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Synthesis: Interactions Between Fire and Climate in the California Sierra Nevada

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> *"Anyone who says they have a grasp on how climate change will impact future fire regimes possesses an impressive level of optimism."*
> *-Keeley and Syphard (2016).*

Summary

In the Sierra Nevada Mixed Conifer (SNMC) system, climate variability is projected to contribute to increased frequency and intensity of wildfires. Although managers will likely be unable to prevent this shift in the fire regime, creating lower density forests with increased heterogeneity across landscapes could create more resilient forests. Key tools to consider are the application of restoration thinning, prescribed fire, and managed fire, which can build long-term ecosystem-level resilience to the predicted climatic changes. These activities can support resilience to climate change by decreasing fuel loads, decreasing stand-level water demand, and creating and maintaining heterogeneity in a forest mosaic landscape. By mitigating the effects of drought, these restoration activities can reduce the risk of severe, stand-replacing fire and promote long-term ecosystem resilience to climate change. Given the changing disturbance regimes and climate, there is a critical need to take decisive and extensive actions in the next 1-2 decades to conserve Sierra Nevada forests.

Introduction

Climate plays a long-recognized role in fire activity (Swetnam and Betancourt 1998). Overall in the western United States, the 20th century has been in a fire deficit as compared to the past 3,000 years (Marlon et al. 2012) .Climate change, ecological differences, and human activities (including fire suppression and reduced indigenous burning) have all contributed to this fire deficit. As anthropogenic climate change progresses, fire regimes will shift not only as a result of changing temperature and precipitation, but also as a result of increased variability in these drivers. As noted in California's Fourth Climate Change Assessment, the SNMC ecosystem is expected to experience some of the largest year-to-year climate fluctuations in the United States (Dettinger et al. 2018). Although climate variability will exert a large influence on vegetation and fire activity, we find evidence that adaptive forest management can support resilience to climate change in this system.

Management Implications

Climate change is impacting California fire regimes but changing forest structure through treatments such as restoration thinning and prescribed fire can support long-term forest resilience *today* through several pathways:

- Decreased fuel loads → reduced risk of severe stand replacing fire
- Decreased stand density → decreased water demand, increased water availability, reduced water stress-induced mortality
- Increased landscape heterogeneity → reduced risk of large patches of severe stand replacing fire, increased resilience to uncertain and non-homogenous climate impacts

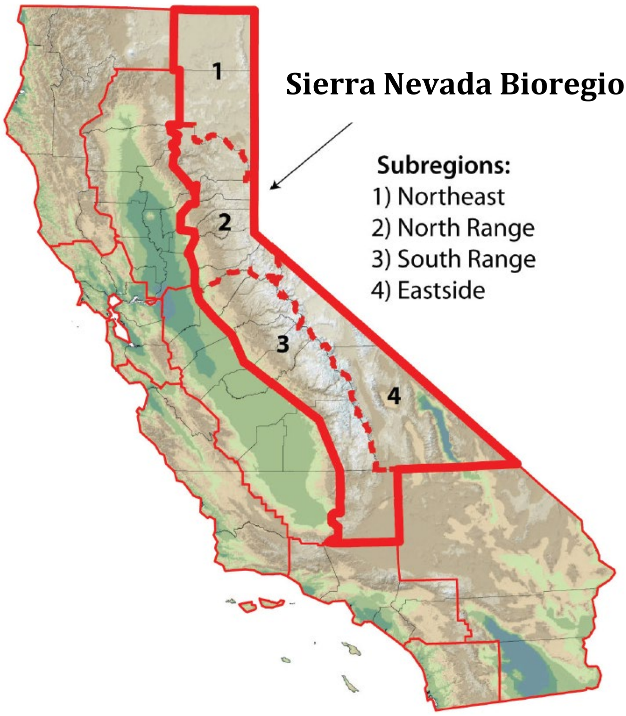

Figure 1. *The Sierra Nevada region and subregions (Source: Dettinger et al. 2018).*

Here, we first consider the effects of variability in precipitation and temperature on wildland fire, and the role of restoration in the SNMC ecosystem. We review these potential effects at multiple scales and highlight the role of feedback loops between these ecological drivers. We then discuss emerging research regarding the role of restoration strategies on ecosystem resilience to climatic variability and suggest several approaches for adaptive management.

Sierra Nevada Mixed Conifer Ecosystem

The SNMC ecosystem includes the montane forests that cover a wide swath of the Sierra Nevada (Figure 1). Ranging in elevation from approximately 3,000 to 7,000 feet, these forests generally consist of up to five conifer species: ponderosa pine (*Pinus ponderosa*), sugar pine (*P. lambertiana*), Douglas-fir (*Psuedotsuga menziesii*), white fir (*Abies concolor*), and incense-cedar (*Calocedrus decurrens*) (Evans et al. 2011). Other common tree species include canyon live oak (*Quercus chrysolepis*), black oak (*Quercus kelloggii*), giant sequoia (*Sequoiadendron giganteum*), and Jeffrey pine (*Pinus jeffreyi*).

Prior to Euro-American colonization, the SNMC forest was characterized by a frequent, low- to moderate-severity fire regime, though high-severity (stand-replacing) patches also occurred (Evans et al. 2011, Stephens et al. 2015). Studies of the region have indicated that historic mean fire return intervals ranged from 4 to 30 years, with an average of 13 years (Evans et al. 2011). Fire frequency and severity were variable across this ecosystem, reflecting the underlying differences in terrain, elevation, latitude, and dominant tree species. Most fires occurred during late summer and early fall when fuel moisture was lowest. The historic fire regime likely contributed to the heterogeneity of the SNMC ecosystem, which is characterized by a mosaic of "individual trees, clumps, and openings" in the forest (Larson and Churchill 2012) (Figure 2).

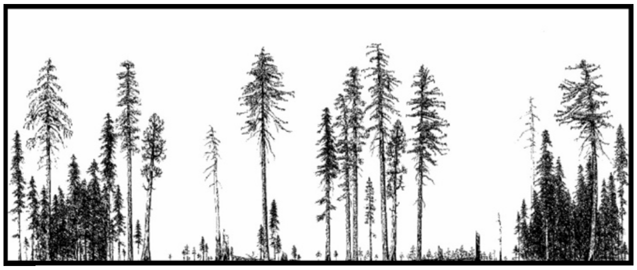

Figure 2. *Graphical depiction of the structure of a typical pre-colonization mixed conifer forest in the Western SCMC. (Source: Schmidt et al. 2006, reproduced from the original drawing by Robert Van Pelt for the Sierra Nevada Ecosystem Project.)*

Climate and Fire: What We Know

In general, climate change influences fire in two ways: increasing the occurrence and severity of fire weather conditions (hot, dry, and windy (Abatzoglou et al. 2018)) and changing the vegetation patterns and growth that acts as fuels for fire.

According to California's Fourth Climate Change Assessment, the Sierra Nevada region has already begun to experience climate change in the form of higher nighttime temperatures, lower proportions of precipitation falling as snow rather than rain, decreased snowpack, and earlier peak flow in snow-fed streams (Dettinger et al. 2018). Climate models predict that these trends will continue and likely accelerate. By the end of the 21st century, temperatures in the Sierra Nevada are predicted to increase by as much as 6 to 10 degrees F. While climate models forecast a less dramatic change in *total* precipitation over this region, they indicate a shift toward greater extremes, including an increase in both the number of dry days *and* in the amount of precipitation from the largest storms.

The impacts of climate-driven changes in temperature and precipitation on the fire regime in the SNMC ecosystem are less certain. Keeley and Syphard (2016) describe two general mechanisms through which climate influences the fire regime:

- **Impacts on fuel moisture.** In the months immediately preceding the fire season, climate influences the moisture content of live and dead fuels. For example, warm and dry weather prior to fire season reduces the moisture content of fuels and increases the likelihood of fire ignition and spread.
- **Impacts of fuel volume.** One to two years prior to a fire season, climate can influence the volume of herbaceous fuels. For example, fire may be more likely to start and spread during fire seasons preceded by high precipitation years, which produce high volumes of fuel (especially fine fuels).

However, these two mechanisms are not equally influential in all locations. In the SNMC system, fuel moisture during the active fire season is more important than past-year fuel accumulation (Keeley and Syphard 2016). This is because litter (like needles and twigs) is a more significant driver of fire ignition and spread in mixed conifer forests than is the presence of dried herbaceous fuels.

Complexities and Feedback Loops

Geography and Topography

The SNMC ecosystem inhabits a diverse geographical and topographical region. Spatial diversity across all scales will influence how climate shapes future fire regimes. Climate models predict that as elevation increases, warming and shifts in precipitation patterns will happen more quickly (Dettinger et al. 2018). However, soil and fuel moisture will experience a less straightforward pattern; by the end of the century, these values are expected to decline by at least 15% relative to historic values at the lowest and highest elevations but increase by 20-40% in mid-elevation areas (Dettinger et al. 2018). The speed and degree of change will also vary regionally, with the fastest warming predicted for the northeast and southeast range (Figure 1), followed by the southern range and the northern range, respectively. At the local level, studies indicate that south-facing slopes may be more vulnerable to climate change, given their potential for increased impacts from summer drought (Halofsky et al. 2020).

Intra-annual Shifts

The seasonality, or intra-annual timing of climatic variability is an important factor in how it will impact the fire regime. While historic data indicate a strong positive relationship between temperature and area burned in the Sierra Nevada, only spring and summer temperatures show a significant correlation with annual area burned (Keeley and Syphard 2016). Given the identified fire area deficit in the western US (Marlon et al. 2012) studying severity of areas burned rather than just area burned may be a better metric to understanding changes in fire patterns over time.

Interannual and Multidecadal Shifts

The temporal relationship between climate change and fire transcends the seasonal scale and acts on longer timeframes. Analysis of historical fire data in the Sierra Nevada show that the strongest variable contributing to area burned in the early 20th century (1910-1959) was spring precipitation, while summer temperature was strongest in the late 20th century (1960-2010) (Keeley and Syphard 2016). This suggests that the relationship between climate and fire has changed over time. The changing relationship between climate and fire could be related to a number of factors including changes in human activities, differences in how we recorded fire statistics over the 20th century, and shifts in low-frequency climate oscillations (Collins et al. 2006). Because climate change has the potential to result in novel combinations of temperature and precipitation, this long-term variability may become more important and harder to predict using historical data. Historical data compared to recent records showed that an increase in aridity (in summer and, to an extent, fall) has increased fire activity in forested areas (Williams et al. 2019)

Vegetation

Climate-driven changes in vegetation and fire activity will interact on seasonal and multidecadal scales. In wetter future scenarios in the Sierra Nevada, broadleaf trees may replace mixed conifer forest at low and mid elevations. Drier scenarios, in contrast, may cause shrub and grassland to expand into mixed conifer forests. Both drought and changes in the fire regime (increased fire frequency and severity) could lead to this state-shift of forests to shrub or grassland (Lenihan et al. 2003, 2008). Under the predicted fire regime in the Sierra Nevada, it is possible that mixed conifer stands will be unable to regenerate following frequent high severity events, supporting an additional cause of this state-shift to shrub and grasslands (Halofsky et al. 2020).

Human Demographics

While regions of Southern California show that anthropogenic ignitions are more important in determining the fire regime than climate, current information shows a stronger connection between climate and fire in SNMC (Keeley and Syphard 2016). In the future, as human populations expand farther into the foothills, the wildland urban interface will grow, and human drivers are predicted to have an increasing influence on fire ignitions (location and timing). Studies of Mediterranean ecosystems indicate a nonlinear relationship between population density and number of fires: as population density increases, ignitions also rise, but only to a point; the highest wildfire frequencies are associated with areas of intermediate population density (Prestemon et al. 2013). The abundance of ignitions is not necessarily correlated with the size of the area burned (Keeley and Syphard 2018). Disentangling human from climate influences will thus present a challenge in predicting future climate regimes.

Historic Management

Past management strategies, particularly fire suppression and exclusion contrary to Indigenous fire management, undoubtedly reduced fire activity during the 20th century and will play a continuing role in the interannual and multi-decadal interactions between climate and fire (Fulé et al. 2012). The results of suppression — fuel accumulation and dense forest structure — are thought to have already contributed to increased forest area burned and increased fire severity over the past several decades (Hurteau et al. 2014, Stevens et al. 2017). As climate change progresses, increased forest density may precondition sites for high mortality loss during periods of drought, thereby also increasing fuel loads and severe fire risk (Keeley and Syphard 2016, Stephens et al. 2018) (Figure 3).

Figure 3. A). *The 2012-2016 drought had devastating impacts on SNMC forests, as illustrated by this image of dead and dying ponderosa and sugar pine in Sequoia National Forest (Source: USDA Forest Service). B.) In contrast, the Sierra de San Pedro Mártir forests in Baja California illustrates a resilience to both severe drought (1999-2002) and fire (2003 wildfire) with a historical forest structure and frequent low intensity fire (Source: Scott Stephens 2019).*

Drought and Climate Water Deficit

Although uncertainties abound, multiyear severe drought conditions in the Sierra Nevada have been correlated with an increase in both wildfire size and severity, a trend that is consistent throughout the western United States (Crockett and Westerling 2018). Drought conditions, which can perhaps more accurately be characterized by measures of Climate Water Deficit (CWD), depend on the interplay between temperature, precipitation, and evapotranspirative demand (Crockett and Westerling 2018). Some researchers hypothesize that the relationship between drought (or CWD) and fire is driven by snowpack, where higher spring temperatures cause earlier and more rapid snowmelt. Rapid snowmelt is thought to contribute to a decrease in water uptake, lower live fuel moisture, and cause longer periods of dry soil conditions (Keeley and Syphard 2016). These authors also suggest that the timing of snowmelt is less important in determining fire activity than the direct effect of higher temperatures (and lower precipitation) in drying both live and dead fuels during the fire season. Warming and drying effects due to climate change were found to be a major factor in the 8-fold increase of summertime forest-fire area acres burned in California since the 1970's (Williams et al. 2019), although the best metric to evaluate wildfire effects over time is fire severity since it is describes forest mortality patterns.

Opportunities to Promote Resilience

Droughts, bark beetles, and wildfires have been severely impacting California forests for decades. However, there are sites within the Sierra Nevada bioregion that are showing signs of greater resilience to these major disturbances and may offer insight into forest and fire management.

There is evidence that both managed wildfire and prescribed fire may increase forest resilience to drought. While the impact of drought on wildfire size and severity has been studied with some attention (see CFSC synthesis "Drought and Fire in California, 2016), emerging research also shows the impact of wildfire on an ecosystem's water balance (Vose 2016). For example, Boisramé et al. (2017) analyzed the impacts of 45 years of managed wildfire on soil moisture and runoff in the Illilouette Creek Basin in Yosemite National Park as compared to similar watersheds where fire was excluded. The authors found that the runoff ratio in the managed wildfire watershed remained stable or increased over the previous four decades, while it decreased in the unburned watersheds. Interestingly, tree mortality associated with the most recent extreme drought in California (2012 to 2016) was much lower in the Illilouette Creek Basin than in surrounding unburned areas (Figure 4). Similarly, van Mantgem et al. (2016) found that tree mortality during the recent extreme drought was lower in areas with past prescribed burning than in unburned areas across a wide swatch of the Sierra Nevada. These studies suggest a potential feedback loop in which fire (prescribed or low/moderate severity wildfire) increases an ecosystem's resilience to drought, which in turn decreases the risks of a catastrophic wildfire.

This result may vary at different spatial and temporal scales. For example, wildfire may reduce an ecosystem's resistance to drought in the short-term by increasing soil exposure, leading to higher rates of evaporation and snow melt (Neary et al. 2005), while increasing its drought resilience in the long-term by increasing landscape heterogeneity and decreasing stand density (van Mantgem et al. 2016; Boisramé et al. 2017; Pausas and Keeley 2019).

Another example of resiliency comes from comparing the effects of drought in southern California forests. A period of severe drought from 1999-2002 affected the San Bernardino National Forest and the floristically similar forests 200 miles south in the same mountain range (the Sierra de San Pedro Mártir (SSPM)) but with drastically different results.

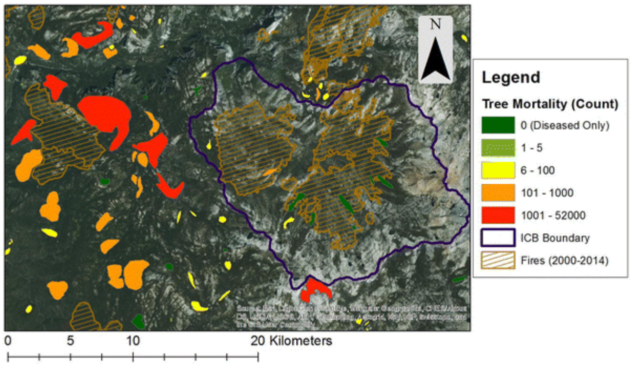

Figure 4. *Managed wildfire increases forest resilience to drought. This map shows drought-related tree mortality and disease areas relative to burned areas in the Illilouette Creek Basin. Burned areas do not significantly overlap with large mortality patches, even though burned areas contain many large trees (Source: Boisramé et al. 2017).*

Due to past forest management actions including fire suppression, the San Bernardino National

Forest had many more trees per acre than they did historically (Minnich et al. 1995). This higher density of trees with limited water resources resulted in tens of millions of trees dying. Without access to adequate water, these trees were unable to survive and defend themselves from additional stressors, especially that of bark beetles.

Within the same drought period, the SSPM forest demonstrated incredible resilience with limited tree mortality to these same stressors (Fig. 3B). Here, tree mortality from drought and bark beetles was 25 times lower than in the forests of southern California (SSPM had only 0.5 trees/acre die). Not only was there less tree mortality from this drought, but the SSPM also demonstrates resilience to wildfire. In 2003, the year after the severe drought ended in 2002, a wildfire burned in the SSPM. Even with this succession of events, ~80% of the trees survived (Stephens et al. 2008). For additional comparisons between the SSPM and Southern California forests, see the CFSC synthesis "Stand Structure in the SSPM, 2020."

Looking to the Future

Despite the promise of this research, it is impossible to accurately predict future trajectories and interactions between wildfire and climate change in the Sierra Nevada. Therefore, we recommend a strategy of managing for uncertainty, which may entail planning at a larger landscape scale for heterogenous mosaics within SNMC. Prescribed fire and restoration thinning are ways to achieve heterogeneity (Figure 5). A heterogenous forest mosaic (and the decreased forest density that results) has been shown to result in higher soil moisture and reduced competition for limited water resources, resulting in a forest ecosystem more resilient to current and future climatic changes in California (van Mantgem et al. 2016; Boisramé et al. 2017). The combination of mechanical thinning and prescribed fire treatments (or other surface fuel treatments) shows the most promising effects for reducing overstory tree mortality from wildfire (Safford et al. 2012) and improving overstory tree vigor (Collins et al. 2014; Low et al. 2021).

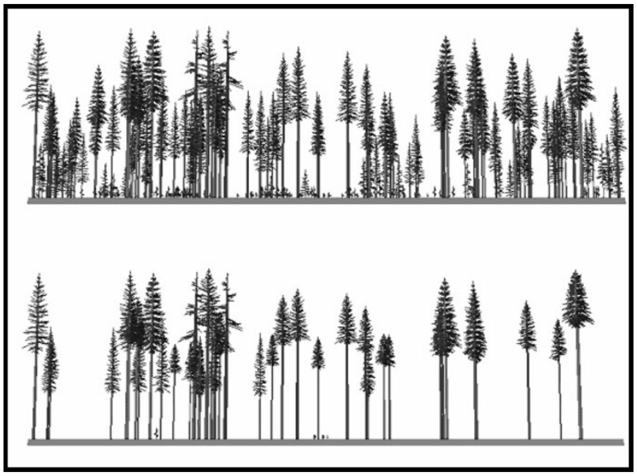

Figure 5. *Forest structure before (upper figure) and after (lower figure) a restoration project that employed high intensity prescribed fire in a Northern SNMC stand. The post-fire structure includes gaps, elevated crown base heights, and near removal of understory trees (Source: Schmidt et al. 2006, originally from McGaughey 1997).*

Mechanical treatments (especially ones that target ladder fuels) may provide the most opportunity for improving tree health and resilience but they come with the potential for increased fire hazard risk in the short term. Of the different treatment types compared in Collins et al. (2014), all treatment types were predicted to increase resilience when compared to the controls. Low et al. (2021) also showed the long-term benefits from restoration thinning to individual tree vitality and forest stand resiliency around Lake Tahoe. For southwestern ponderosa pine forests, mechanical and prescribed fire treatments were also shown to increase the carbon sequestration potential of forests (Hurteau et al. 2016). Modeling of climate and fire predictions by Liang et al. (2018) show that implementing forest treatments can effectively increase carbon sequestration if administered at a large scale. To further support ecosystem resilience, Halofsky et al. (2018) also recommend management actions that reduce the impact of ecosystem stressors such as invasive species and fragmentation.

Incorporating active fire management into forest climate adaption now ― rather than mid-century when fire activity is expected to increase markedly ― will likely improve long-term landscape and ecosystem level resilience to climate change (Halofsky et al. 2020).

Importantly, these fire-based and thinning management strategies must be maintained over time to remain effective. Given the importance of continuing fire-management and the limited availability of funds and personnel, restoration thinning, prescribed fire, and managed wildfire should be prioritized in **(1)** locations where climate impacts are expected to be most pronounced (e.g. south facing slopes), **(2)** high value habitats, and/or **(3)** high-risk locations (e.g. wildland urban interface) (Halofsky et al. 2020).

Authors

This synthesis was adapted from a synthesis written in fulfillment of a graduate level college course at UC Berkeley by Jessica Katz, Annie Taylor, and Rachel Ward.

Further Reading

***California's Fourth Climate Change Assessment: Sierra Nevada summary report* (Dettinger et al. 2018).** This study represents the State of California's most recent synthesis of climate change research, and the Sierra Nevada Summary Report provides region-specific information about climate change scenarios and their implications.

***Climate Change and Future Fire Regimes: Examples from California* (Keeley and Syphard 2016).** This review paper uses examples from California ecosystems (with a strong emphasis on the SCMC) to illustrate the spatial and temporal factors that drive climate-fire complexity.

CFSC synthesis paper on "Drought and Fire in California." This research brief summarizes the conclusions of a 2016 study on drought, applies these conclusions to drought and fire regimes, provides examples of how these conditions impact ecosystems in California, and synthesizes management implications.

CFSC synthesis paper on "Stand Structure in the Sierra de San Pedro Mártir (SSPM)." This research synthesis summarizes the numerous studies done in the SSPM and provides a potential example of how to manage for resiliency.

***Managed wildfire effects on forest resilience and water in the Sierra Nevada* (Boisramé et al. 2017).** This study assesses the impacts of 40 years of managed wildfire on soil moisture and runoff in the Illilouette Creek Basin compared to nearby areas without managed wildfire and provides an example in which managed fire increases drought resilience. A summary of the Illilouette Creek Basin research can be found here >

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