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Special Topic: Synthesis for Resource Managers

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Mixed-conifer forest resilience: from theory to practice

Defining Forest Ecosystem Resilience

Dynamic ecological systems, such as Sierra Nevada mixed-conifer forests, rarely persist in stable equilibrium states, but instead can persist in various alternative states (Holling 1973). Generally, a system is classified as resilient if it can persist following a disturbance (Holling 1973). However, because forests can occur in alternate states, it is difficult to quantify resilience (Levine 2017). Thus, an improved definition of resilience is the ability of forest ecosystems to absorb and recover from natural disturbances and return to their prior condition with little degree of change in ecosystem structure and function (Levine 2017; Koontz et al. 2020). Resilience can also be considered a measure of forest health: healthy forests are resilient to the naturally-occurring disturbance regimes with which they evolved (Battisti et al. 2010). Forest ecosystem resilience is maintained when interactions between different ecosystem components either preserve negative feedback loops that promote stability or disrupt positive feedback loops that would otherwise promote transitions to other habitat types (Koontz et al. 2020).

Levine (2017) defines forest ecosystem resilience using four dimensions, as follows:

1) Heterogeneity in forest stand structure (size, height, and spatial arrangement) and composition (species evenness and richness).
2) Landscape-level complexity in species diversity, forest structure and composition, and availability of seed sources.
3) Forest health as defined by population quality and individual tree vigor and productivity.
4) Presence of a seed bank and/or reserves of nutrients, carbon, and water that individual trees can use.

Levine (2017) states that each of these dimensions of ecosystem resilience improve forest resistance to disturbances.

Management Implications

- Understanding the relationship between landscape-level forest resilience and disturbance regimes is necessary for effective forest management.
- Silvicultural treatments that are guided by historical patterns of density and structural heterogeneity are likely to promote resilience.
- Reforestation efforts that follow an individuals, clumps, and openings pattern and use species adapted for anticipated future conditions are likely to promote resilience.
- Collaborative adaptive management is essential for developing long-term resilience in Sierra Nevada mixed-conifer forests.

Disturbance Regimes of the Sierra Nevada

While the resilience of historic mixed conifer forests was maintained by natural disturbance regimes and Indigenous stewardship, changes in management practices (including fire suppression) and exposure to stressors (including droughts and insects) have reduced the resilience of these ecosystems (Levine 2017). Although fire frequency varied among stands due to differences in structure and composition, the mixed-conifer fire regime was characterized by frequent low-to moderate-intensity fires occurring every 8 to 20 years (Stephens et al. 2007). This fire regime promoted a heterogenous stand structure, which allowed for the retention of larger diameter and fire-tolerant species (Dolanc et al. 2014; Stephens et al. 2015). Climate also plays an important role in influencing wildfire activity, with greater fire activity associated with warmer spring and summer temperatures and earlier spring snowmelt (Westerling et al. 2006).

Over the past 150 years, dramatic changes to the physical structure, species composition, and age structure of mixed-conifer forests resulted from the forced removal of Indigenous populations and their cultural burning practices, along with Euro-American logging and fire suppression. Fire exclusion and suppression favored the establishment of even-aged stands composed of smaller diameter, shade-tolerant species (Dolanc et al. 2014). Greater tree density and surface fuel loads have led to increased fire risk, particularly following extreme drought periods (Stephens et al. 2018). High stand density increases the vulnerability of stands to forest insect outbreaks (Stephens et al. 2018). Areas with severe bark beetle outbreaks tend to have greater fuel loads, which can affect subsequent fire behavior and lead to increased fire severity, making forests more vulnerable to altered disturbance regimes (Stephens et al. 2018). The combination of these processes challenges the resilience of mixed-conifer forests (Levine 2017).

Applying Forest Ecology for Greater Resilience

One strategy for improving forest resilience is to implement treatments that emulate historical conditions that existed under an intact disturbance regime (Churchill et al. 2013). Historic forest structure in dry, formerly frequent-fire forests can be generally characterized as a pattern of individuals, clumps, and openings. These individual, clump, and opening patterns can be re-established using various silvicultural treatments (Churchill et al. 2013). Before treatments are implemented, managers should consider stand-specific objectives and how they relate to surrounding management strategies and climate adaptation (Churchill et al. 2013, Dudney et al. 2018, Rissman et al. 2018). Maintaining forest ecosystem resilience can require managing for different combinations of species or varying forest structure and function depending on management objectives (Figure 1, Dudney et al. 2018; Rissman et al. 2018). An additional silvicultural strategy is to use SPLATs (strategically placed landscape area treatments), in which treatments are strategically incorporated within a broader landscape to both reduce fire severity and improve post-fire conifer regeneration (Tubbesing et al. 2019).

Understanding natural disturbance regimes can provide a framework for adapting silvicultural treatments to ecological principles (Franklin et al. 2007). Traditional silvicultural practices that are guided by key disturbance characteristics like severity, frequency, and average patch size can help to restore historic structural characteristics (Franklin et al. 2007). Managers can consider 1) using thinning and group selections of varying sizes while only occasionally creating large openings with clear-cuts to create a similar gap size distribution, or 2) preferentially harvesting less fire-resistant species. Since fire is the dominant disturbance agent in mixed-conifer forests, managers could also consider applying prescribed fires either independently or coupled with other treatments to effectively reduce fuel loads and restore the desired stand structure (Schmidt et al. 2006).

A New Strategy for Resilience-Based Silvicultural Restoration Treatments

Reforestation provides an opportunity to control the composition, density, and heterogeneity of a forest after disturbance, potentially enhancing forest resilience. Traditionally, forest planting strategies emphasized planting trees at high density in a systematic, grid-like pattern, followed by competition control and/or pre-commercial thinning (North et al. 2019). Unfortunately, the increased prevalence of high severity fires, drought, and decreased funding for pre-commercial thinning activities means that these traditional planting practices may lead to forests

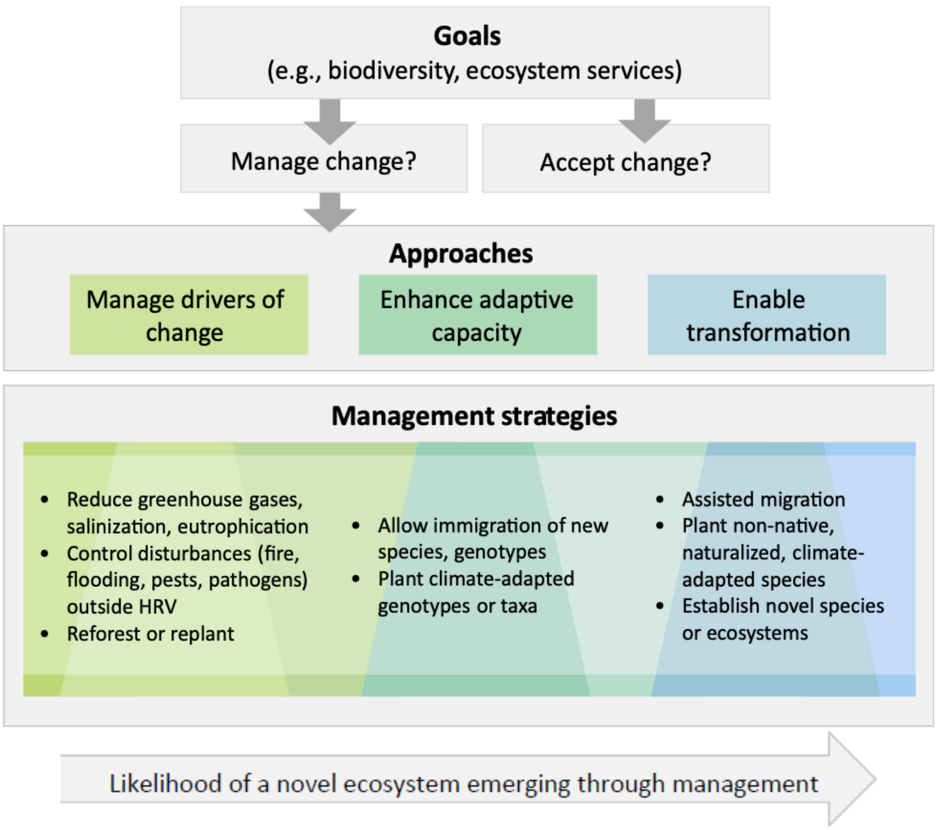

Figure 1: The conceptual model of resilience-based management presented by Dudney et al. (2018). Based on their objectives, managers can employ various approaches to manage drivers of change, enhance adaptive capacity, or enable transformation. The key to resilience based management is to be clear about management objectives and to understand how different management approaches will increase resilience and/or lead to ecosystem novelty (Figure is from Dudney et al. 2018, Figure 1, p. 864).

that are less resilient. North et al. (2019) provide a framework for improving resilience in reforestation efforts (view Research Brief PDF >.) This framework begins with managers dividing the area that needs replanting into three zones depending on planting feasibility. The first zone is near live trees where seed source availability is high and where natural regeneration is likely to be successful, the second zone is outside the dispersal range of live trees, but accessible to managers, and the third zone is outside dispersal range and too costly or inaccessible to replant (North et al. 2019). Planting strategies can be adapted to each of these zones but planting efforts should be concentrated in the second zone. North et al. (2019) suggest that managers plant individual scattered trees in a matrix of shrubs and trees, combined with a mixture of clumps and openings (an "ICO" pattern). The authors suggest planting with variable densities according to topography, water availability, soil conditions, and other local factors. North et al. (2019) suggest that, while there may be some mortality of planted seedlings, prescribed fire should be considered in juvenile stands to promote future resilience of the stand to drought and wildfire (view Research Synthesis on prescribed fire in young stands PDF >). Further, North et al. (2019) suggest that future site conditions be considered when prioritizing planting projects. For instance, sites that are projected to be hotter and drier may benefit from regeneration with seeds sourced from lower elevational zones. For additional guidance on postfire restoration steps, Meyer et al. (2021) describes a set of considerations and steps for managers (view research brief PDF >).

An additional strategy for restoring structural heterogeneity to mixed-conifer forests in the Sierra Nevada is variable density thinning. The goal of variable density thinning is to restore stand density, basal area, species composition, and size distribution to historic levels. Variable density thinning can modify stand structure more quickly than using prescribed fire (Knapp et al. 2017). Trials comparing variable density thinning with conventional thinning and prescribed fire treatments in the Stanislaus-Tuolumne Experimental Forest found that the combination of variable density thinning and prescribed fire best restored forest heterogeneity to historic levels and reduced fuel loads (Knapp et al. 2017). Knapp et al. (2017) suggests that the combination of variable density thinning and prescribed fire improve forest resilience and reduce the potential for future high-severity wildfire. Implementation of silvicultural treatments like variable density thinning or individuals, clumps, and openings can be facilitated by modern technology that improves efficiency and enables more accurate planning. For instance, one study found that the use of an Android OS tool improved on-the-ground operations by providing real-time feedback on the size and placement of clumps and gaps (Maher et al. 2019). Technologies like this make increasingly complex management plans possible.

Challenges to Developing Forest Resilience

Quantifying forest resilience is a challenge for scientists and forest managers due to the longevity of forest species, widespread geographical distribution of forests, spatial complexity of forest ecosystems and disturbances, uncertainly in future conditions, and the wide array of definitions of resilience (Reyer et al. 2015; Levine 2017; Koontz et al. 2020). Several methods have been proposed for quantifying forest resilience. For instance, Valor et al. (2020) compared resistance and resilience to drought and fire among pine species using tree-ring analysis. Levine (2017) developed a flexible resilience framework that incorporates resilience theory into management decisions across multiple forest-types. Koontz et al. (2020) quantified forest resilience in yellow pine and mixed conifer forests of the Sierra Nevada, and found that increased forest structural variability increased resilience by decreasing the prevalence of high severity fire. These examples and others can serve as a template for forest managers who wish to quantify resilience.

A second challenge in managing for long-term resilience is climatic uncertainty. While a significant body of data and research on historical conditions for Sierra Nevada mixed-conifer forests exists, future climate conditions are uncertain. Projected climate impacts include increases in temperature, increases in carbon dioxide concentrations in the atmosphere, and increased variability in precipitation (FCAT 2018). Higher temperatures and changing precipitation patterns are expected to increase the frequency, extent, and severity of disturbances including wildfire and drought (Millar and Stephenson 2015).

Climate uncertainty also challenges forest ecosystem management. "Megadisturbances" due to the interactions between drought, insects, and wildfire can lead to tree mortality events that are unprecedented in frequency, severity, and size (Millar and Stephenson 2015). For instance, the interactions between drought, increased fire size and severity, and bark beetle outbreaks have killed more than 100 million trees over the past decade (Stephens et al. 2018), and could be considered an example of a megadisturbance (Millar and Stephenson 2015). The interactions between these different disturbances may cause ecosystems to exceed resilience thresholds and experience significant ecological transformations (Millar and Stephenson 2015). The temperate mixed forest biome is among the most vulnerable to vegetation shifts due to the effects of climate change, thus, forest-type transformations should be expected in the Sierra Nevada mixed-conifer forests during the 21st century (Gonzalez et al. 2010). If future forest transitions are anticipated due to changing disturbance regimes, management decisions can promote a smooth transition between different ecosystem types in order to better retain ecosystem services (Millar and Stephenson 2015).

Management Solutions for an Uncertain Future

Practicing sustainable forest management under uncertain future conditions may require different strategies depending on the location and objectives. These strategies can generally be categorized into one of three approaches: resilience, resistance, and transition (Millar et al. 2007; Nagel et al. 2017). The resilience-based allows for gradual change in response to changing climates and ecosystem conditions and enables post-disturbance recovery by promoting a return to historic reference conditions (Nagel et al. 2017). The resistance-based approach promotes actions that attempt to prevent ecosystem change and maintain current forest conditions in the face of changing climates and disturbance regimes. The resistance approach may be especially useful in the face of uncertain future conditions (Millar et al. 2007). The transition-based approach promotes actions that allow ecosystems to change in response to future conditions, by promoting changes in species composition or forest structure. Transition-based management acknowledges that future conditions may not support the desired reference conditions on a site, and allow the ecosystem to respond adaptively to future conditions (Millar et al. 2007). Although difficult, transition-based management may be the best chance for maintaining forest cover on a site. Any one of these three strategies may be used depending on forest management goals, a forest manager's willingness to accommodate change, and anticipated future conditions.

The observed and expected rapid changes in climate and forest conditions emphasize the need for collaborative adaptive management. The Sierra Nevada Adaptive Management Project is one such example of a collaborative adaptive management group (http://snamp.ucanr.edu/, SNAMP 2015). The SNAMP defined collaborative adaptive management as a "science-driven, stakeholder-based process for decision-making while dealing with the scientific unknowns." A framework for collaborative adaptive management is founded on partnerships between scientists, stakeholders, and managers, and is the optimal way to maximize transparent and two-way information sharing for research and management applications (SNAMP report 2015; Millar et al. 2014). By incorporating experimentation that addresses management questions and needs proactively, rather than passive trial and error research, collaborative adaptive management can be an effective strategy for promoting forest resilience in the increasingly uncertain future of the Sierra Nevada mixed-conifer forests (SNAMP 2015).

Authors

This synthesis was initially drafted in fulfillment of an upper-level college course at UC Berkeley by Christian Jordan, Kathryn Low, and Adam Taylor during Spring 2020 and was revised by Alison Paulson.

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