned, uninvaded soil directly adjacent to the burned soils, we will modify a 0.25m x 0.25m area in the uninvaded patches to imitate the invaded soil characteristics (using techniques outlined in sub-hypothesis 1). We will then plant 10 *Bromus* seeds through a template (so we can retrieve the seeds) at 1 cm in both invaded and uninvaded plots. We will assess germination and emergence of planted seeds by collecting all emergents and all un-germinated seed (digging them out, using the template), within 3 weeks of the first noted emergent (to prevent introduction of any additional *Bromus* seeds). 5) *Bromus* does not germinate in low rainfall years. However, there is almost no information as to what level it does not germinate and how this is affected by temperature. To better establish this threshold, needed for modeling of predicted invasions under future conditions, we will grow *Bromus* under different climate regimes. We have climate data for high and no germination years; we will use rainfall and temperature from those years to bracket a total of 10 treatments (10 replicates each), using a full factorial design. 6) For experiments #2–5, we will count the number of un-germinated and germinated seeds, as well as the number and size of emergent in plots/pots.

8.6. Additional Tree Die-off under Hotter Drought - Leveraged Experiment (Fig. 3: *d* vs. *d'*; *e* vs. *e'*)

There are very few field experiments to date on tree mortality focused on saplings or reproductively mature adult trees with drought-by-temperature treatments (Allen *et al.* 2015*), none of which have been conducted under field conditions, in part because they are very costly to implement. Rather than attempt to conduct costly tree mortality experiments, our LTER will leverage the SUMO experiment led by McDowell adjacent to our supplementary REMNANT FRAGMENT site. Based on related studies (Adams *et al.* 2009*, Pangle *et al.* 2015), and current plant water stress levels, we anticipate that both species will undergo mortality sometime near the initiation of our LTER or shortly afterward. If so, these experiments will provide direct insights into tree mortality and will enable us to test hypotheses *d* and *e* and the specific conditions under which mortality for each species occurs. Should the experiment fail to trigger mortality or be curtailed prior to mortality, we will still have valuable information on a range of stress conditions that both piñon and juniper are able to survive. This information would then be used with the existing drought-by-heat-glasshouse experiment for piñon (Adams *et al.* 2009*), unpublished data indicating saplings respond similar to adults, and conditions preceding recently observed juniper mortality to refine our estimates of mortality thresholds for both species. Therefore, we will successfully advance our LTER goals especially if the experiment successfully triggers tree mortality, but even if it fails to do so.

8.7. Post-disturbance Dynamics – Projections Modeling (Fig. 3: all, including *f* vs. *f'* and *i* vs. *i'*)

Drought-driven disturbance is already becoming widespread in western North America, and in particular in the Southwest. It is thus critical that our proposed PJP LTER integrate understanding using state-of-the-art models that can, in turn, be used to make use-inspired projections of future ecosystem change and the impacts of this change. We will focus efforts on the use and improvement of existing models, and will also seek out collaboration with other modeling groups, as well as those using the output of models to support decision-making. Our overarching goal is to create a new LTER that integrates a rich legacy of existing data and understanding with a fundamentally more powerful framework for understanding ecosystem dynamics under a rapidly changing climate. To integrate our results and make projections of ecological dynamics into the future under different scenarios, we will draw on the vegetation dynamics component of the VMTran (**V**egetation **M**odulated **T**ransport of aeolian sediment) model (Breshears *et al.* 2012*, Michelotti *et al.* 2013*) that was developed to account for disturbances including die-off and wildfire and initially parameterized for the PJP landscape. These results will be interfaced with several other established models and supplemental calculation approaches. The modeling will apply to our entire framework (all segments in Fig. 3 are also studied by other methods except for *f* vs. *f'* and *i* vs. *i'*, which will be studied only via model simulations for the first LTER funding cycle).

Overview of the VMTran vegetation dynamics component. The VMTran model simulates vegetation-moderated transport of contaminated soil by wind (the following description is excerpted from Breshears *et al.* 2012*, Fig. 5). The vegetation component simulates the pattern of succession over the period of time simulated. Disturbance events, such as fire or drought, can reduce vegetation cover and climate changes can impact the trajectory of succession. The trajectory of succession under the canopy of woody plants is assumed to be different than succession in the intercanopy areas. The model simulates ecological succession by dividing the surface of a 50m x 50m cell into 2500 cells of one m² each and using a Markov-like transition matrix (Horn 1974) to simulate the history of each cell. Cell types include trees (piñon, juniper, or ponderosa), shrubs, grasses, litter, and bare soil. The transition matrix specifies the annual probability of dying, of being replaced by a plant of another growth form, or of remaining in the same state. Woody plants can influence neighboring cells via effects of shading. Growth of woody plant canopies are logistic when not shaded by taller woody plants, and reduced when they are. Vegetation cells are also categorized as being inter- or under-canopy. VMTran can modify the current state of vegetation or modify the trajectory of succession in response to disturbance events, which increase in frequency with climate change, and can include surface fire, crown fire, and drought. The changes invoked by disturbance events depend on the type of disturbance, the successional stage (grassland, shrubland, woodland, or forest, based on % woody cover) and % ground cover. The type and date of disturbances can currently be implemented prescriptively or stochastically.

SHIFT: Semiarid Hotter-drought Impacts Forcing Transitions. We propose to modify the VMTran Vegetation Dynamics component to create an expanded model **SHIFT—Semiarid Hotter-drought Impacts**

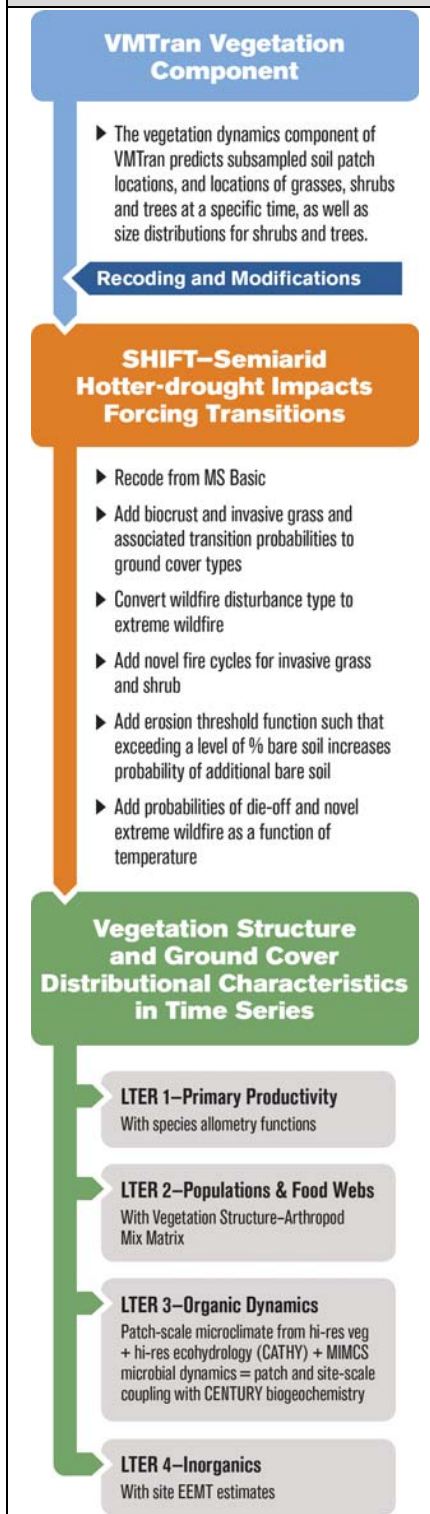
Forcing Transitions—that accounts for additional aspects of our conceptual framework (Fig. 3) not originally accounted for in VMTran (Fig. 5). The model output will include time series of vegetation characteristics by lifeform and of ground cover characteristics that are fundamental to more specific predictions of LTER Core Areas (1–4). Model modifications will be informed initially with results from Sections 8.1 and 8.2 (to be updated later with results from 8.3–8.6).

LTER Core Area 1: Patterns and controls of primary production. The vegetation structural data predicted from SHIFT can be used to readily estimate primary productivity when integrated with relevant allometric equations, which are available from the literature (e.g., Rich *et al.* 1993, Martens *et al.* 1997* [including new relevant LIDAR approaches: Swetnam *et al.* 2015*]; see related text in Section 8.3) and will be further refined with transect data.

LTER Core Area 2: Spatial and temporal population dynamics & food web interactions. Our predictions of arthropod populations and associated brown-food-web response will initially be based on a hypothesized set of relationships between vegetation structure, recent transitions, and relative abundances and distributions of arthropod types (soil microbiota responses are discussed in the next section). As presented in related text in Section 8.3, drawing on a suite of studies of ground-dwelling arthropods in semiarid woodlands (Steinberger *et al.* 1991, Lightfoot *et al.* 2008*, Delph *et al.* 2014, Higgins *et al.* 2014, Meyer *et al.* 2015*), we hypothesize relationships between arthropod types and vegetation structure. Relevant findings informing our predictions include: *i*) transition from a tree-dominated habitat to more open habitats (from die-off or wildfire) had different arthropod communities; *ii*) burned habitats had greater overall arthropod abundance and greater abundances in all major taxa and functional groups except for spiders/predators, which were more abundant in old growth habitats; *iii*) species composition was significantly different between burned and old-growth habitats, which combined with the finding of little variation in species richness, suggests similarly diverse habitats had distinct assemblages; and *iv*) burned habitats were dominated by grasshoppers, beetles, and ants reflecting the increase in herbaceous ground cover and bare ground, while old-growth arthropod communities were characterized by more mesic species of detritivores/fungivores and spiders (Higgins *et al.* 2014). Overall these results indicate a high degree of habitat affiliation by arthropods. These responses are likely also be related in part to near ground temperature and relative humidity, which are both desiccating factors and can influence arthropod diversity patterns (Meyer *et al.* 2015*). We will also evaluate changes based on arthropod traits from legacy and new data. The vegetation and ground-cover predictions of SHIFT will serve as the basis for predicting arthropod community change.

LTER Core Areas 3 and 4: Patterns and controls of organic matter accumulation and decomposition, and patterns of inorganic inputs and movement of nutrients. For organic and inorganic matter-dynamics modeling, we will implement both patch- and landscape-scale models (Fig. 5). Patch-scale predictions are needed due to the importance of “hot spots and hot moments” in semiarid biogeochemical processes.

Fig. 5. Plan for the **SHIFT** model as applied to 4 LTER Core Areas.



We will use high-resolution vegetation structure to predict microclimate by conducting LiDAR driven analyses accounting for detailed landscape topography and vegetation canopy structure, including isolation of individual trees. We will use multiple images to reconstruct individual plant structures via LiDAR and structure from motion multi-view stereo (SfM-MVS) data (Eltner *et al.* 2016) by various different platforms [e.g., terrestrial laser scanning, simultaneous localization and mapping (SLAM, Durrant-Whyte & Bailey 2006)]. This will provide high-resolution digital representation resolving microtopography from vegetation structure influencing microclimate (Lague *et al.* 2013), enabling microclimate characterization (e.g., Sankey *et al.* 2013*).

We will link these high-resolution microclimate predictions with a distributed hydrological model (CATHY), which will then be linked to the newly developed MIMICS model (Wieder *et al.* 2014) to account for the soil microbial community. MIMICS (and other similar modeling approaches, e.g., Allison *et al.* 2010, Sulman *et al.* 2014, Fan & Liang 2015) improves upon established soil organic matter models, such as CENTURY, by explicitly including microbial physiological constraints on the turnover of litter and production of stable soil organic matter. This represents a significant advance in modeling soil organic matter dynamics and has been demonstrated to provide improved estimates of soil organic turnover and stabilization relative to established models that do not explicitly include microbial physiology (Weider *et al.* 2015). The model structure of MIMICS is similar to that of CENTURY but includes a microbial “filter” or “valve” through which litter passes on its degradation pathway towards CO₂ or stabilization by mineral association or organic matter chemical composition. This type of functionality allows incorporation of microbial community dynamics expected under the ecosystem trajectories and maintains the soil organic matter stabilization mechanisms foundational to existing model structures and empirical measures. We will project changes in litter and soil C stocks and chemistry under the various ecosystem trajectories, at both the patch scale for specific “hot spots” and at the landscape scale.

Additionally, we will build on advances of the Jemez Mountains CZO, which has as its central conceptual model that the transfer of energy and mass to the critical zone via carbon derived from net primary production and water in excess of evapotranspiration are key predictors of critical zone (CZ) evolution, structure, and function (Rasmussen *et al.* 2011*)—and is directly relevant to the ecologically critical sliver in our post-disturbance systems (Fig. 2). These transfer terms are called “effective energy and mass transfer” (EEMT) because, while these carbon and water terms approximate only a fraction of the total energy and mass balance of CZ systems, these fluxes have been found highly relevant to predicting subsurface physical, chemical, and biological properties. The components of EEMT include the transfer of energy and mass to the subsurface from net primary production (E_{BIO}) and effective precipitation (E_{ePPT}) in units of $J\ m^{-2}\ s^{-1}$, or $W\ m^{-2}$ where: $EEMT = E_{BIO} + E_{ePPT}$. The components of EEMT can be calculated using relatively simple monthly water balance techniques and net primary production estimates for large scale estimates, or may be calculated taking into account local hillslope-and-aspect-scale controls on water redistribution and primary production (Rasmussen *et al.* 2015*). The EEMT framework is built around the premise that CZ processes and evolution are a direct function of gradient-driven fluxes of energy and mass, including solar radiation, carbon, water, and mineral/sediment supply. Cycling and storage of energy and mass occurs through processes such as infiltration and recharge, primary production and carbon cycling, physical and chemical weathering, and erosion and sediment transport. Export of energy and mass occurs through evapotranspiration, CO₂ respiration, runoff and base flow, and denudation. We will further advance the application of EEMT by calculating vegetation modified EEMT for the critical sliver (Fig. 2) for the DIE-OFF (CORE), EXTREME WILDFIRE, and REMNANT FRAGMENT sites.

8.8 Syntheses across Sites and Systems

8.8.1 Scaling up across Piñon-Juniper landscapes

1. Scaling up across the PJP landscape. We will use PJP Legacy datasets from broad gradients of elevation, topography, climate, and disturbance histories (Fig. 3) to scale up site-specific observations to synthetically resolve spatial and temporal patterns and processes over the PJP landscape. Data from numerous long-established and repeatedly measured vegetation plots, transects, soil-surface arthropod traps, and other sources will be analyzed to determine species-specific patterns of vegetation and arthropod responses to climate and disturbances across PJP landscape gradients. Legacy-plot data and surveys across landscape gradients will be combined with time-series of vegetation maps, aerial photography (Allen 1989*), remote sensing (Garrity *et al.* 2013*), and LiDAR data (2000, 2010, 2013; e.g., Swetnam & Falk 2014*) to assess patterns of tree die-off and ecotone shifts, including upslope retreat of

tree distributions (e.g., [Allen & Breshears 1998*](#)). Further tree-ring studies will determine changes in climate-growth-mortality relationships across the PJP (e.g., [Macalady & Bugmann 2014](#)).

2. Scaling up across Piñon-Juniper woodlands of the Southwest. Research findings from the PJP LTER will be compared and contrasted to patterns and processes found regionally in other southwestern PJ woodland ecosystems ([Romme et al. 2009*](#), [Margolis 2014*](#)), including: piñon-juniper sites not yet subject to tree die-off or extreme wildfire disturbances, including sites on similar tuff substrates in the western & northern Jemez Mts.; other Southwest piñon-juniper sites affected by recent piñon die-off (e.g., [Breshears et al. 2005*](#), [Shaw et al. 2005](#), [Floyd et al. 2015](#)); other piñon-juniper sites burned by high-severity wildfire ([Floyd et al. 2004](#)); other piñon-juniper sites with post-wildfire shrublands ([Floyd et al. 2004](#)); and other piñon-juniper sites with novel invasive grass-fire cycles developing ([Floyd et al. 2006](#)).

8.8.2. Cross-site and cross-system syntheses

We propose five cross-site and cross-system syntheses to place our work in broader contexts both across the LTER Network as well as other related networks such as NEON and CZO.

1. Energy- and water-limited systems. Fundamental ecohydrological differences exist between LTER ecosystems relative to limitations of energy vs. water ([Fig. 1](#); [Jones et al. 2012](#)). This relationship is also central to grassland-forest gradients ([Breshears 2006a*](#)) and is reflected in the relative roles of below- vs. above-ground limitations in ecosystems ([Martens et al. 1997*](#)). Importantly, PJP landscape is located close to the inflection point between energy- and water-limited systems. We will evaluate ecosystem responses for the PJP site and other LTER sites most closely aligned with the energy-to-water-transition and their sensitivities to loss in vegetation cover. The EEMT parameter ([Rasmussen et al. 2015*](#)) allows for a quantitative comparison and characterization of the environmental context and drivers among the various NSF supported observatories, i.e., LTER (all terrestrial sites), CZO, and NEON. The central components of EEMT are largely climatically derived such that it readily accommodates predicted changes in climate into defining potential changes in the environmental context of a given location.

2. Consequences of extreme events and sequences. We propose to coordinate a cross-LTER synthesis paper that infuses experiences from each LTER with local disturbances events, interpreted within the context of the [Smith \(2011\)](#) framework. Although extreme events are increasingly recognized as key drivers of ecological change in the Anthropocene, we are not aware of an integrated cross-LTER synthesis that cross-walks site-specific knowledge on disturbance events with the generalities of the [Smith \(2011\)](#) framework. We will initially explore qualitative comparisons and explore the potential to also include quantitative comparisons. We will also consider the role of sequences of extreme events (e.g., [Miao et al. 2009*](#)). We anticipate at least one synthesis paper from this effort.

3. Broader risks of hotter drought in other forested ecosystems. Although semiarid piñon-juniper woodlands have undergone some of the most dramatic transformations due to hotter drought ([Breshears et al. 2005*](#)), other sites that have not yet experienced tree mortality will likely be vulnerable as warming progresses ([National Climate Assessment 2014*](#), [Allen et al. 2015*](#)). We will evaluate sub-annual critical climate periods ([Barnes et al. 2016*](#)) for other forested research sites in the US (i.e., at LTER, CZO, and NEON sites) for which required data exist. Additionally, in a related NSF EAGER project (NSF EF-1550756, PI Breshears), we are compiling data from drought by heat experiments triggering mortality of seedlings, saplings, or adults (recently summarized in [Allen et al. 2015*](#)) to estimate percent decrease in time to mortality per °C increased during extreme drought. We are making physiological interpolations based on plant hydraulics to apply to dominant tree species for each forested NEON Domain; as part of the PJP LTER effort we will also extend this approach to each forested LTER site (i.e., AND, BES, BNZ, CWT, FCE, HFR, HBR, LUQ, NWT; see [Jones et al. 2012](#) for site abbreviations here and below).

4. Interactions of woody and herbaceous plants. Interactions between woody and herbaceous plants drive the amount of woody cover at a site, which fundamentally determines where a site lies within a continuum between grassland and forest ([Breshears 2006a*](#)). Numerous theoretical frameworks posit how shifts in the ratio of woody to herbaceous plants (in terms of cover, biomass, or primary productivity) occur ([House et al. 2003*](#)). We will synthesize across LTERs that are intermediate in the grassland-forest continuum (i.e., JOR, SEV, KNZ) to test these cross-site hypotheses on climate change disturbances.

5. Major transformations in arid and semiarid ecosystems. Collectively, the ultimate result of mortality events, altered disturbance regimes, recruitment limitation, and soil ecological changes is likely to lead to widespread alternative states in comparison to those currently existing ([Law & Morton 1993](#), [Beisner et al.](#)

2003, Staver *et al.* 2011). We will coordinate with comparison of conceptual models of major transformations in arid and semiarid systems across LTERS (i.e., JOR, SEV, SGS), and cross-walk these frameworks with the Smith (2011) framework to evaluate the degree to which they have accounted for extreme climate events and to consider how collective insights and use of a common framework could aide in improving conceptual models related to abrupt change.

9. Education and Engagement Activities

Our *Broader Impacts* will leverage the PJP LTER location, particularly the proximity to multiple Native Pueblos (e.g., Santa Clara, Jemez) and federal lands. As such, we propose to provide a STEM (Science, Technology, Engineering and Math) based pipeline that ranges from K-12 to graduate education to citizen outreach as well as incorporating science-driven land management policy recommendations co-produced with the managers and communities that need effective decision-making. Making informed decisions about how to manage risk and support cost-effective land-management decisions in the context of rapid ecological change requires ongoing, inclusive, and iterative decision-making processes, and the continual exchange of best practices and lessons learned. Recognizing that the PJP landscape has been shaped by intensive human land uses for millennia, we plan a co-produced knowledge approach with current federal land managers, Native and other communities, incorporating indigenous traditional knowledge and the scientific knowledge provided by the proposed research. Recognizing that changes in personal and societal values necessary to meet the challenges of climate change cannot be addressed by LTER science alone, a majority of the LTER sites have incorporated arts and humanities projects into their programming. Surveys of lead LTER PIs reveal the perceived benefits of increasing arts and humanities inquiry at LTERs, but cite the lack of funding and expertise as limiting factors. The need for documentation, archiving coordination, and dissemination is also stated (Goralnik 2015). Thus, we propose to incorporate dissemination of the PJP LTER-related arts and humanities projects through the UA Arts, Humanities, and Environment Network. Finally, we include traditional graduate and post-doctoral development opportunities as well as publication. This LTER will support three PhD students and three post-doctoral researchers. We plan to publish results of this work in journals like those we have been publishing in (see Biosketches), and will present at relevant conferences such as at annual Ecological Society of America meetings.

We have four *Broader Impacts* goals. These include:

1. Providing a strong education pipeline for Native American students (Section 9.1). The goal is to expose Native American students to high-quality local STEM career opportunities near their homelands (e.g., positions related to land and resource management with state or federal agencies or at Los Alamos National Lab). Currently, 20–28% of Native American students do not graduate from high school; of those that enter higher education, 50% do not pass their freshmen year. Native American students have the lowest rate of obtaining a bachelor's degree for students of all race/ethnic groups (Howards 2013).

2. Nurturing a strong Native community-researcher partnership model (Section 9.2). Acknowledging Pueblo sovereignty, we will build a collaborative model between the local communities and members of the research project. This model enables the exchange of knowledge between the research scientists and the ancestral land owners, offering opportunities to co-facilitate learning experiences that address notions of indigenous knowledge, identity, and self-determination in relation to land and environmental sustainability (Grande *et al.* 2015, McCarty & Lee 2014).

3. Encouraging knowledge transfer between scientists, land managers, and local communities (Section 9.3). Networks and partnerships can help to scale up the utility and impact of ongoing scientific assessment activities. This goal encourages the “co-production” of knowledge with regional communities and resource managers by integrating the work of the PJP LTER with on-the-ground decisions.

4. Providing public access to the PJP LTER work through the arts, humanities, and social media (Section 9.4). The ability of the arts to “develop empathetic relationships with the natural world and stimulate inspiration, awe and wonder” is essential for scientists to reach the public (Swanson 2015). Effectively communicating research results requires active engagement with the media, particularly as higher impact papers are published.

Finally, due to investigator cross-over and research synergies with other funded research projects, PJP LTER researchers will build upon education and *Broader Impacts* opportunities of the Critical Zone

Observatory Network (especially the Jemez-Santa Catalina led by UA), the Southwest Climate Science Center, the US National Phenology Network, and an international group including Spain and Latin America on advancing assessment of ecosystem services. By leveraging collaboration with an existing international network on ecosystem services in Latin America and the Iberian Peninsula, we will expand the focus of our research assessment to highlight how potential local-to-regional changes can affect regional-to-global ecosystem service dynamics. Combined the proposed *Broader Impacts* will provide significant societal benefits regionally, nationally, and globally.

9.1 Education Pipeline

The education pipeline efforts focus on the surrounding Native Pueblo communities. The efforts are led by UA College of Education Director for Education Outreach, Chavarria, with onsite coordination by the PJP LTER tribal and education coordinator. Efforts include K-12 teacher professional development (PD) workshops, an REU program, and K-12 classroom and field opportunities. The K-12 teacher PD workshops and K-12 classroom and field experiences will be part of our Schoolyard LTER program. These efforts leverage UA's existing education outreach initiatives in northern New Mexico such as the Jemez FHiRE Project, which engaged UA students, faculty and staff, and New Mexico Native Pueblos (see letters of collaboration).

Education learning objectives. During the course of the first LTER funding cycle, our approach is to achieve two short-term learning objectives (below). [Table 8](#) outlines our timeline.

*Objective 1: STEM career pathways awareness through **student-led research activities** for K-16*

Each year, two REU students in STEM related fields will be recruited from Arizona and New Mexico universities and community colleges to participate in onsite research activities ([Pender et al. 2010](#)). Once the program is established, we plan to expand our recruitment strategy nationwide. REUs will take place each summer for up to 10 weeks with continued experience during the fall semester in faculty labs. The program includes research and reporting activities as well as a tiered-mentoring experience with faculty, post-docs, and graduate students. Participants will engage in the PJP LTER *Broader Impacts* activities, such as community forums and teacher professional development workshops (see Objective 2). To ensure we are targeting a diverse STEM audience, we will leverage our network of U.S. Department of Education Student Support Services offices, which are located at the AZ and NM universities. We will also work closely with the relevant university departments, such as the UA's American Indian Studies program, and with the universities' Native American Student Affairs offices for our recruiting efforts.

Students will apply to the REU program by submitting a proposal of what they expect to learn and why the project would help them with their intended plan of study. Up to two mentors from the research team will be assigned to each REU student based on the student's research interests. The faculty mentor(s) will guide the students through the field and lab research processes. By week two, students must propose up to three possible research projects. Selection of the final research project will occur upon consultation with the mentor(s). REU students will meet weekly with their mentor(s) and with the onsite education coordinator to discuss progress. The REU's are designed to overlap with the teacher professional development workshops (weeks 3 and 4). Students will present their proposed research to workshop participants, the rationale for the research, their investigative questions, their data collection strategy, and any observations to date. By the end of the summer, students should have collected data, taken digital images/film of their work, and be ready analyze data in their fall semester under the guidance of their mentor(s). Their final product will be a digital story outlining their research, their data analysis, their results, and next steps in the research process. The digital story will be presented in the appropriate introductory undergraduate courses as selected by the mentor(s) and PI. To further the REU experience, students will be eligible to be student workers in researcher labs the following spring.

In Learning Objective 2 (described below) we aim to build upon our existing network of K-12 educators from the nearby school districts and Pueblos. We have existing relationships with Santa Clara Pueblo, Pojoaque Pueblo, Cochiti Pueblo, Zia Pueblo, Jemez Pueblo, Bernalillo School District, and Española School District in New Mexico. Utilizing this network, we will offer K-12 field research experiences to help students uncover relationships between field research and ecological challenges. Candidate field experiences include gathering data from insect traps, observing litter bag decomposition rates, observations of erosion bridges and growing soil crusts, recording vegetation along designated transects, and monitoring plant seedlings-soil types-heating relationships at experimental plots at the PJP

LTER. We will encourage students to present their field experiences in their classrooms, as well as to their respective tribal councils. Quantitative evaluation data on K-16 student interest and career awareness through pre/post interest surveys and career exploration surveys will be collected. Evaluation will include data on REU participation and persistence in STEM fields, pursuit of graduate school, and jobs in environmental fields, with foci on underrepresented student persistence and on high school student higher education college applications and major declarations. We will also collect demographic metrics of student participants. All data will be collected and analyzed utilizing UA Human Subjects Protection Program guidance. LTER Schoolyard funds will be leveraged to support classroom and field trip teaching materials and field trip transportation support.

Objective 2: Curriculum design via *teacher professional development workshops*

Our target audience is K-12 science and social studies educators from the PJP LTER neighboring pueblos and community school districts. Before we can best serve K-12 students, we must work closely with New Mexico teachers to co-design classroom lessons that contextualize the ecological and ancestral narratives. Curriculum materials must teach indigenous cultural and landscape knowledge, an approach will privilege indigenous knowledge and help teachers and students view STEM from an indigenous lens driven by a social-justice ecology. Our aim is to have 3–4 units per cohort team. LTER Schoolyard funds will be leveraged to support stipends for the teacher workshops and classroom research materials. Materials resulting from these workshops will be incorporated into the LTER Education Library.

Teacher workshops will take place annually starting in Year 2, resulting in curriculum materials and video tutorials to accompany the co-designed classroom lessons. The video tutorials will be incorporated in the science communication component (*Section 9.4*). We will begin with secondary education teachers in Years 2 & 3 and incorporate elementary education teachers in Years 4 & 5. Teachers will receive stipends for their participation in the workshops. Cohorts 1 (Years 2 & 3) & 2 (Years 4 & 5) teachers will participate in a 3-week program, each for two consecutive years. Each cohort will be made up of up to 8 teachers from 2–3 Pueblos. Teachers will apply to be a part of these curriculum ‘design’ teams and their applications will be reviewed by the education team which consists of Chavarria, Garcia, Johnson, and and the onsite coordinator. These two teacher cohorts will in turn demonstrate to other teachers their designed materials in shorter 1 week (secondary) or 1 day (elementary) dissemination workshops as outlined in *Table 8*. These smaller teacher workshops will also provide stipends for the up to 32 total participants. Qualitative evaluation approaches following the curriculum design process from the teacher perspective will include formative evaluation interviews and surveys protocols.

Table 8. Timeline of education activities.

	Y1	Y2	Y3	Y4	Y5	Y6
Objective 1: Student-led Research Activities	# of student participants					
REU Program	2	2	2	2	2	2
Secondary students conduct research at Pueblo sites	0	25	25	25	25	25
Elementary students at Bandelier	0	0	0	25	25	25
Objective 2: Teacher Professional Development Workshops	# of teacher (or artist) participants					
<u>Artist Cohort</u> : 5-7 day immersive field experience.	10	2	1	Art displays: 4 sites		
<u>Cohort 1</u> : 15-day Teacher professional development (PD) STEM investigative lesson design for Grades 7-12	0	Cohort 1: 8		Not Applicable (NA)		
— 4 day PD program for new teachers	NA			8	8	8
— PD delivered by Cohort 1 team members				2	2	2
<u>Cohort 2</u> : 15 day Teacher PD on lessons honoring ancestral land relationship for use in Grades 3-6	NA			Cohort 2: 6		NA
— 6-7 hour PD program for new teachers	NA					20
— PD delivered by Cohort 2 team members						2

We will incorporate elements from the Arts, Humanities and Environment Network (described below) within the teacher workshops. In addition, we will incorporate findings from the Iconic Trees & Groves workshop. This 2017 workshop, funded separately, will be led by TS Swetnam, Allen, Breshears and

McMahon and will address the global status and risks to large ancient trees and further determine the drivers of old-tree mortality, the ecological and cultural consequences of the loss of the world's last great trees (e.g., effects on biodiversity, genetics, ecosystem services, indigenous community impacts and societal values at risk), and identify options that could increase protection for iconic trees and groves at risk; the PJP team will hold a subsequent workshop to apply insights to the greater Colorado Plateau.

9.2. Community-Researcher Partnership Model

*Objective 3: Exchange local landscape knowledge through **Pueblo community-building forums***

These forums will enable the understanding of long-term and near-term human disturbance legacies and interactions on the Pajarito Plateau. Researchers will be able to join the dialogue on balancing indigenous cultural knowledge with the scientific prediction of the PJP LTER. Community forums at each of the Pueblos will take place annually. Through qualitative evaluation of forum discussion, Chavarria's team will assess via observation and note-taking the levels of interest and concern per forum topics, community questions, and community information requests. Synopsis of forum discussion will be posted on-line in blog format with a digital community feedback form. Thus, not only will this effort provide a mechanism for effective collaboration and communication regarding the PJP LTER science efforts, it will also provide UA's education researchers the opportunity to help identify how scientific prediction can be used to inform indigenous cultures about threats to their lands and resources, thus providing a mechanism that enables action or request of remedies prior to catastrophic ecosystem failure. This could lead to a framework for those who work with indigenous cultures to put protections in place.

9.3. Co-produced Knowledge Transfer

Objective 4: Scale up the utility and impact of ongoing scientific assessment

We propose stakeholder engagement in which we will facilitate **co-production of knowledge, particularly among scientists, land managers, and local communities**. The UA Center for Climate Adaptation Science and Solutions (CCASS) will design and lead the stakeholder engagement strategy, with a two-part focus: 1) Maximizing access to partners through existing federal science networks, including NOAA's Climate Assessment for the Southwest, the DOI Southwest Climate Science Center and Desert Landscape Conservation Cooperative, and the USDA Southwest Climate Hub; and 2) Ensuring that local resource managers and community members are integral to the science team and the research design. Leveraging the previous work of CCASS core team we will oversee and encourage "co-production" of knowledge with regional resource managers by integrating the work of the LTER with on-the-ground decisions. We will focus on engaging the National Park Service and the US Forest Service. Co-production requires serious, ongoing engagement with partners, and the CCASS team has decades of experience in achieving better scientific outcomes while connecting actionable science to decisions. We will coordinate one-on-one meetings and/or virtual meetings at least quarterly with our partner land managers as we co-develop the LTER agenda and outcomes, promote cross-network communication, and facilitate biannual network science meetings. CCASS Director Jacobs and Chavarria will coordinate to ensure that federal land managers and indigenous land managers have the opportunity to also work collaboratively. We have split these goals and objectives due to our knowledge of onsite operations.

9.4. Public Access and Communication of PJP LTER Science

Objective 5: Make PJP LTER science accessible to the public by through the arts and the media

The ability of the arts and humanities to engage and inform the public about long-term ecological research is well documented (Goralnik 2015, Swanson 2015) and especially critical at sites impacted by human-caused climate change. Through ongoing collaboration via the Arts and Environment Network co-hosted at UA, founding executive member and art professor McMahon will develop an artist field immersion/exhibition/publication program, in coordination with PJP LTER scientists and the onsite tribal and education engagement lead. The program will convene ten visual artists and writers (with strong local indigenous representation) to undertake immersive onsite field experience, research scientific and traditional indigenous perspectives, and create new works foregrounding the cultural meaning and significance of the Southwestern forests. Final works will be incorporated into K-12 (through the teacher professional development workshops) and UA art-science curricula, presented and discussed in Pueblo community forums, and disseminated through a digital gallery/journal, an exhibition (originating at UA Museum of Art and traveling to galleries and visitor centers in the proximity of the PJP LTER site), and the National LTER Ecological Reflections Archive. The success of this project will be assessed by the number

of people who attend the exhibitions, the extent of local media coverage, the level of interest in artists to continue working with scientists on environmental issues, and the change in conservation ethics in audiences measured by short before and after questionnaires at the exhibitions. Effectively communicating research results requires active engagement with the media, particularly as higher impact papers are published. PI Breshears has been trained in interacting with media and policy makers through the Aldo Leopold Leadership Program. He has provided interviews to cover his research for numerous local newspapers as well as by the New York Times, USA Today, NPR All Things Considered, and the Washington Post. By nature, this type of activity is opportunistic and difficult to plan for precisely. Nonetheless, planning to leverage media opportunities when a paper is accepted in a prominent journal affords the best opportunity to reach a broad public audience with relevant research results (Baron 2010). Also, Co-PI Gallery will lead efforts to pursue social media outlets for communicating about PJP LTER research, ecology, and climate change (in addition to websites for the PJP LTER and LTER Network).

10. Future Directions

Our conceptual framework (**Box 1**) sets out our long-term approach. We expect that future PJP funding cycles will build on the same conceptual framework. Additional opportunities for expansion include: *i*) elevational gradient connections from lower drier sites where piñon did not exist pre die-off reset up through ponderosa pine ecotones (Allen & Breshears 1998*); *ii*) contrasts with higher elevations of ponderosa pine and mixed conifer associated with the Jemez Mountains CZO, also located within BNM (Chorover *et al.* 2011*; Pelletier *et al.* 2013*); *iii*) upland and canyon bottom riparian relationships (Johansen *et al.* 2003*); *iv*) differential responses of thinned and unthinned woodland sites that have also undergone die-off reset (Hastings *et al.* 2003, 2005*, Jacobs 2015); *v*) key variation with soil types (especially with and without pumice; Hastings *et al.* 2003); *vi*) avifauna community dynamics (Fair & Myers 2002); *vii*) large-mammal influence and connectivities across the larger landscape including impacts of large-mammal exclosures (Rupp *et al.* 2001a, 2001b, Kleintjes Neff *et al.* 2007); and *viii*) integration of erosion as related to ecological and archeological factors across the cultural landscape.

11. Team Expertise

PI Breshears (*LTER 5: Disturbance*) has led research on hotter-drought impacts related to tree die-off and wildfire through observational and experimental studies and development of conceptual and predictive models; has researched PJP for >25 years; is a Co-PI on the Jemez Mountains CZO (Rasmussen and Gallery are also part of this CZO); and has led outreach through media coverage and art-science collaborations. **Lead Collaborating Researchers:** Allen has led research at PJP for >30 years focused on drought and wildfire-triggered woodland transformations via long-term observational studies and management-relevant manipulations placed in a global context, including long-term vegetation and arthropod pitfall data sets core to PJP; **McDowell** has led the advancement of determining the physiological processes underlying tree mortality change, large-scale mortality experiments, and will facilitate LANL collaborations. **Co-PI Monson** (*LTER 1: Primary Productivity*) has 15 years of LTER Co-PI experience at Niwot Ridge, and core expertise in both plant ecophysiology and ecosystem ecology. **Co-PI W. Moore** (*LTER 2: Population Dynamics and Food Webs*) has extensive taxonomic and curatorial expertise on arthropods, has related arthropod dynamics across elevation with climate change, and leads the annual Arizona Insect Festival outreach program. **Co-PI Gallery** (*LTER 3: Organic Matter Dynamics*) has prototyped new landscape microbial activity metrics using digital soil mapping to interpolate from pedon to watershed; examines microbial-mediated soil-plant responses to press and pulse disturbances; and integrates large, metadata-rich, open-access microbial and biogeochemical datasets (e.g., NEON, CZO) into project-based classroom activities. **Co-PI Rasmussen** (*LTER 4: Inorganic Inputs and Nutrient Dynamics*) has extensive experience in modeling soil spatial properties, carbon cycling and mineral weathering and has developed a theoretical framework applicable to soil processes (EEMT) **Information Management Director Durcik** is a recognized leader across the CZO Network. For *Broader Impacts*, overall coordinator **Chavarria** guides UA environmental education initiatives and has specific experience recruiting from underrepresented populations in northern NM; **Garcia** leads research on community engagement and indigenous education, **Johnson** evaluates education initiatives, **Jacobs** directs the *Center for Climate Adaptation and Science Solutions*, and **McMahon** has exhibited juried artwork on tree die-off. Technical expertise of other **Senior Personnel** (see Biosketches) will further enable PJP success.

12. Results from Prior Support

EF-1340624 Macrosystems Biology (\$764,991; 4/1/2014 – 3/31/2017). *Collaborative Research: Ecoclimate Teleconnections between Amazonia and Temperate North America: Cross-Region Feedbacks among Tree Mortality, Land Use Change, and the Atmosphere*. UA (Lead) - **PI: DD Breshears**. *Intellectual Merit*: This project addresses how large-scale forest change from die-off and deforestation in N. or S. America could affect climate conditions through ecoclimate teleconnections, using microclimate measurements and modeled cross-continental forest response to climate. Completion of 5 field campaigns (AK, AZ [2], NM, and Amazonia). *Broader Impacts*: co-organized special AGU sessions (2014 and 2015); a newspaper article (Peninsula Clarion); an art-science collaborative installation at UA, and support for two post-docs and a female Hispanic NSF Research Experience for Undergraduates scholar. *Publications & Products*: 9 journal publications and 1 book ch.; 4 in review.

EF-1065790 Macrosystems Biology (\$2,949,061, 5/11/2011 – 5/10/2016). *Collaborative Research: Processes and Patterns in the North American Monsoon Macrosystem*. UA (Lead) – **PI: R Monson**. *Intellectual Merit*: Assembled a suite of models from local weather forecast to watershed-scale runoff; produced intercomparison of 4 long-term NDVI datasets based largely on AVHRR sensor and 3 datasets from newer sensors (SPOT, Terra, Aqua), and evaluated effectiveness of homogenizing datasets using green vegetation fraction (GVF) and impact on ecosystem phenology; focused on model-data fusions. *Broader Impacts*: Trained 4 graduate students, 8 post-docs; supported research of 2 Hispanic early-career faculty members; trained 1 Hispanic graduate student. *Publications & Products*: 11 journal publications, 3 in press, 1 in review; WRF-Hydro modeling system allows open community process, organized at NCAR, access to model coupling framework to interface with terrestrial hydrological models.

EAR-0724958 (\$4.25M, 9/1/09 – 8/31/13). *Transformative Behavior of Water, Energy, and Carbon in the Critical Zone: An Observatory to Quantify Linkages among Ecohydrology, Biogeochemistry, and Landscape Evolution*; **EAR-1331408** (\$5M, 10/1/13-9/31/18) *Transformative Behavior of Energy, Water and Carbon in the Critical Zone II: Quantifying the Interactions between Long- and Short-term Processes that Control Critical Zone Services*. UA (Lead, both awards) – **0724958: CoPI: C Rasmussen, Sr. Personnel: R Gallery**; **1331408: CoPI: DD Breshears**. *Intellectual Merit*: Support for Santa Catalina Mountains & Jemez River Basin Critical Zone Observatory. Key results include: an open system conceptual model of CZ forcing that integrates water and carbon fluxes into the subsurface; co-located measurements of matter and energy flux at multiple scales with static and continuous data streams; a coupled numerical process model and landscape evolution modeling informed by climatic forcing; resolving how these coupled processes underpin CZ services and how a longer time scale geoscience perspective can inform and improve characterization of ecosystem services. *Broader Impacts*: Supported 9 postdoc researchers, 21 graduate students, and >25 undergraduates; science tour app, adult science café series, podcast series, and a K-12 Critical Zone Discovery program; presentations to state and federal agency stakeholders. *Publications & Products*: 100 peer-reviewed publications (Co-PI Rasmussen author or coauthor on 22 of these); public data via National CZO; conceptual & process models, including Effective Energy and Mass Transfer (EEMT) and Terrestrial Integrated Modeling System (TIMS).

DEB-1256976 (\$532,948, 2/15/2013 – 1/31/2017) *Explosive Radiation, Extreme Phenotypic Diversity, and the Evolution of Morphotypes within Ant Nest Beetles*. **PI: Moore Brusca**. *Intellectual Merit*: First phylogeny of the beetle genus *Paussus* from 5 genes and revision of species groups. Underway testing if adaptation to macrohabitat (host ant) preceded evolution of microhabitat (geography), and if adaptation to macrohabitat (rather than to microhabitat) drives greater phenotypic change. *Broader Impacts*: 1 postdoc researcher, 1 grad student, and 2 undergraduates trained. *Publications & Products*: 8 journal publications.

IOS-1354219 (\$653,072, 6/15/2014 - 5/14/2017) *Bacterial Controls of Endophyte Ecology: An Unexplored Dimension of Diverse Plant-Fungal Symbioses*. **PI: Gallery**. *Intellectual Merit*: Initial results point to bacterial symbionts within these fungi as drivers of decomposition process. Model system (*Luteibacter* + various fungi) appears to be at an initial stage of symbiosis; genomes of bacterial symbionts do not show signs of deterioration and minimization as other intracellular symbionts; assessment of ecological and evolutionary implications underway. *Broader Impacts*: Enhanced high school curricula and training in professional skills for science or other fields (e.g., HS science camp, molecular microbiology program, peer mentoring network). HS participants from urban, Hispanic-serving schools; >50% female. *Publications & Products*: 1 journal publication, 1 in press, 1 in review; website for dissemination.

13. Anticipated Reviewer Concerns

Table 9. Anticipated reviewer concerns and responses based on our research experience, iterative planning, and preliminary feedback.

<i>Doesn't testing your hypotheses depend on lack or occurrence of additional disturbances?</i>	Our design is neither dependent on nor derailed by the occurrence of an additional hotter drought impact. We have specifically targeted a site that has already been impacted by disturbance, and our conceptual framework is robust enough to account for subsequent disturbances, should they occur.
<i>Is the modeling approach proposed sufficiently sophisticated to address the relevant complex ecosystem dynamics?</i>	The vegetation dynamics component of VMTran was specifically designed to account for Anthropocene effects resulting in tree die-off and wildfire. Ecological modeling entails tradeoffs between complexity, prediction, realism, and detail. We advocate starting from a model focused on abrupt change transitions rather than from existing models developed for other purposes.
<i>How will you account for the human impacts important in your landscape?</i>	We recognize human impacts have a legacy in our landscape and we have land-use information back through the 1200s. We will initially explore how to qualitatively explore factoring human impact before accounting for them quantitatively.
<i>Isn't locating field sites within NPS Wilderness and on a National Lab too restrictive for needed LTER activities?</i>	Protection of research infrastructure is of paramount importance, especially for long-term research. BNM and LANL afford PJP protected sites with minimal land management interference and low probabilities of vandalism. BNM has a track record of >25 years of research in wilderness, and our preliminary designs have been vetted with them. LANL is able to provide access to citizens from all but a few countries with short advance notice and modest coordination. Our onsite research coordinator and LANL support personnel ensure needed timely plot access.
<i>Can you effectively run the site remotely?</i>	UA will invest in an onsite research manager and an onsite education/engagement coordinator and associated onsite office space. UA runs PJP-adjacent Jemez Mountains CZO (with Breshears, Rasmussen, and Gallery as CoPIs/Sr Personnel), which just completed a successful programmatic review. Breshears has 15 years experience researching PJP landscape. Several other LTERs are operated from a distant institution.
<i>Do you have adequate facilities for meeting and lodging?</i>	We have potential access to meeting space at our installed trailer at BNM, at BNM Headquarters, at LANL, at BLM in Santa Fe, and, if need be, through rented conference room space at any one of numerous casinos near PJP. Due to large education programs at LANL, lodging in Los Alamos is limited, but there is plenty of adequate lodging at casinos between Santa Fe and BNM or in Santa Fe itself.
<i>Many claim they will reach a more diverse community through education and fail – can you really succeed?</i>	To reach underrepresented groups requires a substantial and focused investment. When focused on increasing participation from Native American groups, engagement must account for annual changes in Tribal Councils. We are specifically investing in an identified onsite Native American education/engagement coordinator with proven STEM experience with northern NM Native American pueblos.
<i>Why not focus primarily on reducing impacts via management of tree genetics and fuels?</i>	The PJP landscape was completely transformed by the recent die-off and extreme wildfire—leaving only a few small remnant fragments with adult piñons—highlighting that hotter drought threatens to overwhelm resistance conferred by genetics or fuels management in practical time frames.

14. Synthesis

Global change disturbances driven by drought under ever hotter conditions have and will continue to trigger plant die-offs and extreme wildfires in piñon-juniper woodlands of the western US and in semiarid systems globally. These transformations have become an iconic poster-child of climate change consequences for arid and semiarid ecosystems worldwide (IPCC 2014*). *The biggest opportunity for the LTER Program to simultaneously advance ecological science and societal relevance regarding climate change is to consider ecosystems already undergoing the most rapid, disturbance-triggered transformations—those of sufficient magnitude and geographic extent as to be of imminent concern to the public as well as to ecologists and land managers.*

Recap of Intellectual Merit. No other LTER so centrally focuses on the rapid, pronounced, and extensive disturbances directly tied to climate that have potential for state change and novel trajectories. Semiarid woodland is arguably the most widespread biome absent from the current LTER network. Hotter-drought driven tree die-off and wildfire directly address identified LTER arid/semiarid needs: *“rapid changes due to climate, land use, fire and shifting biotic interactions”* and *“resultant reduced productivity, shifts in vegetation structure, changes in plant-soil feedbacks, and the importance of legacy effects”* (NSF 16-509). There is a critical need to build on recent conceptual frameworks that consider the ecological consequences of extreme events (e.g., Smith 2011) to factor in potential for novel ecological trajectories and ascertain the nature of underlying mechanisms that determine ecological trajectories, while also accounting for legacy effects, current ecological conditions, and protracted climate conditions (i.e., decadal to multi-decadal) that provide constraints on potential responses. While all LTER sites consider “disturbance patterns” as one of the five Core Areas for long-term data and research, none to date has specifically targeted from the onset an ecosystem undergoing rapid, climate-driven transformation.

Our *expected outcomes* of an initial cycle of LTER funding for PJP include the following, as linked to LTER Core Areas 1-4: *i)* observationally and experimentally determined key factors differentiating the initial divergences post-die-off (re-establishment of piñon or not) and extreme wildfire (resprouting shrubs or invasive grasses); *ii)* characterized range of variability in key climatic, soil moisture, and vegetation conditions pre-disturbance; *iii)* improved predictions of climate conditions triggering die-off and extreme wildfire; *iv)* developed/modified more generally applicable models accounting for the suite of extreme events, climate conditions and processes of interest; *v)* evaluated, in a variety of ways, our overarching hypothesis: *amplifying feedbacks associated with plant–biocrust–brown-food-web–soil feedbacks in the near soil-surface sliver mediate disturbance-initiated state change and novel trajectories in rapidly transforming ecosystems (influenced by favorable/unfavorable climate and extreme events)*; and *vi)* developed a suite of more general insights through cross-site synthesis activities.

Recap of Broader Impacts. Our *Broader Impacts* leverage the PJP LTER location, particularly the proximity to Native nations and federal lands, to provide significant societal benefits. Our *Broader Impacts* recognize that changes in personal and societal values necessary to meet the challenges of climate change cannot be addressed by science alone. In light of this, a majority of the LTER sites have incorporated arts and humanities projects into their programming. Surveys of lead LTER PIs reveal the perceived benefits of increasing arts and humanities inquiry at LTERs, but cite the lack of funding and expertise as limiting factors. We will address four *Broader Impacts* goals: *i)* provide a strong education pipeline for Native students; *ii)* nurture a strong Native community-researcher partnership model; *iii)* encourage knowledge transfer between academic research scientists and federal scientists; and *iv)* provide public access to the PJP LTER work through the arts, humanities, and social media. Our expected outcomes for *Broader Impacts* include a fostered vibrant education and engagement program that affect the education pipeline, co-produces knowledge (rather than the more typical one-way transfer of information via outreach), and reaches broad national and international audiences regarding our results.

Recap of Team Expertise and Site Legacy. Our *team* expertise includes transformational hotter-drought research on tree die-off (e.g., Breshears *et al.* 2005*) and wildfire (e.g., Williams *et al.* 2013*); observational data sets spanning > 25 years; 15 years prior LTER experience (Co-PI Monson); expertise in all five LTER core areas; a demonstrated record operating a long-term study site from a remote campus (Jemez Mountains CZO by Univ. Arizona); and a compelling track record of *Broader Impacts* reaching underrepresented groups with novel engagement approaches. PJP leverages numerous long-term data sets and a state-of-the art drought x heat tree mortality experiment. PJP includes more than 35 papers with >100 citations each, together totaling >13,000 citations (Google Scholar).

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FACILITIES, EQUIPMENT, AND OTHER RESOURCES

PJP LTER Onsite Facilities, Equipment, and Other Resources

The University of Arizona (UA) is experienced in managing remote research sites; specifically PJP LTER PI Breshears and Co-PIs Gallery and Rasmussen have experience with the NSF funded Catalina-Jemez Critical Zone Observatory (PJP is part of the Jemez Mountains in New Mexico and located just below the Jemez River Basin portion of the Catalina-Jemez CZO). To facilitate research and provide office space for the onsite personnel, UA will provide a three room trailer (two offices, one storage room, and one-half bath) located at Bandelier National Monument. Utilities for the trailer will be provided by UA. One of the offices will be dedicated to the full-time (FTE) onsite Senior Research Specialist. The other office will be available for visiting researchers and the 0.75 FTE Tribal and Engagement/Education coordinator. The climate controlled offices will be equipped with a desktop or laptop, printer/copier/fax, internet access, and a data web server. The data and web server will be a Dell PE R710 with redundant RAID disk storage 3TB. The storage room will be used for field equipment and office supplies.

The onsite *Senior Research Specialist* and *Tribal and Engagement/Education Coordinator* will be employed by UA. The *Senior Research Specialist* will be responsible for providing onsite support for researchers assisting with equipment maintenance, data collection and management, and facilitation of external researchers at the LTER site.

The *Tribal and Engagement/Education Coordinator* has expertise working with New Mexico's Native American communities. The *Coordinator* is especially well networked with the Pueblo communities, small cities/towns, and multiple school districts in Northern New Mexico.

This project will utilize two UA-owned dedicated vehicles. One crew cab four-wheel drive truck will be located onsite in New Mexico for use by visiting researchers and the *Senior Research Specialist*. An additional crew cab four-wheel drive truck will be located at the UA for researchers to travel to/from the site as well as for hauling equipment and supplies to/from the site.

Additional Facilities

PI & Co-PI Laboratories

Terrestrial Ecology Lab: Breshears maintains a terrestrial ecology lab focused on ecohydrology with resources to test hypotheses and develop theory on the interactions and feedbacks between vegetation, microclimate, and soil water. Particularly relevant to this proposal, the lab has a state-of-the-art hemispherical photography system and a complete pair of portable mast systems for energy balance – canopy structure campaigns (including 4 component net radiometers, portable weather stations, soil heat flux plates, soil thermocouples, and Campbell data-loggers). The lab has sufficient space and equipment for analyzing soil samples: texture, structure, bulk density, percent organic matter, water holding capacity, plant available water, soil water potential, and hydraulic conductivity. Breshears' lab has a LI-6400 Portable gas exchange System (LI-COR Biosciences, Lincoln, NE) and a leaf porometer (SC-1, Decagon Devices, Pullman, WA). In addition, the Breshears' lab has a PMS-1000 Scholander pressure chamber (PMS Instrument Company, Albany, Oregon) for measuring plant xylem water potential. The Breshears' lab has the necessary computing equipment to analyze hemispherical photographs for a variety of canopy metrics. These computers also have data analysis software: SAS, SPSS, sigma plot, and MatLab. The lab has a Trimble handheld GPS (Trimble Navigation Limited, Sunnyvale, CA) with antennae for measuring microsites to a resolution of 10 cm. Breshears has two four-wheel drive pick-up trucks for travel to sites in the Southwest partially available for this project. Breshears supervises one full-time *Senior Research Specialist* with expertise in tree mortality, who will coordinate greenhouse construction in the experiment portion of the project.

Gallery Soil Ecology Lab: Gallery maintains a Biosafety Level 2 (BSL-2) and Chemical Safety Level 2 (CSL-2) laboratory of approximately 1,600 sq ft separated into three dedicated workspaces for wet-lab and soil processing, biotic and chemical incubations and assays, and clean room space for microbial culturing and maintenance and PCR preparation. Laboratory equipment includes a Biotek fluorescence/absorbance microplate reader with a dedicated Dell PC, Sorvall Legend T+ ultracentrifuge with microplate adaptor, five desiccators with vacuum pump and accessories, Biospec Mini-Beadbeater for cell lysis, capacity for sample and chemical storage in three Thermo Fisher Scientific (-80) Ultralow freezers, three Thermo Fisher Scientific (-20) freezers, two refrigerators, chemical flow-hood, incubators,

shakers, heating blocks, two Fisher PCR biosafety cabinet workstations, two Eppendorf Master cycler pro gradient Thermocycler (96 well), OWL Model A2 electrophoresis gel box with accessories, and multiple electronic and manual multichannel pipettors. Other standard equipment for soil biogeochemical and biotic analyses includes Milli-Q water purifier, pH meter, microbalances, hot plate-stirrer, microwave, two drying ovens, and a muffle furnace. One desktop high performance, dual processor mac computer is dedicated to assisting with data processing and analysis. A Shimadzu TOC-L Series Total Organic Carbon (TOC) and nitrogen analyzer equipped with auto sampler for water samples (TOC-LCSH). A SSM-5000A unit for analysis of solid samples is located at UA's Biosphere 2 facility, run by Dr. Katerina Dontsova; samples from Gallery's projects are processed at cost of chemical and disposable replacement. Through colleagues in SNRE, Gallery has access to shared Licor LI-8100A Automated Soil CO₂ Flux System. The UA Genomics and Technology Core (GATC) is a centralized sequencing facility providing competitively priced, high-quality, and fast-turnaround ABI 310 Genetic Analyzer and Illumina sequencing services. UA data backup includes 1 TB of storage dedicated to the Gallery lab, of which < 3% has been used.

Moore Lab: The Moore lab contains state-of-the-art equipment for molecular and morphological analysis. The molecular lab contains three Mastercycler Eppendorf thermocyclers, one is a gradient block; Sybr green gel VWR digital imaging system, which wirelessly connects to an iMac and HP LaserJet printer, three VWR -20 °C freezers, a Sanyo VIP -80 °C freezer, a 4 °C refrigerator, single and multi-channel Biohit and Eppendorf pipettors, two Eppendorf microcentrifuges, four VWR vortex mixers and two VWR aluminum heatblocks, one Labnet VorTemp 56 oscillating incubator, an Air Sentry fume hood, and a UV Crosslinker for sterilization. The Moore lab has a separate room that houses a Mac-Pro with 3.7 GHz Quad-Core Intel Xeon E5 processor with 64 GB of memory. For long-term storage of high-throughput sequencing reads, the lab has a Pegasus2 R8 system of linked eight x 3TB drives. This machine is devoted to transcriptome and genome assembly, RNA-Seq analyses, gene annotation, and includes CLC Genomics Workbench, Blast2Go, Geneious software programs. An adjacent area houses a S6E Leica stereomicroscope with LED fiber optic light sources and Dell desktop PC. Additional backup (10TB) and script-based program execution for next generation sequencing (NGS) analysis has been secured through the University of Arizona High Performance Computing/High Throughput Computing (HPC/HTC) system. On the HPC/HTC, the lab has access to programs for *de novo* assembly and downstream analyses, for example: Trinity, Velvet, Bowtie, Blast, MrBayes, and RAXML. The laboratory has ample counter space (20 m²) for processing and curating specimens. Specimen processing, DNA archiving and extracting, and amplification occurs in a separate wet lab area. A manager supervises and maintains the lab.

The associated morphology lab is used to process specimens and perform morphological analysis. The lab contains a 20-drawer half cabinet and 5 half-tall cabinets for specimen storage and processing, a new Leica M125, Olympus compound scope with camera tube for digital imaging, a Wild M3Z dissecting scope with tube and fiber optics, three work tables, a station for morphological dissections, and area for generating specimen labels. The facility contains an HP PhotoSmart d7560 printer for alcohol-tolerant labels, and a laptop for label production. A separate, yet neighboring, photography room contains a complete BK+ Visionary Digital Imaging station, including a Dynalite Studio Pro 1600 flash generator power pack, 2 NEC MultiSync EA241 flat screen monitors, a BK Visionary Digital System tower with BD Rewriter, light stand, a Canon EOS 7D digital camera, a Wild M5 scope with fiber optics, and ultrasonic cleaner. The PI's office contains two half-cabinets to store specimens, a Leica 205 dissecting scope, one -20 freezer and a Macintosh computer. The room adjacent to the PI's office contains one half-cabinet to store specimens, a Leica 165 dissecting scope, and new Macintosh computer (2.8 GHz Intel Core i7).

In addition, the Univ. Arizona Insect Collection (UAIC)/Entomology Department is fully capable of shipping /receiving specimens and supplies under the most current national and international shipping standards. Specimens stored in vials of ethanol are shipped with absorbent material in double, heat-sealed polyethylene bags. These shipping supplies are maintained in the UAIC shipping room. UPS, FedEx shipments are received directly at the UAIC/Entomology Department. Molecular sequencing capabilities and Scanning Electron Microscopy are easily accessible in shared research facilities conveniently located in the building next door to Forbes on campus. The University of Arizona Insect Collection resides on the same floor and has a dedicated room for visiting scientists.

We benefit substantially from our association within the larger University community. We receive administrative/secretarial support from the department secretarial staff. We also benefit tremendously from the computer/technology support of CALSNET, the IT facility associated with the UA College of Agriculture and Life Science. The UA library has substantial holdings of entomological literature (current and historical) and on-line access to all the major literature search engines. Paper publications not present on campus are obtained efficiently by Interlibrary Loan Services.

Environmental Pedology Laboratory: Rasmussen runs the Environmental Pedology Laboratory and serves as Director for the University of Arizona Center for Environmental Physics and Mineralogy (CEPM). The Environmental Pedology Lab and CEPM currently occupy roughly 4,000 square feet of recently renovated laboratory space with separate sample storage and preparation areas. All analytical instrumentation is state-of-the-art and was recently purchased or fabricated within the last three years. The following provides a brief overview of available instrumentation:

- *Particle Size Analysis:* Equipment for particle size analysis includes a fully automated Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyzer. The LS 13 320 is equipped with a multi-wavelength optical bench that incorporates Polarization Intensity Differential Scattering (PIDS) technology that allows highly accurate measurements over a particle size range from 0.04 μm to 2,000 μm . An automated sample preparation station with sample carousel facilitates high throughput and high consistency. In addition, we have a computer controlled dry/wet sieving system available to measure particle size distributions for sandy materials and larger particle sizes.
- *Surface Area and Micro Pore Size Distribution Analysis:* Equipment for surface area analysis includes a Beckman Coulter SA 3100 Gas Adsorption Surface Area Analyzer and WP4-T Dewpoint Potentiometers to measure water adsorption isotherms. The SA 3100 with internal PC and flexible software provides accurate measures for BET and Langmuir surface area, BJH Adsorption and Desorption, Pore Size Distribution, t-Plot, and total pore volume. Nitrogen, Krypton, or Argon can be used as adsorbent gases. An external degassing station facilitates high throughput. Analysis of water adsorption isotherms obtained with the WP4-T offer a second advanced avenue to determine surface area.
- *Liquid Retention and Hydraulic Conductivity:* A fully automated permeameter system that was developed for precise determination of saturated and unsaturated hydraulic conductivities is available. Decagon WP4-T Dewpoint Potentiometers, Tempe cells, pressure plate devices, vacuum chambers, vacuum pumps and controllers, are available for accurate determination of liquid retention characteristics.
- *Mineralogical Analysis - X-ray Diffraction:* The CEPM includes a PANalytical X'Pert Pro MPD X-ray Diffractometer (XRD) for the qualitative and quantitative identification of crystalline mineral and organic phases. The XRD unit produces Cu-K α radiation, with the option of a graphite monochromator or Ni-filter for removal of Cu-K β radiation and background noise from Fe-fluorescence, utilizes fixed divergence and convergence slits, a sealed xenon detector, and associated X'Pert Highscore Plus software with the full ICDD Powder Diffraction File database for analysis of diffraction patterns. The XRD unit also has a 15-sample autosampler for efficient sample throughput. All components of the XRD unit are machined and pre-aligned allowing for the easy interchange of all components.
- *Organic and Inorganic Thermal Analysis:* Equipment for thermal analysis of organic and inorganic materials includes a Perkin-Elmer Diamond TG/DTA with a high temperature range (ambient to 1500°C) and vacuum capable furnace with forced air cooling. The Diamond TG/DTA uses a simultaneous thermoanalytical technique measuring weight loss/gain with a horizontal differential balance and change in temperature or heat flow as a function of temperature or time. The heating rate is programmable from 0.01 to 100°C/min and can operate with various purge gasses and flow rates. The simultaneous TG/DTA measurement system may be readily converted to calorimetric units using tin and indium standards. Thermal analysis may be used to quantify mineral and organic phases, energies of hydration, and energies of combustion.
- *Soil Dielectric Analysis:* CEPM has eight TDR100/CR1000 Time Domain Reflectometry (TDR) datalogger multiplexer combinations for water content measurements in laboratory columns and at

field sites. In addition, we have two Tektronix 1502C cable testers that are more suitable for mobile field characterization of soil water content.

- *Computer Infrastructure and Data Storage:* Available computer equipment includes a dedicated computer with all analytical instruments (LS 13 320, SA 3100, WP4-T, XRD, etc.); each machine is networked and routinely backed up. A high capacity Linux file server is available for data storage and database applications (two 2.8 GHz dual core AMD-64 CPUs, 8 GB RAM, and 4 TB in RAID 5 storage). CEPM also has two servers for computationally intensive tasks (two 2.8 GHz dual core AMD-64 CPUs, 32 GB RAM each). The latter two systems are capable of running 64-bit versions of Linux or Windows 7, depending on software requirements.
- *Other Available Equipment & Infrastructure:* Other available equipment includes a TestEquity 1007H Temperature/Humidity Chamber for sensor development, calibration, and testing, and a vast array of sensors and loggers for field moisture, salinity and temperature measurements. Machining facilities within the CEPM, including metal/plastic lathe, band saw, drill press, table saw, and extensive hand tools, facilitate fabrication of instrumentation and accessories at substantial cost savings as well as provide flexibility and rapid response to specific research requirements. For larger machining projects, we have access to three highly specialized machine shops at the University of Arizona Campus Agricultural Center, and Environmental Research Laboratory. A Ford F-100 pickup truck and a Dodge Ram 1500 pickup are available for field campaigns.

Additional Labs and Research Facilities Available

Barron-Gafford Lab: Maintains a well-instrumented ecosystem ecology lab with capabilities for measuring CO₂ and water vapor flux from chambers to whole ecosystems and conducting indoor experiments ranging in scale from growth chambers to the entire Biosphere 2 glasshouse facility. In association with collaborator Dr. Russ Scott at the USDA Southwest Watershed Research Center, Barron-Gafford maintains six eddy covariance towers used to estimate ecosystem-scale carbon, water, and energy exchanges. These sites have a full complement of eddy covariance measurements including both open path IRGAs (LI-7500, LI-7200, LiCor Biosciences, Inc), sonic anemometers (CSAT3, Campbell Scientific), data loggers (CR5000, Campbell Scientific), and CO₂/H₂O profilers. The sites have meteorological (PAR, solar and longwave radiation, air temperature/relative humidity, wind speed/direction, rain gages) and soil instrumentation (soil moisture and temperature profiles, ground heat flux plates). In addition, Barron-Gafford maintains three LI-6400 Portable Photosynthesis Systems (LiCor Biosciences) and a custom portable soil respiration system, which operates off of an LI-840 (LiCor Biosciences). Barron-Gafford coordinates use of the Biosphere 2 departmental ground-based Light Detection And Ranging (LIDAR) Leica ScanStation C10 (Leica, San Ramon, CA), which will be prioritized for use in association with this project, should the need arise.

Biosphere 2 Labs: Biosphere 2 Biogeochemistry laboratory is equipped with all necessary equipment needed to process a large number of samples (chemical hoods, centrifuge, source of ultra-pure water, analytical and table top balances, pH and conductivity meter, soil sampling equipment, mortars/pestles and sieves to prepare samples for analyses). Biosphere 2 also retains a full time visual design staff member available to help in the development of professional displays/kiosks for use on the Biosphere 2 campus. These displays are used to highlight research efforts to the ~110,000 visitors a year.

The Arizona Remote Sensing Center (ARSC): ARSC is a research unit in the School of Natural Resources and the Environment (SNRE). It contains a data server room and two 900 square foot labs for remote sensing training, research, image processing, and GIS analysis. Conference rooms and a 35 seat geospatial teaching lab with dual monitors are available for this project through SNRE. The center has a senior systems administrator and a senior research technician on staff to maintain systems and research continuity.

The facilities of the ARSC include advanced data acquisition, processing, and analysis hardware and software encompassing all aspects of remote sensing, GIS, GPS (GARMIN and external Units), and web database development. ARSC also has a full range hyperspectral radiometer (ASD Fieldspec 3), ASD integrating sphere, Leaf Area Index (LAI) sensor, and Fraction of Photosynthetically Active Radiation (FAPAR) sensor, FLIR thermal imager, a quadcopter drone DJI Phantom 3 professional with a mini-iPad available for field based data acquisition and research projects. For this project, we will use and make the following hardware and software available - Computers: 1 Xeon 24 core and 1 Xeon 32 core high

performance computing workstations, each with 256GB memory, 1 virtual domain with 1 GB connectivity, webserver, software, and security software server, several windows data servers with ~60TB RAID, backup server system (80TB), Windows 7 and 10 professional workstations, and laptops; Printers: DesignJet 800PS - 1200dpi 42 color inkjet, HP Color and black and white LaserJet printers; Software: Image Processing and GIS - ESRI ARCGIS 10.3, ENVI/IDL/LIDAR 5.3, ERDAS 2016, See5, AgiSoft photostan, ATCOR, Geo-statistics, MatLab and IDL.

U.S. Geological Survey Biological Resources Discipline: The USGS-BRD office in Moab, Utah, where Belnap is based, has a fully equipped laboratory for soil nutrient and biocrust biomass physiological ecology analyses. Equipment includes a gas chromatograph, microscopes, an HPLC, portable and benchtop fluorimeters, C and N analyzer, plate reader, soil microfauna extraction equipment, a growth/incubation chamber, and six portable and one on-line laboratory LiCor gas exchange system and 20 NEE chambers in the field. A greenhouse for growing plants and biocrusts is also available.

University of Arizona Core Facilities

Arizona Research Labs: Arizona research labs maintains the University Spectroscopy and Imaging Core Facility. This permanently staffed facility includes all of the equipment necessary to obtain high quality digital SEMs, including environmental SEMs which do not necessitate sputter coating specimens with gold. Equipment includes a Hitachi S-4800 Type II/ThermoNORAN NSS EDS: Field-Emission SEM and a Hitachi S-3400N Type II / ThermoNORAN NSS EDS: Variable Pressure SEM.

University of Arizona Genetics Core Facility (UAGC): The UAGC is a state-of-the-art laboratory that provides genomic and DNA sequencing resources and solutions to all UA faculty, staff, collaborators, and scientists. The UAGC provides high quality, fast turnaround, high throughput sequencing runs on an Applied Biosystems 3730XL DNA Analyzer. Plates are submitted containing 96 PCR products plus forward and reverse primers, and are rapidly sequenced usually within 2-7 days. DNA sequences are available online and are quickly downloaded through a Mesquite portal specifically designed in conjunction with the UAGC. The UAGC offers RNA and genomic DNA extraction, provides transcriptome and whole genome sequencing services, and houses an Illumina HiSeq 2000/2500. Raw NGS reads are accessible through a data transfer service called iRODS. The UAGC is fully staffed and supervised by extremely capable and knowledgeable scientists who are also available for troubleshooting and consultation.

Computer

Investigator Computing Resources: All UA investigators and senior personnel on this project have dedicated desktop and/or laptop computers, with a minimum of Microsoft Office Suite, that support their work on campus as well in the field. On average, computers are replaced every three years. Computers are networked with high speed black and white and color printers. All faculty, staff, and students are provided with a unique NetID, a secure, efficient way for the UA and its computer systems to ensure the identity of an eligible user before allowing access to potentially sensitive information. NetID is tied to most campus systems including email, analytics, and multiple software and Software-as-a-Service suites (e.g. Enterprise Box.net, Google for Education). Also included is Windows Lync (now Skype) on all UA computing systems to provide instant messaging capabilities. University Information Technology Services (UITS) centrally operates the UA campus network. Information regarding the network and additional centralized computing resources is below.

Central UA Data Centers, Computational Resources, and Support: UA provides centrally managed and maintenance of high performance research computing systems to all campus faculty and researchers. The following systems are available at no cost to researchers:

- General purpose cluster (purchased 2016) with 8400 cores, 57TB of Memory, FDR Infiniband (IB) Interconnect, 10G ethernet, and virtual shared memory (vSMP) software. In addition to vSMP, a 48 core dedicated node with 2 TB RAM is available.
- SGI Integrated Computing Environment (ICE) cluster with 2148 2.66 GHz Xeon Westmere-EP cores with 4.3TB of memory and QDR IB Interconnect.
- SGI UV1000 shared memory system (SMP) with 116 2.66 GHz Xeon Westmere-EX processors (928 cores) and 2.68TB of memory and NUMalink 5 node interconnect.

- IBM System X iDataPlex dx360 M3 high throughput system with 208 2.66 GHz Xeon Westmere-EP processors (1248 cores) and 3.74TB of memory.
- An isolated testing platform dedicated for prototyping and proof of concept studies: 16 nodes with 2x6 Intel 2.67GHz X5650 cores, 128GB RAM, and 5 x 2TB SATA disks.
- Storage is Data Direct Networks SFA12KX40D-56IB: 1.5PB of shared storage expandable to 4.5PB. Initial disk allocations are 15GB per account, with additional storage available for lease at a rate of \$41/TB/year.

Access to UA's HPC systems includes 24,000 CPU hours/month per PI group member with additional windfall processing time available. A specialized Nvidia GPU high-performance cluster was purchased with an NSF MRI grant awarded to faculty in Astronomy and the School of Information, Sciences, Technology, and Arts (SISTA.) The MRI grant stipulates that 30% of system resources be available for general campus research. This configuration includes 2176 Intel cores, FDR IB interconnect, 26TB of RAM, 140 Nvidia Tesla K20X GPUs, 40 5110P Intel PHIs, and 190TB of DDN SFA12K shared storage.

The UA has two facilities available to house research computing resources:

1. Research Data Center (RDC): 1200 ft² raised floor data center designed for water-cooled racks dedicated to centrally managed research computing systems and large grant funded systems, with capacity for 40 standard racks. RDC capacity allows UITS to maintain two generations of centralized large computer clusters simultaneously, providing continuity of research while each new system is phased in.
2. Co-location Data Center: 1900 ft² of raised floor data center space for air-cooled research computing systems purchased and administered by colleges, departments, and research projects, with capacity for 70 standard racks.

UITS has six full-time consultants with expertise in HPC, statistics, and visualization, and five full-time staff dedicated to UA HPC Systems Administration. Research Computing Support consulting include: multi-core/processor programming, support for scaling and analysis of parallel codes, porting parallel code on different platforms, and expertise in specialized accelerator technologies such as GPU and Xeon Phi coprocessors.

UITS data centers are located in the Computer Center with 1325 kW of battery backup and a 1750 kW generator for backup power. Cooling in the RDC is both in-rack cooling with chilled water heat exchangers and 70 tons of Computer Room Air Conditioning (CRAC) units. The UA Data Center is cooled with chilled water CRAC units. Both data centers are equipped with 18" raised floors that allow full coverage of cooling to all the equipment, and equipped with leak detection systems in the subfloor. The fire suppression system is a multi-tiered defense with clean agent compressed gas, dry pipe pre-action sprinkler, and EPO (Emergency Power Off) systems zoned to deploy in affected areas. Storage of combustible materials such as cardboard, flammable liquids, and other hazardous materials is prohibited within the data centers.

UITS data centers have badge swipe access with two-factor authentication and video surveillance in the data centers and throughout the building. The data centers are monitored by a co-located 24/7 operations staff and dedicated infrastructure team. Automated environmental and system monitoring assist with issue triaging and escalation. All personnel with unescorted data centers access have undergone background checks and are required to be US Citizens.

In addition to direct connection to commodity Internet carriers, UA is a member institution of Internet2 (I2). I2 is a not-for-profit organization that has built a 100Gb (gigabit) ultra-high speed backbone network for advancing Research and Education nationwide. The UA connection to I2 is through the Sun Corridor Network – a regional network established through a collaborative effort by Arizona State University (ASU), Northern Arizona University (NAU), and UA. The Sun Corridor Network provides advanced networking services beyond those available from the individual Arizona Universities and builds an environment essential to leading-edge education, research, and the sharing of digital communications resources, network services, and applications among eligible members. UITS manages and operates the Sun Corridor Network. The current connection from UA to Sun Corridor is dual 10G, while Sun Corridor is connected to I2 via dual 100G connections in Tucson and Phoenix. The UA campus network consists of eight redundant core routers in two core sites and twelve distribution routers in three distribution locations. The core and distribution layer devices are interconnected at 10Gbps and most campus

buildings are connected at 10Gbps. All buildings on campus are dually connected to the campus core. Most customer ports are 1Gbps.

Researchers may also use a Science DMZ for fast and high volume data transfers to outside collaborating institutions. The Science DMZ is deployed at the UA network perimeter, outside border firewalls, and is directly connected to Sun Corridor via 10G link. It is secured via static access lists deployed at the Sun Corridor router. There are two high-performance Data Transfer Nodes (DTNs) deployed in the Science DMZ.

The UA Research Data Center provides 40Gbps connections to the UA core with all the servers connected by 1Gbps or 10Gbps connections. Servers are connected to two Cisco FEX switches for redundancy. This Data Center is located within the University network and is protected by both the campus border firewalls and by additional firewalls specific to the Data Center, providing a higher-security option for data that may demand a more rigorous security posture than that available in the high-speed Science DMZ.

CyVerse's Data Centers and Computational Resources: Funded by the National Science Foundation's Directorate for Biological Sciences, CyVerse provides life scientists with powerful computational infrastructure to handle huge datasets and complex analyses, thus enabling data-driven discovery. CyVerse's powerful extensible platforms provide data storage, bioinformatics tools, image analyses, cloud services, APIs, and more.

CyVerse data centers residing at UA are equipped with long-term, fail-over building generators, high speed gigabit networking, and state-of-the-art facilities. CyVerse computational grid clusters (500 processing cores), virtualization clusters (Atmosphere cloud service platform) servicing more than 1000 virtual machines with 8TB RAM (maximum resources per instance is 32-cores and 256G RAM), CyVerse's data services, and 450TB of storage are located in two data centers at UA: the BIO5 Institute and the UITS Data Center. Both facilities have redundant internet and power. These facilities are connected with high performance 10G networking. A third facility is used for disaster recovery and monitoring of CyVerse services located at the Texas Advanced Computing Center (TACC) in Austin, Texas. TACC also stores a full backup copy of the entire CyVerse Data Store (1.2 PB) which is updated nightly. The CyVerse Collaborative and TACC's facilities have 10G connectivity using Internet2 via Sun Corridor networking backbone, a necessity for the large-scale data transfers to the supercomputers at TACC. TACC contains additional storage in excess of 2 PB along with supercomputers with >50,000 processing cores and 6 high-memory nodes (1 TB RAM). These supercomputers are:

- Stampede: Running CentOS Linux with 522,080 processing cores, 270TB RAM, 1.6PB local storage, and 14PB shared storage.
- Lonestar 5: Running Linux with 30,048 processing cores, 80TB RAM, 5PB high performance storage.

If additional resources beyond UA and CyVerse are needed, the XSEDE national supercomputer network, which includes the Jetstream cloud-based computing platform may be employed.

Other

Onsite Meeting Space: Meeting space for visiting researchers will be available in a number of locations. Due to our collaborations with LANL and BNM, meeting space either at the lab or monument will be available. We have successfully utilized this strategy to host an onsite meeting to prepare this proposal.

Lodging for visiting researchers will be located in the surrounding communities. These communities include Los Alamos, White Rock, Espanola, and Santa Fe. A number of commercial lodging options exist.

Virtual Meetings & Telecommunications: Each of the participating departments provide conference space for their faculty. The meeting spaces are generally equipped with Polycom conferencing systems or speaker phones, white boards and/or smart boards, and computing equipment. These rooms are designed for twelve to fourteen participants in a boardroom setting. In addition, UITS provides fully-equipped video and tele-conferencing space for UA staff available upon reservation.

DATA MANAGEMENT PLAN

The PJP LTER will follow current standards of good data management and data preservation, discovery and access (Michener & Brunt 2000). Our data management will be built on practices established by LTER and complemented by those of the CZO and Biosphere 2 research projects. The Information Manager Director, together with a Data Manager and researchers, postdocs, students and field technicians, will carefully select the types of instrumentation, their installation, and plan the mode of data collection that includes on-site data download or automated real-time data access, depending on network accessibility and need. Collected data will be processed and quality controlled using specific guidelines based on data type, accompanied with standardized metadata, archived and published in the LTER Network Information System Data Portal. Our LTER will adopt and implement the LTER Data Policy and share with a broad research community as soon as possible but no later than two years after data collection and processing, modelling or analysis.

Data and Material Produced

The proposed work will use PJP legacy data (PROJECT DESCRIPTION section: 7) and generate continuing and new data streams. The following data and sample types will be continuously measured or periodically sampled and then analyzed and used in models to synthesize new datasets and to test hypotheses

Meteorological: 1) Eddy covariance and fluxes: heat, radiation, water vapor, CO₂, evapotranspiration, albedo, net radiation, latent heat flux, bowen ratios, vapor pressure deficit; 2) Meteorological variables: precipitation, temperature, relative humidity, pressure, wind speed and direction, solar radiation; 3) Surface: roughness, cover (8.1, 8.2, 8.3, 8.4, 8.5, 8.7, 8.8).

Physiological: 1) Tree basal area and overstory density; 2) Net primary productivity; 3) Sap flow; 4) Phenological camera images; 5) Gas exchange: photosynthesis, respiration, transpiration, stomatal conductance, PAR, CO₂ and H₂O; 6) Biological crust establishment; 7) Seedling establishment; 8) Virtual forest (8.1, 8.2, 8.4, 8.5, 8.7, 8.8).

Biogeochemical: 1) Soil moisture, electric conductivity, temperature, water potential; 2) Soil respiration: CO₂; 3) Fluid: chemistry and isotopes for organic and inorganic solutes; 4) Solids: mineralogy, isotopes, organic matter content, texture, physical characteristics, soil chemistry; 5) Dust deposition; 6) Erosion bridges; 7) Surface microtopography; 8) Microbial composition; 9) Chlorophyll fluorescence: cyanobacteria (8.1, 8.3, 8.5, 8.7, 8.8).

Geospatial: 1) Airborne LiDAR: Digital Surface Model (DSM), Digital Elevation Model (DEM), Canopy height, intensity, biomass; 2) Terrestrial LiDAR: DEM, DSM, canopy density and height; 3) sampling locations; and 4) area boundaries (8.1, 8.2, 8.7, 8.8).

Samples: 1) Arthropod pitfall data; 2) Vegetation clipped from plots; 3) Course woody debris; 4) Soil samples: surface soil and cores; 5) Biological crust; 6) Tree cores. (8.1, 8.3, 8.5, 8.7, 8.8)

Standards, Formats and Metadata

Raw and quality controlled time-series data will be stored in databases (Oracle and MySQL) using the CUAHSI Observation Data Model (ODM) and newly developed ODM2 together with the metadata (7). ODM has implemented all core metadata elements to be compliant with ISO 19115 standard. The soil samples and geochemical data will be store in the ODM2 database with the EarthChem metadata and data extension. The geo-spatial data will be stored and distributed as vector data (ArcInfo shapefile, JSON and KML) and gridded/raster datasets (GeoTIFF, JPEG, Imagine IMG). Each dataset has metadata stored in the XML and textual format based on the FGDC metadata standard. Meta'omic data in fasta, fatsq, and biom file formats with associated metadata adheres to MlxS descriptions developed by the Genomics Standards Consortium. Besides the dataset specific metadata format, both geospatial and non-geospatial datasets will be described and provided with the metadata format based on the Ecological Metadata Language schema (EML) and LTER controlled vocabulary. Additional formats to store data are JPEG, TIFF, delimited text files such as csv, JSON, NetCDF and other binary files.

Roles and Responsibilities

PIs will take responsibility for the collection, management and sharing of the research data. Investigators will be responsible for the site selections (8.1, 8.3), instrumentation and installation (8.3); planning sample collections and appropriate data analysis (8.1, 8.2, 8.4, 8.5, 8.7, 8.8); prepare inputs for

data description/metadata; approve data publication (8.8). Field and lab managers will be responsible for installation (8.3), instrument maintenance, data and sample collection (8.1, 8.2, 8.4, 8.5), sample preparation and analysis (8.1, 8.4, 8.5). The Information Management Director will oversee the Data Manager and they will be responsible for setting up and maintaining databases and data storages; store raw data in the database; maintain data and metadata integrity in accordance with LTER EML best practice; archiving data and metadata; secure private datasets and make them available to authorized users and LTER investigator; help to create data distribution package and submit it to the LTER Data Portal; and keep all information presented on the website up to date.

Dissemination Methods

All collected, analyzed, computed and modelled data will be available to all PJP LTER researchers and students immediately after processing via PJP LTER website (8.8). Quality controlled data will be formatted, described and packaged in LTER publication format and submitted to the LTER Network Data Portal to be visible and accessible to the LTER and broader scientific community (8.8).

Policies for Data Sharing and Public Access

PJP LTER will adopt and implement LTER Data Access Policy and NSF data sharing requirements. All data will be available to the general public within two years from collection or after the publication of peer-review journal articles, whichever comes first. Each dataset will be accompanied with metadata in LTER format (EML) and a data use agreement, which more specifically describes data use restrictions, redistribution, citation, acknowledgment, notifications and collaboration. All publically available data products may be freely copied, distributed, edited, and built upon for scientific purposes. Each PJP LTER data user agrees to provide acknowledgment with each usage of the data. The acknowledgment will include investigator name, dataset title and NSF grant number. Any data use restriction will be listed in the data use agreement. PJP LTER investigators and collaborators agree to provide raw and quality controlled data and data description to the Data Manager within one year of collection. These datasets will be stored in the private repository and available to LTER investigators or authorized collaborators.

Archiving, Storage and Preservation

Collected and computed electronic data will be preserved on multiple backups: 1) by the field managers which are responsible for the data collections, 2) by investigators responsible for analysis and computations, and 3) by the data manager. All collected and computed data will be stored in the database and file systems located on the servers with the RAID configuration to prevent any data loses. In addition to the local data storage, the NSF funded CyVerse cyberinfrastructure will be used to store and publically access PJP LTER datasets. Long term data preservation and accessibility will be achieved by submitting all generated datasets to the LTER NIS Data Portal or other NSF funded and international data repositories such as NCBI GenBank and EMBL-Bank for genetic data (8.8).

Soil samples will be archived for the duration of and following NSF support of PJP. Soil samples will be dried and stored at room temperature in the dark. Subsampled soil will be stored at ultralow temperatures in nucleic acid preservation buffer to enable future analyses of composition not capable with current technology. These samples will be registered with the System for Earth Sample Registration (SESAR) to obtain the unique sample identifier, International Geo Sample Number (IGSN), which makes these samples visible and available to the general public. An arthropod collection from legacy data housed at UNM Museum of Southwestern Biology will be expanded with specimens of new species as needed.

Expected Milestones and Deliverable Products

PJP LTER will adopt and implement the LTER Data and Data Sharing Policy and setup the information and data infrastructure (which includes website, data and metadata tools for data collection, processing and publishing) not later than one year from the beginning of the project. Data collection methods will be documented and published simultaneously with the installation of instrumentation. The legacy data (7) will be published on the website and submitted to the LTER NIS Data Portal in the first 18 months of the project. Data from analyses of legacy data (8.1) and newly collected time-series data (such as flux tower, meteorological station, soil moisture, soil gas datasets) will be published on yearly basis after quality control and processing and the other datasets (such as microbial, geochemistry, LiDAR, virtual forest) as soon as they will be processed and quality controlled based on the data collection plan. All current and in-press publications will be listed in the Publications section of the website, stored in the website CMS database and linked to the original publisher.