FINAL REPORT

Resilient landscapes and fire regimes: Meaning, metrics, and management

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List of Abbreviations/Acronyms

AMSL – height above mean sea level
BA – basal area
EFBR – East Fork of the Bitterroot River
FRV – future range of variation
HRV – historical range of variation
IQR – interquartile range
LiDAR - light detection and ranging
PCA – principle components analysis
RCP - representative concentration pathway
USFS – United States Forest Service
VTC – vegetation type conversion
WFDSS – wildland fire decision support system

Keywords – restoration, historical range of variation, climate change, adaptation, ecological resilience, fire regime, resistance, reorganization, persistence, forest plan, Planning Rule

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Abstract

The National Cohesive Wildland Fire Management Strategy (hereafter: Cohesive Strategy) mandates the restoration and maintenance of landscapes, with the goal that “landscapes across all jurisdictions are resilient to fire-related disturbances in accordance with management objectives.” This policy includes using wildland fire to improve ecological resilience, but because the term resilience is ambiguous, difficult to measure, and rarely quantified, there are no clear, consistent methods for translating resilience science into resilience policy and eventually into resilience management. Resilience may be a concept that managers and policy makers can understand in a general sense, but how can this concept be operationalized to guide ecosystem management in practice? There is a lack of guidelines for translating resilience theory into operational management actions, particularly in the context of fire management and current socio-political frameworks. As one of the most influential disturbance agents in western US landscapes, wildfire is central to the development of resilence-focused management strategies; yet the complex nature of fire across climate gradients, fuel types, fire regimes, and management history resists any simple definitions of what resilience ecosystems look like, when they are vulnerable to change, and how fire-driven changes in landscapes may be. A coherent assessement of resilience, grounded in theory, meaning and metrics that are central to fire ecology and fire management, is needed to guide management actions due to the strong link between resilience and sustainability. Large-scale policy directives such as the Cohesive Strategy call for transformative change in how the US manages fire, while local-to-national level legislation generally works through incremental changes in land management. This dilemma is exemplified in Forest Plan revisions under the 2012 National Forest System Land Management Planning Rule, which directs National Forests to manage for resilience but provides little concrete guidance regarding what this is or how it can be accomplished.

We conducted a literature review examining the national regulations and policies associated with US Forest Service National Forest planning. Forest planning is a three-tiered process and the 2012 Planning Rule and forest plans represent the first two tiers. Both now allow, or even encourage, the management of natural-ignition fires for resource benefit. As such, forest plan revisions are now a viable vehicle for changing fire management paradigms. Going forward, incident-level decision-making will provide the needed growth and change in fire management in the USFS. The cumulative impact of these decisions will determine if the USFS fire management programs will fulfill the intent of the 2012 Planning Rule and Cohesive Strategy.

We summarized how current research is re-defining ecological resilience and describe the challenges and opportunities of implementing therories of resilience into operational land management strategies in fire-prone forests. Our concept papers emphasized several aspects of ecological resilience, including 1) it is highly scale-dependent process, 2) climate changing is transforming some ecoystems, but this degree and pace which this is occuring depend on local and regional factors, and 3) historical range of variation (HRV) is still a viable benchmark for assessing resilience, but future range of variation (FRV) should also be evaulated. We demonstrated how simulation modeling to derive time series representing HRV and FRV can be used to quantify resilience and produce resilience indices based on the departure of current conditions from HRV.

Objectives

Our original study objectives were to advance the clarity and applicability of resilience with respect to:

- ***Meaning***: Synthesize the concept of resilient ecosystems and landscapes, with particular reference to fire in western forested landscapes in an era of extended droughts, climate change, and other stressors; bridge ecological and social resilience concepts, especially in the context of policy and forest planning.
- ***Metrics***: Develop a Resilience Assessment method, adapted from existing vulnerability analysis that can be inverted to target ecological resilience, leading to quantitative assessments of how management objectives and actions can influence ecosystem resilience to disturbance and climate change.
- ***Management***: Demonstrate and evaluate the application of the Resilience Assessment in three representative low, mixed, and high severity fire regime landscapes, illustrating the fundamental importance of ecological and social-political context (i.e., no "one size fits all").

Our original objectives were met; however, we are still finalizing some papers for publication and archiving data.

Background

The 2012 Rule requires forest plans "to maintain or restore the ecological integrity of terrestrial and aquatic ecosystems and watersheds in the plan area, including plan components to maintain or restore structure, function, composition, and connectivity," taking into account "wildland fire and opportunities to restore fire adapted ecosystems" (36 C.F.R. §219.8). In the assessment phase of plan revision, the responsible official must evaluate information pertaining to multiple resource issues, including "system drivers, including dominant ecological processes, disturbance regimes, and stressors" including wildland fire and the ability of ecosystems in the plan area "to adapt to change" (36 C.F.R. §219.6). In 2016, 68 land management plans of the 127 plans in the National Forest System were past due for revision. Revisions are written pursuant to the 2012 Rule, but it is uncertain how forest plans will "plan for resilience" and intersect with fire planning processes, including the Cohesive Strategy. Forest Service policy recognizes the interplay between fire planning and forest planning, but the exact nature of how best to integrate the two remains unclear (Haber 2015). The 2012 Rule provides a new opportunity to integrate fire and forest planning and to give more precise meaning to "planning for resilience."

The first steps in any policy implementation towards achieving landscape resilience is to clearly define terminology and develop a method to assess resiliency in order to know if and how land management has met resiliency-related objectives. As one of the most influential disturbances in temperate forests, savannas, and grasslands systems, wildfire is central to resilience-focused management strategies. Yet the complex nature of fire across climate gradients, fuel types, fire regimes, and management history challenges any simple definitions of what resilient ecosystems look like, when they are vulnerable to change, and how management actions can be effectively implemented, particularly in the context of current socio-political frameworks (Folke 2006, Falk 2016). Fire is a keystone process in many terrestrial ecosystems, playing a dual role. One on hand it is an integral part of their maintenance and ecological functioning (Agee 1993), creating and maintaining biological diversity (Turner 2010), enhancing productivity (Wardle et al. 2004), and facilitating nutrient cycling (White and Pickett 1985). On the other hand, wildfires can also disrupt ecosystems and change elements of the biological and physical environment. As climate alters characteristics of fire regimes (Bowman et al. 2009), however, fires can cause rapid reorganization of ecosystems (McKenzie et al. 2011), and post-fire recovery can extend over years or even decades or lead to ecological changes that are essentially irreversible. An improved concept of landscape ecolgical resilience, with clear definitions and a quantifible method to evaluate change, is needed to guide management actions in fire-prone ecosystems. We addressed this need by developing a resilience assessment that defines resilience, includes metrics for evaluation, and explores policy barriers and opportunities to implementation.

Materials and Methods

Integrating Fire into Revised Forest Plans under the 2012 Rule

We conducted a literature review detailing the decision-making framework for integrating fire and forest planning. This included a review of land management as it has changed throughout the history of the USFS and the foundational laws and policies that previously guided the USFS and their more modern counterparts that currently direct agency decision making. The literature review also examined the national regulations and policies associated with National Forest planning, such as the National Forest Management Act, and the 1982 and 2012 Planning Rules. Agency interpretation of these policies was also reviewed by exploring the USFS Directives, including the Handbooks and Manual, and relevant agency white-papers. We evaluated revised forest plans (or drafts) for 11 National Forests including the Chugach, Cibola, El Yunque, Flathead, Francis Marion, Helena - Lewis & Clark, Inyo, Nez Perce - Clearwater, Rio Grande, Sequoia, and Sierra National Forests using an evaluative rubric to organize and compile notes and observations on the different approaches used by each National Forest. Interviews with fire managers and Interdisciplinary Teams were also conducted to add context to the findings from forest plan evaluations and provide learning opportunities for other forests. We held a 2-day meeting with approximately 20 FS Region 4 fire staff about how to incorporate fire into forest plans and the concept of resilience in fire-dependent systems. In this workshop we presented a preliminary version of our resilience framework to get input from managers if such a tool would be useful and ways to improve it.

Defining Concepts of Resilience

We summarized how current research is re-defining ecological resilience in Keane et al. (2018), Falk et al. (2019), Falk et al. (In Review), and Loehman et al. (In preparation). These papers focus on different aspects of resilience such as theory, scaling, and the complexity needed for assessment to describe the challenges and opportunities of implementing therories of resilience into operational land management strategies in fire-prone forests (see results and discussion section for detail).

Methods to Quantify Resilience

In Keane et al. (2018), we developed a historical range of variation (HRV) resilience model. We used simulation modeling to derive time series representing HRV and future range of variation (FRV). Simulations provide the necessary temporally deep, spatially explicit historical data that can be difficult to obtain elsewhere. Moreover, modeling provides a single, consistent platform for generating the required data to characterize HRV for multiple ecological attributes and for generating projections of FRV under future climates.We used box-and-whisker plots to summarize HRV for one variable (univariate) and principal components analysis (PCA) to describe HRV for multiple variables (multivariate) to quantify resilience and produce resilience indices based on the departure of current conditions from HRV.

Falk et al. (2019) demonstrated the essential scale dependence of concepts of ecological resilience. Resilience is expressed across three primary axes: space, time, and biological scales. Spatial scale relates most directly to the spatial extent and heterogeneity (e.g. patch size) of a disturbance, which is a central control on post-disturbance pathways. The time axis expresses primarily the time scale of recovery, which is correlated with the spatial extent of disturbance (i.e., other things being equal, larger disturbances take longer to recover, due to increasing dispersal limitations and soil-hydrologic impacts). The biological scale reflects a progression along levels of biological organization, from the individual (persistence), to population (recovery), to community (reorganization; see Falk et al. In Review).

Falk et al. (In Review) is a major overview of the framework of ecological resilience. One consequence of increasing and chronic stress from profound environmental changes is that forest ecosystems are being pushed outside of their recent observed ranges of variation into alternative ecological states. In some cases, these new states are transitory and represent successional stages that may ultimately lead back toward the pre-disturbance condition. In many other cases, these alternative states are persistent and potentially self-reinforcing, especially under prevailing conditions of altered climate, disturbance regimes, and presence of non-native species.

Case Studies

East Fork of the Bitterroot, Montana (low, mixed, and high-severity fire regimes)
We used the mechanistic landscape model Fire- BGCv2 (Keane et al. 2011) as implemented for the 128,000-ha East Fork of the Bitterroot River (EFBR) watershed, located in the interior northern Rocky Mountains in the Bitterroot National Forest, Montana, USA. This landscape includes dry, mixed-conifer ecosystems of ponderosa pine and Douglas-fir at low elevation, montane mixed-conifer of lodgepole pine, Douglas-fir, and subalpine fire at middle elevations, and whitebark pine, subalpine fire, and spruce at high elevations. We simulated historical HRV and three FRV scenarios that varied by fire management and climate. Additonal details are reported in Keane et al. (2018).

Pinaleño Mountains, southeastern Arizona (montane mixed-severity fire regime)
The Pinaleño Mountains are the tallest of the Madrean Sky Islands, reaching over 10,000 ft AMSL. Like all of the major Sky Island ranges, the Pinaleños support extensive areas of montane and subalpine forest, within just a few horizontal miles from the deserts and grasslands surrounding the mountains at lower elevations. The Pinaleños have experience several major

fires with overlapping perimeters in recent years, including 1996, 2004, and 2017. A permanent systematic plot grid was estaslished in 2010, and has been resampled twice since establishement, including after the 2017 Frye Fire. High-resolution aerial LiDAR has also been flown twice over the Pinaleños, providing the potential for analysis of structural change. We analyzed plot and LiDAR data to evaluate drivers of persistence and recovery, as well as trajectories of alternative states (Poulos and Falk, in preparation).

Results and Discussion

Integrating Fire into Revised Forest Plans under the 2012 Rule (text from Graf 2018)

Adaptability of 2012 Planning Rule
The 2012 Planning Rule provides sufficient flexibility for each National Forest to fulfill its requirements while still meeting their unique ecological needs. Each National Forest has used a different approach, or combination of approaches, to integrate fire and forest planning. The only revisions that are similar are from the Inyo, Sequoia, and Sierra National Forests, because they were written collaboratively. Clearly, there is no one-size-fits-all approach for integrating fire and forest planning.

The variety of approaches used demonstrates the adaptability of the 2012 Planning Rule. It shows that methods to fulfill the Planning Rule's requirements can be tailored to meet the distinct needs of each forest. That is, the Planning Rule explicitly requires revised plans to include plan components to restore and maintain ecosystem integrity and consider disturbance regimes and opportunities to restore wildland fire. However, each forest has taken these same requirements and has fulfilled them in unique ways.

The demonstrated flexibility of the Planning Rule is important because each forest is ecologically unique. The Francis Marion National Forest, for example, generally needs frequent fires to maintain ecosystem but land fragmentation complicates their fire management. To address this challenge, two management areas are used to signify where prescribed fire is, or is not, an appropriate management strategy. This system is mostly binary. In contrast, the Flathead National Forest must plan for a much larger range of fire frequencies, intensities, and severities to maintain their ecosystems. The differences in fire ecology are uniquely challenging across forests. These challenges can be addressed because the Planning Rule provides sufficient flexibility to integrate fire and forest planning, regardless of the fire regime or ecosystem.

The flexibility provided by the Planning Rule requirements is why forest plan revisions can successfully integrate fire and forest planning. During interviews, participants unanimously agreed that forest plan revisions are an appropriate platform to integrate them because they can provide guidance without being inflexible. Forest plan revisions offer an opportunity to provide sideboards and broad landscape-level direction to guide fire management while maintaining some flexibility in incident-level decision-making.

Trends in Plan Components
All the revised forest plans are uniquely tailored to suit each forests' fire management needs, however, there are trends in the plan components. For example, standards and guidelines are the plan components least used to address the ecological benefits of fire. Every revised plan includes

standards and guidelines to address fire management, but they are largely used to restrict fire suppression tactics, such as the use of fire retardant near water. Only three revised forest plans include standards, and only four include guidelines, that directly address how wildland fire can be used for ecological benefit. This means that fewer than half of the revised forest plans include standards and guidelines which require the consideration of wildland fire and its role in ecosystems.

Standards and guidelines do not compel agency action, rather, they restrict specific actions that would prevent progress towards the desired conditions. Unless they are written to include caveats or exceptions, they provide little room for management adaptation without plan amendment. As a result, planning teams may be hesitant to restrict fire management decision-making with too many standards and guidelines. This may be appropriate as fire management is replete with risk and uncertainties and fire managers must maintain some discretion to safely manage the unique challenges of each individual fire. However, the plan components, when combined, must provide enough direction to guide the forest towards the desired conditions. If standards and guidelines are minimally used, then the other required plan component, objectives, must provide sufficient direction.

Objectives regarding the ecological benefits of fire are used in five of the revised forest plans. As defined in the Planning Rule, they are less restrictive than standards and guidelines. They do not constrain decisions but dictate a desired rate of progress. When flexibility in decisionmaking is necessary for safe fire management, the increased use of objectives is recommended. When objectives are developed to be specific and measurable, they can guide decision-making to achieve the desired conditions without tying the hands of fire managers.

Within the forest plan revisions, there is also a trend of vague desired conditions. Desired conditions that describe the ecological benefits of fire are included in all forest plan revisions (except the El Yunque which does not include fire-adapted ecosystems). This is a significant and positive development, especially when we consider how rarely fire was incorporated into the forest plans developed under the 1982 Rule.

The 2012 Planning Rule requires that "desired conditions must be described in terms that are specific enough to allow progress toward their achievement to be determined" (36 C.F.R. §219 2012). This requirement applies to every desired condition, and yet, vague desired conditions statements were found throughout the revised forest plans. Developing desired conditions for wildland fire that include specific direction is clearly a challenge. According to the interview participants, the public's negative connotations with fire, perceptions of risk, budgets, and even climate change, all complicate the development of ideal desired conditions.

The challenge of developing specific, measurable desired conditions can be addressed by adding goals and management approaches. Goals and/or management approaches are used in five of the revised forest plans. They are not required plan components, but goals and management approaches can be used to provide specifics and additional guidance and to help set priorities. We recommend that goals and management approaches be used to supplement vague desired conditions.

Developing a monitoring strategy for wildland fire is another challenge that requires careful consideration when developing plan components. Six out of the eight National Forests that have developed a monitoring strategy, explicitly include wildland fire in monitoring questions and use some characteristic of fire as an indicator. The Planning Rule does not require every plan component to be included in the monitoring strategy, but it does require them all to be specific and measurable. Eight of the plan revisions include at least one plan component that is specific and measurable within the lifetime of the plan. However, many of the plan components, particularly desired conditions, are broad, generalized statements that lack specificity or may not be measurable in a fifteen-year planning cycle.

When developing plan components, National Forests must consider how they will translate into a monitoring strategy. That is, plan components must be specific enough to be monitorable. Particularly in complex systems or systems with long fire return intervals, monitoring challenges should be considered early in the planning process. To monitor the effectiveness of plan components, National Forests must be realistic about the data that can be collected, and the trends that can be detected, during the fifteen-year lifetime of a forest plan.

Fire-Specific Area Designations

Five of the eleven revised forest plans have used fire-specific area designations. These area designations geographically represent where certain plan components do and do not apply. Each revised forest plan discusses different areas of the forest that are likely to be appropriate for natural ignition fire management, but the methods used to designate these areas vary. Suitability determinations are largely unused to specify areas appropriate for different fire management options. Several forests have relied on the usual area designations, including management and geographic areas, to spatially depict fire management approaches. Several other forests have geographically structured their plan around fire and different fire management strategies.

The spatial design of several revised forest plans was not influenced by fire. Forests that took this approach included the Flathead, Chugach, and Helena − Lewis & Clark National Forests. In general, these plans designated management or geographic areas based on other resources or location. Almost by default, however, fire strategies often differ between these areas. For example, a common management area designation is for backcountry areas. The management approaches for these areas often discussed minimizing roads and increasing recreation opportunities. Because these areas also tended to be farther from communities or infrastructure, they also generally supported the use of natural ignition fires for resource benefit. Using this approach, fire management strategies were depicted through forest-wide direction or plan components that applied in specific circumstances. Rather than mapping specific areas and assigning a fire management strategy, these forests described the conditions (such as topography, weather, and season) that would be necessary to manage fires for resource benefit.

Another approach used by several forests was to spatially structure fire management strategies through physical delineation of forest areas. This approach has so far been used by the Francis Marion, Inyo, Sequoia, Sierra, and Rio Grande National Forest. In each of these forest plans, physical boundaries describe the range of fire management approaches appropriate in each area. However, the specifics of how the designations were determined and how they relate to other plan components varies among the forests.

The Inyo, Sequoia, and Sierra National Forests developed their forests plans as a joint effort and as such used the same method. These plans delineated strategic fire management zones. These zones each have their own plan components including desired conditions, guidelines, goals, and occasionally, standards and management approaches. The fire zones overlay the other management area designations made in the plans. In contrast, the Francis Marion revised plan did not create overlying zones; rather, it used two management areas to divide the forest based on areas that either permit or prohibit and discourage the use of prescribed fire. Both management areas provide detailed plan components directing distinct fire management strategies. The Rio Grande National Forest used yet another variation. They established two distinct wildland fire management zones that overlay the geographic areas. Unlike the other plans, these zones do not have their own plan components but suggest management strategies for both areas based on risk.

The forests that have fully developed plans, even if they are still in draft form, are already being used as templates for other plans still in development. Interview respondents expressed that they looked at other forests for ideas on how best to geographically define fire management strategies. The Francis Marion, Flathead, Inyo, Sequoia, and Sierra revised forest plans are being studied by the other forests for guidance. These forests all have very fire-focused plans, but the approaches they used for designating areas are significantly different. Additional guidance on why these different approaches were chosen and how they developed would likely be useful for other forests. Specifically, interviewees explained that there is still a great deal of confusion regarding designating fire management zones. This will likely be an approach used by other forests but there is not yet any official direction for how these zones fit within the management or geographic areas required by the Planning Rule.

Whether it be management areas, geographic areas, zones, or suitability designations, landscape-scale spatial fire planning will help facilitate incident-level decision-making. The US Forest Service (USFS) already has spatial fire planning requirements through the Wildland Fire Decision Support System (WFDSS) and fire-specific area designations should work well with this process. Communication with the public could also be facilitated with area-specific designations. A physical, geographic representation of what plan components apply where can help explain the forest plan intent and make communication with the public more straight-forward. Land suitability determinations were rarely used to address fire management in forest plan revisions and provided little to no additional guidance beyond the other plan components. The USFS Directives indicate that suitability determinations should be used for forest uses (such as harvesting timber or motorized recreation) and not the management tool used to achieve desired conditions (such as chemical treatments or prescribed burning) (USDA 2017). However, suitability determinations could still be useful for spatially structuring fire management. Much like delineating where timber harvests are appropriate, designating certain lands as suitable for resource benefit fires could facilitate project-level decision-making. Considering USFS spatial fire planning requirements, suitability determinations could be integrated into WFDSS, especially when other spatial structuring approaches are not used in plan revisions.

When using fire-specific area designations, forests must provide clear direction on the relationship between these areas and the rest of the forest plan. Describing this relationship, however, is one of the greatest challenges expressed by interview participants. The USFS is in the process of developing a technical guide for integrating fire into land management planning

(Barrett et al. 2017). This guide will be a useful resource during the forest plan revision process and when determining the most appropriate approaches for spatial representation of fire management. The technical guide describes how fire can be incorporated in management, geographic, and designated areas and zones. However, it provides minimal guidance on why the different approaches should be used or how best to accomplish specific land management goals. Additional concerns reflect the potential requirement for a plan amendment if fire management zone boundaries are changed.

Influence of the Cohesive Strategy
The Cohesive Strategy is influencing forest plan revisions, although it is rarely referenced directly. The Francis Marion, Inyo, Sequoia, and Sierra National Forests, discuss the Cohesive Strategy in their assessments and environmental impact statements. They describe the Cohesive Strategy as a platform for working with stakeholders and as an information source for risk assessment and risk mitigation. The Cohesive Strategy is not directly referenced in any of the plan components developed so far. However, it is important to note that many of the plan components do fulfill the three goals of the Cohesive Strategy − resilient landscapes, fire-adapted communities, and safe and effective response to wildfire.

Despite the lack of direct reference in plan components, interview participants explained that the Cohesive Strategy is being used during decision-making. They described that it is very broad in scope which makes it unwieldy and challenging to integrate during the revision process. However, these same participants explained that the Cohesive Strategy is helpful for beginning the decision-making process. Many of the interviewees recommended the Cohesive Strategy as a supporting document and an appropriate starting place when revising forest plans.

It is appropriate and beneficial that the Cohesive Strategy is influencing decision-making, but the lack of reference in plan components is a missed opportunity. Referencing the Cohesive Strategy directly in plan components is a missed opportunity because it could be used to address the larger social issues that challenge wildland fire management. All the forest plan assessments or need for change documents discuss the influence that the public and stakeholders can have over fire management decisions. Six of the revised forest plans also include desired conditions for neighboring communities to be more knowledgeable and accepting towards the natural role of fire on the landscape. The Cohesive Strategy is an interagency agreement that provides national direction and regional priorities. This high-level view should be used to leverage partnership opportunities for cross-jurisdictional fire management.

Defining Concepts of Resilience

In Falk et al. (In Review) we address two of the central objectives of this project: "*Synthesize the concepts of resilient ecosystems and landscapes, with particular reference to fire in western forested landscapes in an era of extended droughts, climate change, and other stressors*"; and "*Develop and compare methods of resilience assessment, propose a comprehensive framework for ecological resilience, integrating mechanisms of persistence, recovery, and reorganization*."

We develop and elaborate a framework for ecological resilience, with a particular focus on postfire responses. These varied responses of forest plant species and communities to environmental change represent a spectrum of outcomes across levels of biological organization

(Falk et al. 2019). Some of these outcomes are expressed in continuity of existing communities, maintaining biological legacies despite disturbance and environmental change (Johnstone et al. 2016). In other circumstances, stress and environmental change result in extensive turnover in the relative dominance of species present in the community, including transitions to different functional groups. In more extreme cases, species are extirpated from a community and/or new species not previously present, native or non-native, dominate the community. If the species that comprise this reorganized community are better adapted to current environmental conditions of climate and disturbance, these altered communities may persist and represent the leading edge of ecological response to emerging and novel environmental conditions. These processes can be observed operating simultaneously within many communities; individual species vary, and communities do not respond in a unitary fashion.

Persistence is the ability of individuals to tolerate exposure to environmental stress, disturbance, or competitive interactions. Persistence is the direct expression of life history evolution and adaptation to environmental variation and stress, and is manifested most directly in survivorship (either of the aboveground plant or belowground parts capable of resprouting) and continued growth and reproduction of established individuals. Persistence provides the highest degree of continuity with the pre-disturbance community, maintaining a wide range of ecological legacies (Higgs et al. 2014, Johnstone et al. 2016). When persistence has been overcome (i.e., following mortality events from either climate stress and/or disturbance), populations must recover by reproduction. Recovery requires the establishment of new individuals from seed or other propagules following dispersal from the parent plant. Population recovery is particularly sensitive to the environmental conditions required for germination, establishment, and growth of young individuals, as well as inter- and intra-specific interactions. Both persistence and recovery result in a community with a high degree of similarity to the pre-disturbance state.

When recovery fails to re-establish the pre-disturbance community, the ecosystem will reorganize into a new state (Beisner et al. 2003). Community reorganization occurs along a gradient of magnitude, from changes in the relative dominance of species already present in a community, to individual species replacements within an essentially intact community, to a complete species turnover and shift to dominance by plants of different functional types, e.g. transition from forest to shrub or grass dominance (Fletcher et al. 2014, Guiterman et al. 2018, Miller et al. 2019). When this latter outcome is persistent and involves reinforcing mechanisms, the resulting state is termed a vegetation type conversion (VTC), which in this framework represents an end member of reorganization processes (Syphard et al. 2019). These reorganized states can be persistent or transient depending on the relation to ongoing disturbance, climate adaptedness, and competitive relationships.

Resilience, the ability of an ecosystem to recover or adapt following disturbance, is thus an emergent property that results from the expression of multiple mechanisms operating at the levels of organism, population, and community interaction (Figure 1). Each primary component of resilience (persistence, recovery, reorganization) reflects a set of mechanistic processes that must be understood to interpret and predict resilient responses. This requires moving beyond observation to decompose each component of resilience into its constituent ecological mechanisms. Importantly, we posit that different components of a given ecosystem may manifest different components in operation at a given time; some species may persist, others may

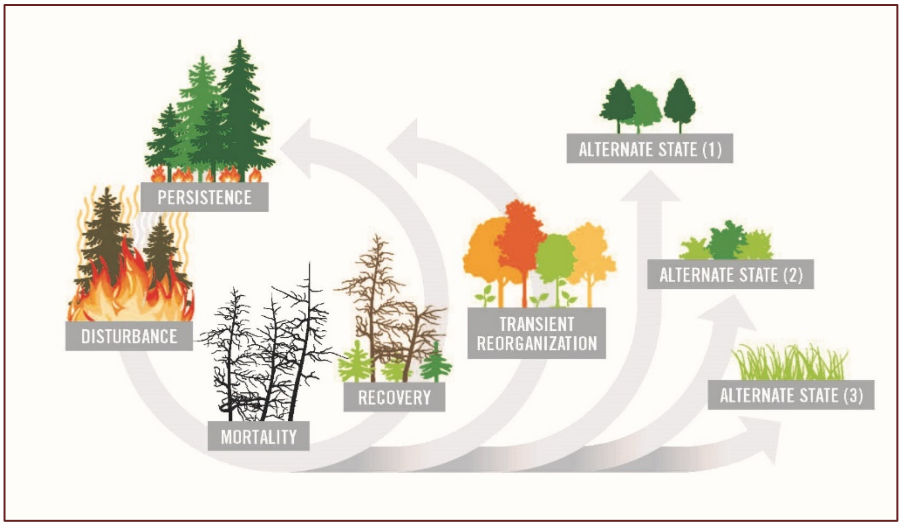


Figure 1. Pathways of post-disturbance persistence, recovery, and reorganization all comprise components of the overall ecosystem capacity for resilience.

experience mortality and recover, while others may pass beyond recovery potential and undergo varying degrees of reorganization or transformation.

In this report we summarize existing observations of persistence, recovery, and reorganization across levels of biological organization, and explore the primary mechanisms that regulate these processes. Our objective is to provide a detailed, mechanistic framework for the science of ecological resilience and its application to ecosystem management (Elmqvist et al. 2003, Suding et al. 2004, Millar et al. 2007, Falk 2017). We develop the foundational theory for reorganization in particular detail, as this phase is both increasingly common and also poorly studied and understood. Key drivers of reorganization include:

1. Trigger events (most commonly disturbance)
2. Widespread mortality, creating open resources space
3. Recolonization failure
4. Landscape species pool of available species
5. Community assembly processes
6. Reinforcing feedbacks (e.g. fire reinforcing a desert- or shrubland-to-grassland conversion). Note that fire can thus act as a trigger event for initial change, and then a reinforcing feedback for the alternative state.

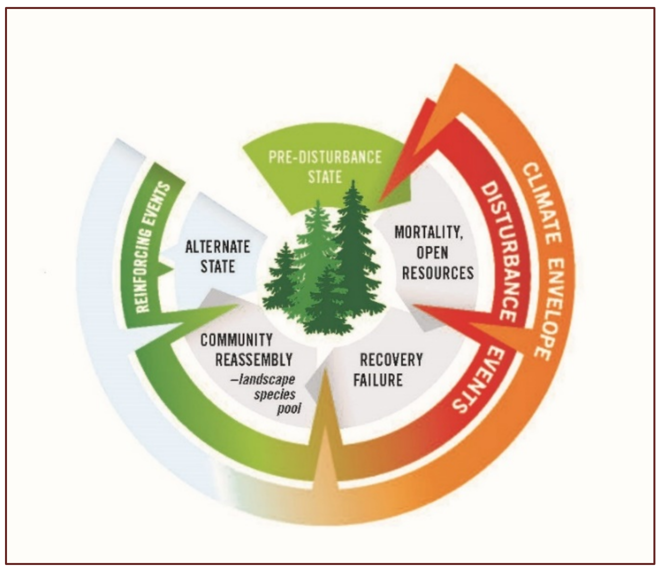


Figure 2: Primary drivers of forest reorganization.

When these drivers operate in sequence following major disturbance (Figure 2), they move the system progressively toward reorganization, which can be expressed initially as transient (decadal) change. Once community reassembly has been initiated, and reinforcing feedbacks (climate and altered disturbance regime) are operating, the system will express persistent vegetation type conversion (VTC). At this state the management actions that may be effective at earlier stages of reorganization may not be sufficient to bring the system back to its pre-disturbance state.

Methods to Quantify Resilience (from Keane et al. 2018)

Our HRV-resilience model can be visualized as the movement of a marble (ecosystem or landscape) in two-dimensional phase space (flat plane or table; Fig. 3). The dimensions of the table define the biophysical envelope or fundamental niche space of key system variables, such as vegetation composition and structure, that are important indicators of ecological pattern and process and are also relevant for management. In this sense, the table is analogous to the basin in the ball-and-cup model, with the difference that by being planar, the table does not imply the existence of a single, stable steady state. A system's fundamental setting is finite, because some forces, such as meteor impacts, human development, and volcanic eruptions, can push the ecosystem (marble) off the table and onto another domain (another biophysical envelope). The marble is constantly acted on by exogenous forces, causing it to move (range) through various states on the table, each an expression of realized niche space. We illustrate four major forces (arrows) in this paper—climate, disturbance, ecological succession, and human activity—but other forces could be used to represent the leading influence on specific ecosystems, or to account for evolutionary processes. The direction of the arrows can vary over time and may or may not be consistent and equal among forces.

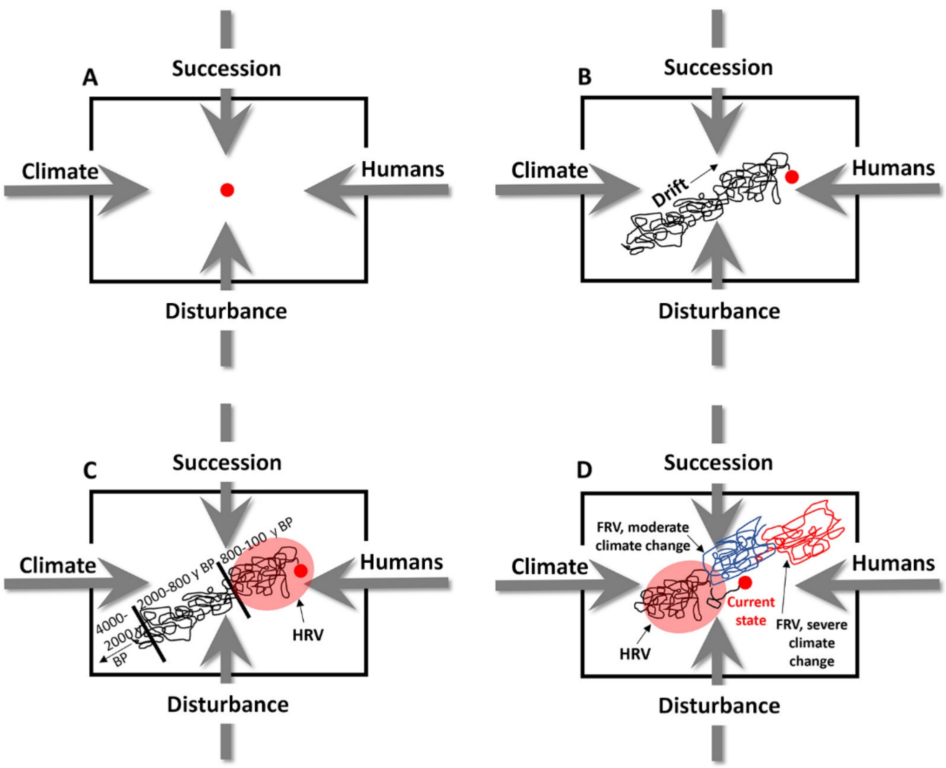


Figure 3.The marble and table analogy to illustrate the concept of resilience. See Keane et al. 2018 for full description.

Because exogenous (climate, disturbance, humans) and endogenous (succession, evolution) forces act continually on the ecosystem, it is constantly in a state of flux as indicated by the path of the marble over time (Fig. 3A). However, during periods of more rapid environmental change, such as the Pleistocene–Holocene transition or the current emergence of the Anthropocene, the path of the system may respond to secular trends in the climate or disturbance signal, developing a non-zero net trajectory in phase space (Fig. 3B). In general, our knowledge of ecosystem paths is confined to the time domain of existing data for the landscape, as there are few detailed data sets of sufficient temporal depth, spatial extent, and appropriate resolution, to evaluate millennial-scale historical dynamics (Keane et al. 2009).

Our modeling HRV-resilience method requires two types of data: values for variables used to describe the current state of the landscape or ecosystem and its representative HRV time series (Fig. 3C). Our starting assumption in using HRV as a reference for resilience is that ecosystems operating within HRV for key variables are resilient *ipso facto* because their behavior falls within the bounds of ecosystem responses (HRV domain in Fig. 3B). When the ecosystem (marble) is outside of HRV for key variables, we infer that ecosystems are less resilient because ecosystem structure and composition may not facilitate an expected return to HRV conditions following disturbance. Thus, the departure of current conditions from HRV can be used operationally as an index of resilience: The lower the departure value, the more resilient the landscape.

Variations of this method could be used to evaluate resilience of the contemporary landscapes or ecosystems with respect to future climate change, exotic invasions, or land management activities. Managers can augment HRV departure analysis with similar analyses of current conditions compared to simulated time series of FRVs of a landscape or ecosystem (Fig. 3D). With different assumptions about climate (e.g., low or high emissions) and land management (e.g., fuel treatments, fire suppression), various future scenarios can be modeled. From these projections, we can determine whether FRV envelopes overlap with the HRV envelope. Where overlaps exist, they can be evaluated as possible focal management areas for resiliency. We acknowledge that the estimation of FRVs using simulation entails uncertainty as mentioned previously. Nonetheless, it can represent quantitatively our best expectations of future conditions and thereby provide useful information informing the design and implementation of possible restoration measures.

Case Studies

East Fork of the Bitterroot, Montana (low, mixed, and high-severity fire regimes)
Range and variation of basal area (BA) differed among the four scenarios that reflected HRV and three different FRVs (Fig. 4). The current BA (Present) is well within the HRV interquartile range (IQR), indicating that this variable is not significantly departed from the modeled HRV ($P < 0.001$). The median BA for the FRV3 scenario also falls within the HRV IQR (i.e., is not significantly departed). The FRV3 IQR is narrower and median BA is higher ($P < 0.001$) than for the FRV1 and FRV2 scenarios because the high (98%) level of fire suppression implemented in this scenario minimizes fire-caused biomass loss. The FRV2 and FRV1 scenarios produce progressively lower median BA, consistent with expected lower fire suppression levels and increased fire-caused biomass loss. The zone of overlap in the IQR between each FRV scenario and the HRV scenario indicates the percent of simulation replicate-years (200) where the comparison variable (BA) resides within the HRV distribution of that variable. For FRV2, BA responses are outside of the HRV-resilience envelope for at least half of the simulation years ($P < 0.001$). There is almost no zone of overlap between HRV and FRV1 because tree mortality from frequent fires and likely climate stress results in persistently lower BA than the HRV reference.

In the univariate method, a simple percentile number can be used as a resilience index. In our example, we calculated the percentile in which the current (Present) landscape BA resides within the HRV distribution of BA (Present was in the 64th percentile) and then used that percentile as a resilience score (64) where 50 would be high resilience and below 25 and above 75 would be low resilience. Other central tendency statistics can be used to determine where in the HRV BA probability distribution is the current value for BA and whether it is significantly different (departed) from the HRV value. For current BA, the probability of the current landscape condition in the HRV distribution is 0.69, which is less than our designated alpha level ($P > 0.05$), so this landscape could be considered resilient. We also calculated a resilience index for each FRV scenario where pairwise t-tests indicate significant departure from HRV ($P > 0.05$). In our example, the two scenarios where BA was significantly departed from HRV are FRV1 and FRV2.

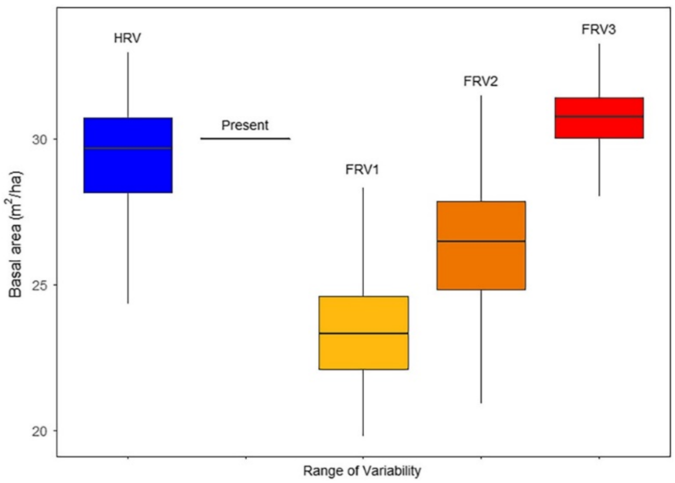


Figure 4. An illustration comparing historical (HRV) and future (FRV) variability in basal area (m2/ha) variability compared with current conditions on the EFBR landscape (Present: the initial conditions at the start of the simulation). FRV1, FRV2, and FRV3 are future simulations with RCP8.5 climate with 0%, 50%, and 98% of fire ignitions suppressed, respectively.

We used PCA to assess multivariate landscape resilience for the 14 variables that were used to represent an HRV and the contemporary conditions. We defined the dimensions of our HRV analysis space using the first two principal components (PC1, PC2), which together explained about 60% of the variance in the simulation variables. Unlike the univariate BA analysis, the current condition of the landscape lies well outside the point cloud for HRV (i.e., departed from historical reference conditions). The large departure of years 100 to 120 from the primary HRV cloud is because it takes more than a century to eliminate initial effects from the model, and the initial conditions reflect 100 yr of fire exclusion.

Comparison of PCA results across the three FRV climate and fire management scenarios and HRV scenario provides insight into the potential impacts of changing climate and fire regimes on future landscape resilience (Fig. 5). Unlike results from the univariate analysis, all three fire management scenarios (0, 50, and 98% fire suppression) under RCP8.5 climate depart from HRV, especially FRV3. Moreover, the state of the contemporary landscape is well outside the PC1–PC2 point clouds of the HRV and of all three FRVs, indicating that it has low resilience when multiple variables are used, regardless of climate or fire management scenario. This illustrates the value of using multiple variables when evaluating resilience. The zones of overlap among the three future fire management scenarios and the HRV scenario become smaller as suppression increases; the overlap for FRV1 and FRV2 scenarios (Fig. 5B, D, F) includes all of the HRV space, such that any treatment or wildfire that moves the landscape toward HRV should be more viable in the future. There appear to be two separate point clouds for each of the three FRV scenarios (Fig. 5A, C, E) which is the result of the slow ramping of predicted climate over the first 100 yr of simulation.

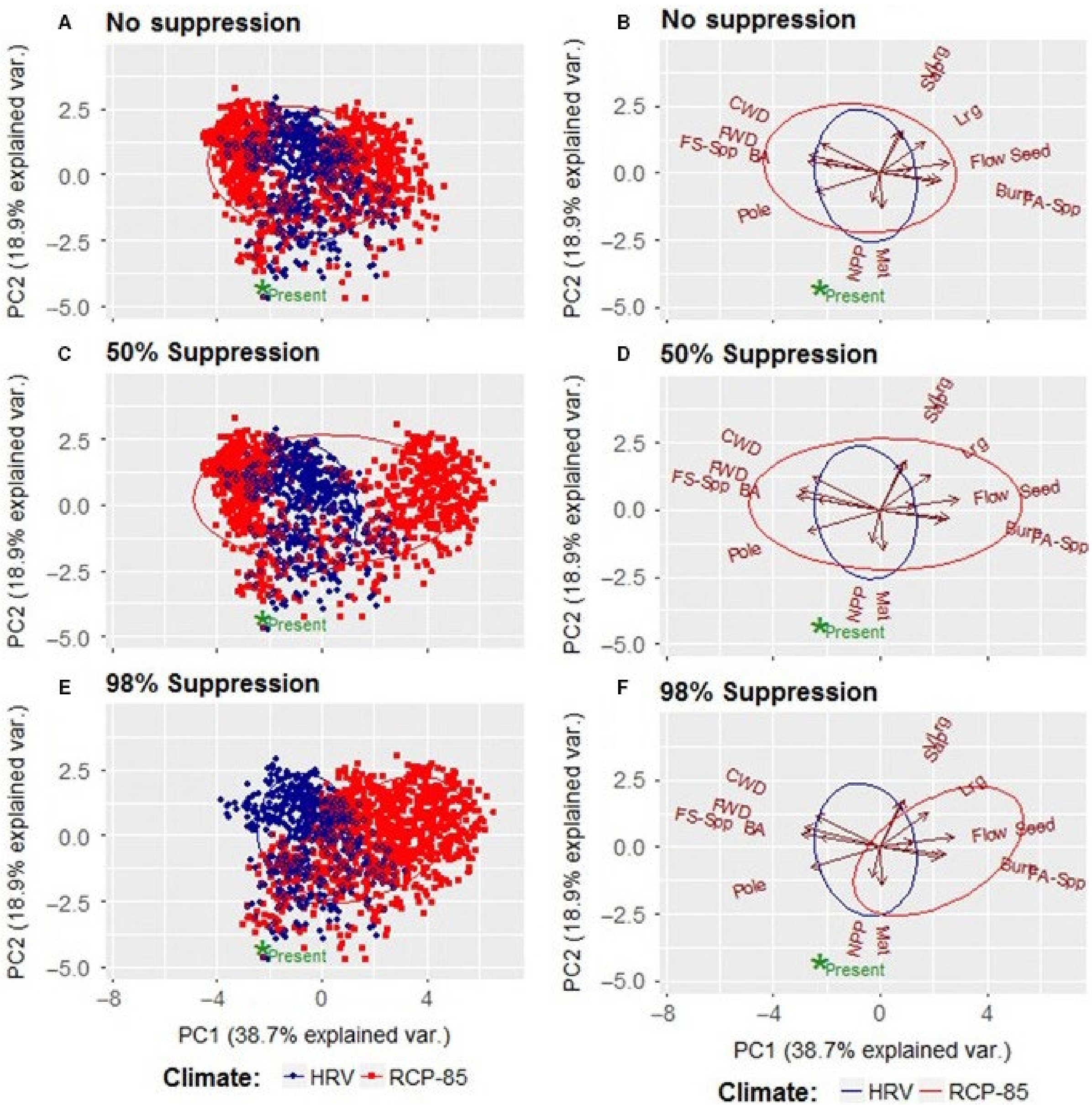
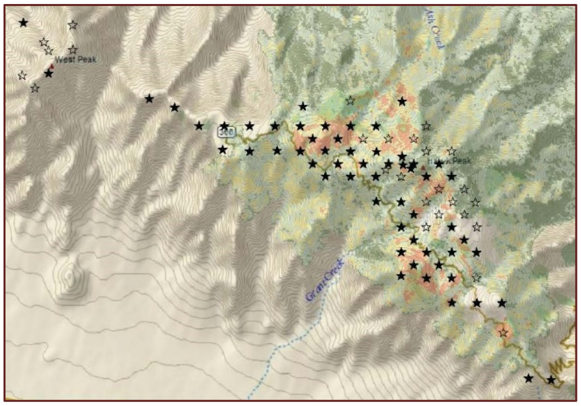


Figure 5. Results of PCA of FireBGCv2 simulations for the EFBR landscape for the historical scenario (HRV; blue dots, reference) and for the three future scenarios (red dots; FRV1, FRV2, FRV3; Table 2). See Keane et al. (2018) for details.

Pinaleño Mountains, southeastern Arizona (montane mixed-severity fire regime)

As annual area burned increases across the US, the probability increases that areas will experience multiple fire exposures over time. The resulting areas of reburn represent novel emerging challenges for fire scientists and land managers. Reburning areas may manifest fire behavior different from areas that have not experienced fire for long periods (Lydersen et al. 2019). Moreover, ecological recovery following reburns is poorly understood, and may lead ecosystems into novel or unexpected trajectories, including the potential for persistent VTCs (Coop et al. 2016, Coppoletta et al. 2016). Although reburning at time intervals on the order of the fire return interval is in theory within the recovery potential of most ecosystem types, many ecosystems are experiencing reburns consisting of uncharacteristically high severity fire at shorter intervals, potentially beyond their adaptive capacity.



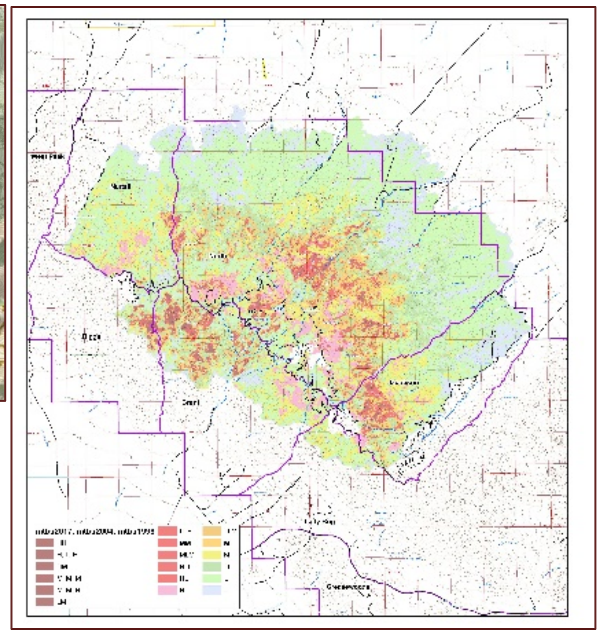


Figure 6. (a) Plot network in the Pinaleño Mountains; background fire severity from the 2017 Frye Fire. (b) Fire exposure and reburn recovery index.

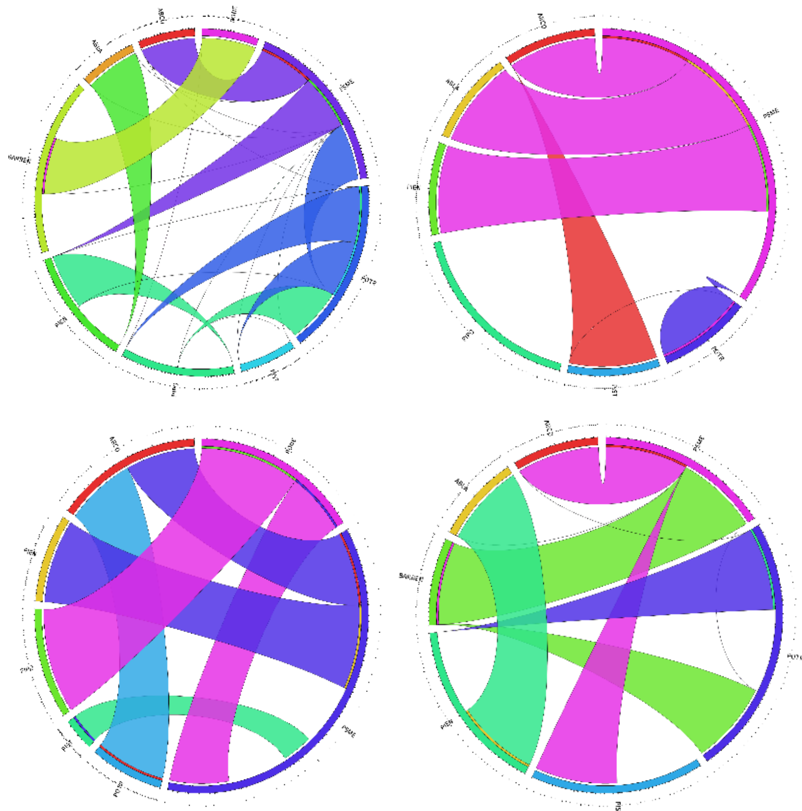


Figure 7. Post-fire transition probabilities. Upper left: all species across severity classes. Upper right: Species transitions under low-severity exposure. Lower left: Species transitions under moderate-severity exposure. Lower right: Species transitions under right-severity exposure.

We mapped the landscape effects of multiple fire events over the past 35 years in the Pinaleño Mountains, SE Arizona, using a pilot version of a fire exposure and recovery index (Figure 6a, b). With data derived from the previously described plot network (Figure 6a), we calculated changes in species density, tree heights, and basal area across the plot network pre- to post 2017 Frye Fire, as primar expressions of persistence and recovery. We calculated transition probabilities in species density and abundance before and after the 2017 Frye Fire using species Importance Values based on relative basal area and relative density (Figure 7), which we calculated for all species combined, and then for low, moderate, and high severity fire exposure. We found significant species differences in transition probabilities. At low severity (Figure 7a, upper right), most communities were stable except for transitions from *Abies concolor* (ABCO) to *Pinus strobiformis* (southwestern white pine). At moderate severity, several conifers (*Pseudotsuga menziesii*, Doublas-fir) and *Pinus ponderosa*, ponderosa pine) were replaced by *Robinia neo-mexicana*, New Mexico Locust and *Populus tremuloides*, quaking aspen) at a high proportion of plots. At high severity, most transitions were toward *P. temuloides* and *P. strobiformis*, as well as a signficant proportion of transitions to unvegetated ground.

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

Integrating Fire into Revised Forest Plans under the 2012 Rule (text from Graf 2018)

As evidenced in the forest plan revisions, the USFS has made important, initial steps towards integrating fire and forest planning. Forest planning is a three-tiered process and the 2012 Planning Rule and forest plans represent the first two tiers. Both now allow, or even encourage, the management of natural-ignition fires for resource benefit. As such, forest plan revisions are now a viable vehicle for changing fire management paradigms. However, they are not action compelling with regards to fire management and change will depend on the final tier of the planning process, incident-level decision-making. Going forward, incident-level decision-making will provide the needed growth and change in fire management in the USFS. The cumulative impact of these decisions will determine if the USFS fire management programs will fulfill the intent of the 2012 Planning Rule and Cohesive Strategy.

These first early adopter National Forests have made important strides in incorporating fire into forest planning and have set the stage for change. The approaches used by these National Forests provide examples of how to begin integrating fire management with forest planning across USFS lands. However, an adaptive, iterative process of planning, implementing, monitoring, and amending will be needed to achieve the desired conditions of these forest plans. Landscape-scale fire planning will require adaptive management which should be a continual learning process where incident-level decisions are cumulatively monitored for trends, triggering changes in management strategies and forest plan amendments. As the second tier of forest planning, these forest plan revisions are a large achievement that provide a foundation for moving forward. The ongoing revision processes across the national forests can benefit greatly from the efforts of these pilot forests.

Defining Concepts of Resilience

We have made numerous advances in the science and application of ecological resilience. Some of our key findings our summarized below:

Resilience is a highly scale-dependent process (Falk et al. 2019). For example, small high-severity burns recover completely differently than large high-severity burns. In this instance, the size of the fire dictates the recovery pathway, recovery time, and susceptibility to VTC. This has important implications for what areas should be prioritized for management intervention.

Changing climate implies potential transformations in plant demography, communities and disturbances, such as wildfire and insect outbreaks (Keeley et al. 2019). Many interacting factors, such as land-use decisions and the presence of invasive vegetation, influence the process of VTC, but fire severity and pre- and post-fire climate appear to be key drivers of irreversible change. Seed dispersal is also important, but seedling recruitment and survival is more likely to be the key limiting life stage. Many older trees can tolerate several years of stressful conditions, but seedlings and young saplings do not have the resources or physiology to survive. Where seedlings fail to establish, the population is eventually fated to disappear, leading to type change. Once this has occurred, warmer and drier climate may preclude return to the pre-disturbance state.

Changing disturbance regimes and climate can overcome forest ecosystem resilience and lead to reorganization, including VTC (Coop et al. 2020). Following high-severity fire, forest recovery may be compromised by lack of tree seed sources, warmer and drier postfire climate, or short-interval reburning. A potential outcome of the loss of resilience is the conversion of the pre-fire forest to a different forest type or non-forest vegetation. Conversion implies major, extensive, and enduring changes in dominant species, life forms, or functions, with impacts on ecosystem services.

Ecosystem management and restoration are influenced by more than just local processes (Falk 2017). The primary axes of change include not only the climate system, but also the spread of invasive species, altered biogeochemical and hydrological cycles, modified disturbance regimes, and land degradation and conversion.

Climate stressors on western forests are shifting species distributions across spatial scales, lengthening potential fire seasons, and increasing the incidence of drought and insect-related die-off (O'Connor et al. 2020). A legacy of fire exclusion in forests once adapted to frequent surface fires is exacerbating these changes. We used an ecosystem process model to simulate the effects of projected climate, fire, and active management interactions along an ecological gradient of shrublands, woodlands, and forests on a mountain range in Arizona in the United States. Simulated desert grassland and shrub communities remained compositionally stable and maintained or expanded their extents while woodland and forest communities lost basal area and total biomass and receded to the coolest and wettest aspects and drainages even without fire. Immediate and future fuel treatments showed potential to mitigate the severity of fire effects under projected conditions and slow the transition from forest to shrubland in some vegetation types, however, a reduction in basal area and spatial extent of some forest species were not counteracted by management actions, indicating a strong top-down climate influence and likely type conversion. We partered with the relevent land managers (Coronado National Forest, Ft Huachuca of the Department of Defense, The Nature Conservancy) to interpret these findings into a treatment plan for the areas indicated by these results as most vulnerable.

Fire severity in forests is often defined in terms of post-fire tree mortality, yet the influences on tree mortality following fire are not fully understood (van Mantgem et al. 2020). Pre-fire growth may serve as an index of vigor, indicating resource availability and the capacity to recover from injury and defend against pests. For trees that are not killed immediately by severe fire injury, tree growth patterns could therefore partially predict post-fire mortality probabilities. Pre-fire conditions affecting tree vigor may influence post-fire tree mortality probabilities.

Environmental conditions (such as rising temperatures and moisture stress), independent of fire intensity, may thus cause expressed fire severity to increase in western forests.

Methods to Quantify Resilience

Looking forward, rapid climate change, ongoing land degradation, altered and accelerated disturbance regimes, exotic species invasions, and a host of other human impacts that are occurring today and into the future demand a still broader assessment than using HRV alone (Falk 2017, Keane et al. 2018). Overlaps between HRV and FRVs may provide ideal targets for specific management-oriented environmental variables. We demonstrate variations of the method using both univariate and multivariate approaches. Inclusion of multiple variables into the assessment can be accomplished using PCAs to compress multiple variables into a smaller number of axes that define the response space of FRV and HRV. We identified several variables that are important to managers and that drive differences between current, HRV, and FRV most strongly (highest factor loadings), and then identify treatments that enhance these variables. We show examples of how to deploy this method into operational use, even in cases where there is little apparent overlap between the HRV and FRV. In these cases, managers may want to set goals that are within HRV but trending toward the FRV as a hedge, given a future that is unlikely to be similar to the past, but characterized by high uncertainty.

Literature Cited

Agee, J. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington DC USA.

Barrett, L., B. Connelly, F. Fay, M. Hale, B. Meneghin, and J. P. Menakis. 2017. Integrating Fire into Land Management Planning: A Technical Guide for Fire Planner and Land Management Planners. U.S. Department of Agriculture, Forest Service, Washington, D.C.

Beisner, B. E., D. T. Haydon, and K. Cuddington. 2003. Alternative stable states in ecology. Frontiers in Ecology and the Environment **1**:376-382.

Bowman, D. M. J. S., J. K. Balch, P. Artaxo, W. J. Bond, J. M. Carlson, M. A. Cochrane, C. M. D'Antonio, R. S. DeFries, J. C. Doyle, and S. P. Harrison. 2009. Fire in the Earth system. Science **324**:481-484.

Coop, J. D., S. A. Parks, S. R. McClernan, and L. M. Holsinger. 2016. Influences of prior wildfires on vegetation response to subsequent fire in a reburned southwestern landscape. Ecological Applications **26**:346-354.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fulé, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K. C. Rodman. 2020. Wildfire-Driven Forest Conversion in Western North American Landscapes. Bioscience.

Coppoletta, M., K. E. Merriam, and B. M. Collins. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications **26**:686-699.

Elmqvist, T., C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change, and resilience. Frontiers in Ecology and the Environment **1**:488-494.

Falk, D. A. 2016. The resilience dilemma: incorporating global change into ecosystem policy and management. Arizona State Law Journal **48**:145-156.

Falk, D. A. 2017. Restoration ecology, resilience, and the axes of change. Annals of the Missouri

Botanical Garden **102**:201-216.
Falk, D. A., P. J. v. Mantgem, J. E. Keeley, R. M. Gregg, A. J. Tepley, D. J. Young, C. H. Guiterman, and L. A. Marshall. In Review. Tamm Review: Mechanisms of Forest Resilience. Forest Ecology and Managment.
Falk, D. A., A. C. Watts, and A. E. Thode. 2019. Scaling Ecological Resilience. Frontiers in Ecology and Evolution **7**.
Fletcher, M.-S., S. W. Wood, and S. G. Haberle. 2014. A fire-driven shift from forest to non-forest: evidence for alternative stable states? Ecology **95**:2504-2513.
Folke, C. 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Global Environmental Change **16**:253-267.
Graf, H. 2018. Integrating Fire and Forest Planning: A Review of National Forest Plan Revisions. University of Montana.
Guiterman, C. H., E. Q. Margolis, C. D. Allen, D. A. Falk, and T. W. Swetnam. 2018. Long-term persistence and fire resilience of oak shrubfields in dry conifer forests of northern New Mexico. Ecosystems **21**:943-959.
Haber, J. 2015. Creating the Next Generation of National Forest Plans. University of Montana, College of Forestry and Conservation, Bolle Center for People and Forests, Missoula, MT. .
Higgs, E., D. A. Falk, A. Guerrini, M. Hall, J. Harris, R. J. Hobbs, S. T. Jackson, J. M. Rhemtulla, and W. Throop. 2014. The changing role of history in restoration ecology. Frontiers in Ecology and the Environment **12**:499-506.
Johnstone, J. F., C. D. Allen, J. F. Franklin, L. E. Frelich, B. J. Harvey, P. E. Higuera, M. C. Mack, R. K. Meentemeyer, M. R. Metz, G. L. W. Perry, T. Schoennagel, and M. G. Turner. 2016. Changing disturbance regimes, ecological memory, and forest resilience. Frontiers in Ecology and the Environment **14**:369-378.
Keane, R. E., P. F. Hessburg, P. B. Landres, and F. J. Swanson. 2009. The use of historical range and variability (HRV) in landscape management. Forest Ecology and Management **258**:1025-1037.
Keane, R. E., R. A. Loehman, L. M. Holsinger, D. A. Falk, P. Higuera, S. M. Hood, and P. F. Hessburg. 2018. Use of landscape simulation modeling to quantify resilience for ecological applications. Ecosphere **9**:e02414.
Keeley, J. E., P. van Mantgem, and D. A. Falk. 2019. Fire, climate and changing forests. Nature plants **5**:774-775.
Loehman, R. A., S. M. Hood, D. A. Falk, R. E. Keane, J. O'Donnell, M. Nie, and B. Hahn. In preparation. Managing for resilience in fire-prone landscapes. Fire Ecology.
Lydersen, J. M., B. M. Collins, M. Coppoletta, M. R. Jaffe, H. Northrop, and S. L. Stephens. 2019. Fuel dynamics and reburn severity following high-severity fire in a Sierra Nevada, USA, mixed-conifer forest. Fire Ecology **15**:1-14.
McKenzie, D., C. Miller, and D. A. Falk. 2011. Toward a theory of landscape fire. Pages 3-25 *in* D. McKenzie, C. Miller, and D. A. Falk, editors. The Landscape Ecology of Fire. Springer.
Millar, C. I., N. L. Stephenson, and S. L. Stephens. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications **17**:2145-2151.
Miller, A. D., J. R. Thompson, A. J. Tepley, and K. J. Anderson-Teixeira. 2019. Alternative stable equilibria and critical thresholds created by fire regimes and plant responses in a fire-prone community. Ecography **42**:55-66.
O’Connor, C. D., D. A. Falk, and G. M. Garfin. 2020. Projected climate-fire interactions drive

forest to shrubland transition on an Arizona sky island. Frontiers in Environmental Science **8:137**.
Suding, K. N., K. L. Gross, and G. R. Houseman. 2004. Alternative states and positive feedbacks in restoration ecology. Trends in Ecology & Evolution **19**:46-53.
Syphard, A. D., T. J. Brennan, and J. E. Keeley. 2019. Drivers of chaparral type conversion to herbaceous vegetation in coastal Southern California. Diversity and Distributions **25**:90-101.
Turner, M. G. 2010. Disturbance and landscape dynamics in a changing world 1. Ecology **91**:2833-2849.
van Mantgem, P. J., D. A. Falk, E. C. Williams, A. J. Das, and N. L. Stephenson. 2020. The influence of pre-fire growth patterns on post-fire tree mortality for common conifers in western US parks. International Journal of Wildland Fire **29**:513-518.
Wardle, D. A., L. R. Walker, and R. D. Bardgett. 2004. Ecosystem properties and forest decline in contrasting long-term chronosequences. Science **305**:509-513.
White, P. S., and S. T. A. Pickett. 1985. Natural disturbance and patch dynamics: an introduction. Pages 3–13 *in* S. T. A. Pickett and P. S. White, editors. The ecology of natural disturbance and patch dynamics. Academic Press, New York, New York, USA.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Articles in peer-reviewed journals

Published

Baughman, C.A., R.A. Loehman, D.R. Magness, L.B. Saperstein, and R.L. Sherriff. 2020. Four decades of land cover change on the Kenai Peninsula, Alaska: Detecting disturbance-influenced vegetation shifts using Landsat legacy data. *Land.* 9:382.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Z. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fule, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K. C. Rodmen. 2020. Wildfire-driven forest conversion in western North American landscapes. *BioScience* 70:659-673.

Keane, R. E., R. A. Loehman, L. M. Holsinger, D. A. Falk, P. Higuera, S. M. Hood, and P. F. Hessburg. 2018. Use of landscape simulation modeling to quantify resilience for ecological applications. *Ecosphere* **9**:e02414.

Keeley, J. E., P. van Mantgem, and D. A. Falk. 2019. Fire, climate and changing forests. *Nature Plants* 5:774-775.

Falk, D. A., A. C. Watts, and A. E. Thode. 2019. Scaling ecological resilience. *Frontiers in Ecology and Evolution* 7:275.

Falk, D. A. 2017. Restoration Ecology, Resilience, and the Axes of Change. *Annals of the Missouri Botanical Garden* 102:201-217.

Higuera, P. E., A. L. Metcalf, C. Miller, B. Buma, D. B. McWethy, E. C. Metcalf, Z. Ratajczak, C. R. Nelson, B. C. Chaffin, R. C. Stedman, S. McCaffrey, T. Schoennagel, B. J. Harvey, S. M. Hood, C. A. Schultz, A. E. Black, D. Campbell, J. H. Haggerty, R. E. Keane, M. A. Krawchuk, J. C. Kulig, R. Rafferty, and A. Virapongse. 2019. Integrating subjective and objective dimensions of resilience in fire-prone landscapes. *Bioscience* 69:379-388.

O'Connor, C. D., D. A. Falk, and G. M. Garfin. 2020. Projected climate-fire interactions drive forest to shrubland transition on an Arizona Sky Island. Frontiers in Environmental Science. 8: Article 137. 8:137.
Republished in D Bachelet, G Lasslop, and JT Abatzoglou, Eds. 2021. *Climate, Land Use, and Fire: Can Models Inform Management?* Lausanne: Frontiers Media SA. http://doi:10.3389/978-2-88966-383-5

van Mantgem, P. J., D. A. Falk, E. C. Williams, A. J. Das, and N. L. Stephenson. 2020. The influence of pre-fire growth patterns on post-fire tree mortality for common conifers in western US parks. International Journal of Wildland Fire 29:513-518.

In Review

Falk, D. A., P. J. v. Mantgem, J. E. Keeley, R. M. Gregg, A. J. Tepley, D. J. Young, C. H. Guiterman, and L. A. Marshall. In review. Tamm Review: Mechanisms of Forest Resilience. *Forest Ecology & Management*.

In Preparation

Falk DA, HM Poulos, CD O'Connor, S Hood, A Rosati, and RA Loehman. In Preparation. Multiple factors regulate post-fire resilience in a Sky Island forest.

Loehman, R. A., S. M. Hood, D. A. Falk, R. E. Keane, J. O'Donnell, and M. Nie. In preparation. Managing for resilience in fire-prone landscapes. Fire Ecology.

Technical reports

van Mantgem EF, PJ van Mantgem, DA Falk, and JE Keeley. 2020. Linking diverse terminology to vegetation type-conversion, a complex emergent property: Research Synthesis for Resource Managers, California Fire Science Consortium, Joint Fire Science Program.

Graduate thesis (masters or doctoral)

Graf, H. 2018. Integrating Fire and Forest Planning: A Review of National Forest Plan Revisions. Thesis. University of Montana. https://scholarworks.umt.edu/cgi/viewcontent.cgi?article=12147&context=etd

Conference or symposium proceedings scientifically recognized and referenced (other than abstracts)

Keane, R., S. M. Hood, R. A. Loehman, L. M. Holsinger, P. E. Higuera, and D. A. Falk. 2020. Using landscape simulation modeling to develop an operational resilience metric. Pages 294-300 *in* S. M. Hood, S. Drury, T. Steelman, and R. Steffens, editors. Proceedings of the Fire Continuum – preparing for the future of wildland fire; 2018 May 21-24; Missoula, MT. Proceedings RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Online.

Workshop materials and outcome reports

2-day Workshop of 20 FS Region 4 fire staff about how to incorporate fire into forest plans and the concept of resilience in fire-dependent systems

Website development

https://www.firelab.org/project/resilient-landscapes-and-fire-regimes

Presentations/webinars/other outreach/science delivery materials

DA Falk and P van Mantgem. Impacts of disturbance and ecological interactions on climate response. USGS SW CSC Review panel. UA, Tucson. February 2019. Invited.

DA Falk. Toward a framework for ecological resilience. USGS Climate Science Center working group on ecological drought. UA, Tucson. March 2019. Invited.

DA Falk. "Stressors generated by drought, fire, insects, and disease." Workshop: Adapting to Drought in the Southwestern Region. US Forest Service, Region 3 and National Office of Sustainability and Climate Change. ABQ NM. June 2019.

G Garfin, DA Falk, E Gornish. Briefing for Arizona legislature on climate change and sustaining resilient ecosystems. Oct 2019. Invited.

DA Falk. "What do we know about ecological resilience (and how do we know it?)?" LTRR Departmental seminar. Nov 2019. Invited.

DA Falk. "How do we map restoration ecology onto a rapidly changing world?" Keynote address, Society for Ecological Restoration-SW Annual Meeting. Albuquerque, NM. Dec. 2019 Invited.

DA Falk. “Restoring ecosystems in the climate change era.” UA Science Café, Tucson Botanical Gardens (January 2019)

DA Falk. “(How) can we map ecological restoration onto a rapidly changing world?”. Society for Ecological Restoration (SER) national webinar (February 2019).

DA Falk. “Fire, climate change, and adapting restoration ecology to a changing world” Keynote address at SER-High Altitude Revegetation Conference, Ft Collins CO (March 2019).

DA Falk. “Restoring adaptive capacity for an unknown future” International Association for Landscape Ecology, Ft Collins, CO (April 2019),

L Yocom, DA Falk, AE Thode, M Crimmins, RA Loehman, and W Flatley. “Gradients of productivity and flammability drive fire regimes in the SW US” North American Forest Ecology Workshop in Flagstaff, AZ (July 2019)

Baughman, C.A., R.A. Loehman, D.R. Magness, L.B. Saperstein. *Disturbance-driven shifts on the Kenai Peninsula, 1974-2016.* 8th International Fire Ecology and Management Congress: Cultivating Pyrodiversity. Tucson, AZ, November 18-22.

8th International Fire Ecology and Management Congress for Association for Fire Ecology, Tucson, AZ, November 2019: Sharon Hood co-organized a 12 talk special session entitled “Effectiveness of fire and fuel treatments to promote resilience to drought” with Jeffrey Kane, Humbolt State University.

DA Falk. “Scaling ecological resilience”. Association for Fire Ecology, November 2019. Contributed presentation.

LL Yocom-Kent, DA Falk, and AE Thode. Association for Fire Ecology, November 2019. “Drivers of fire and vegetation in the southwestern United States.” Contributed presentation.

Loehman, R. 2020. Keynote presentation: Using ecosystem modeling to find management options under multiple climate scenarios. Ecosystem resilience and change in an uncertain world, Center for Climate Adaptation Science and Solutions (CCASS) and the Southwest Climate Adaptation Science Center (SW CASC), University of Arizona, Tucon, AZ May 5-6.

DA Falk DA (2020). “On resilience: Can forests survive the Anthropocene?” University of Arizona School of Law. February.

DA Falk (2021) “Fighting Drought With Fire.” Research talk for New Mexico Statewide Forest and Watershed Health Coordinating Group. January.

DA Falk and L McGuire (2021) “The future of the Santa Catalinas after the Bighorn Fire: Restoration, resilience, and change.” Sustainable Tucson. May.

DA Falk (2021). Panelist for section on forest resilience: Fire and the Future, webinar produced by the Desert Laboratory, Arizona Public Media, and Arizona Institutes for Resilience. 410 attendees. https://environment.arizona.edu/fire-on-the-mountain). June.

DA Falk (2021). “Analytical foundations of ecological resilience.” Departmental Seminar, School of Natural Resources and the Environment. October.

Appendix C: Metadata

The modeling component of the project used existing field data, remotely sensed imagery, landscape data layers, and weather and climate model information to provide spatial and tabular information on vegetation composition and structure, landscape physiography, and contemporary and potential future climatology. Data and the information necessary to interpret those data, and model executables, parameters, and output, will be maintained, shared, and permanently archived via the JFSP-recommended repository (Forest Service Research Data Archive ((http://www.fs.usda.gov/rds/archive/). We will use Metavist or a similar metadata editor to create XML and HTML metadata documents compliant with the Biological Data Profile metadata standard and in accordance with Federal metadata standards (EO 12906), following the guidelines provided on the Forest Service Research Data Archive. The archive will be released to the public after publication of journal articles or the 2-year post-project end date, whichever comes first.