TITLE: Post-fire restoration to avert novel conditions in Sierra Nevada Forests

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List of Abbreviations/Acronyms

CI: Confidence Interval
eDaRT: Ecosystem Disturbance and Recovery Tracker
FACTS: Forest Service Activity Tracking System
GTR: General Technical Report
NAIP: National Agriculture Imagery Program
NDVI: Normalized Difference Vegetation Index
NRV: Natural Range of Variation
PSWRS: USDA Forest Service Pacific Southwest Research Station
R5: USDA Forest Service Region 5
RdNBR: relative differenced Normalized Burn Ratio
YPMC: yellow pine/mixed conifer forest types

Keywords
Ecological restoration; fire severity; mixed conifer forest; California; thinning; prescribed burning; wildfire.

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Abstract

The project examined several key questions regarding the need and strategies for post-fire interventions in California conifer forests through analyses and synthesis of findings in a series of reports and publications. Our team of researchers worked closely with US Forest Service managers and colleagues from other science institutions to provide science-based guidance in determining where interventions may be important for sustaining ecological resilience. These research questions a subject of rapidly developing science. Since we began our project, several more research studies have been published that document the potential for fire-induced shifts from historical conifer forests to non-conifer vegetation types and for other undesirable system dynamics. However, such concerns need to be tempered by the recognition that moderate and severe fires may also be restorative, by promoting shrubs, hardwoods, and less dense forests that may have declined, and they may also be adaptive, by promoting conditions that are more resilient to future disturbances. Our products provide guidance to land managers who are faced with confronting these rapidly evolving challenges, to help plan interventions to effectively steer trajectories toward desirable conditions over the long-term.

Objectives

State the original study objectives and indicate how they relate to the applicable task statement under which the proposal was submitted. In addition, indicate which objectives were met and which were not, and if not why not. If the JFSP approved changes to the original study objectives indicate what those changes were and why they were needed. Any working hypotheses that formed the basis of the research approach also should be clearly stated.

We substantially addressed the study objectives, although we had to modify our approaches to rely upon case study analyses and co-produced science syntheses. Funding constraints were imposed during the project, including a loss of a significant component of the original budget and inability to directly compensate Forest Service personnel. Funds were only provided for a short window. The reduction of funding and other constraints forced us to narrow direct our funding to address development of synthesis products with a strong emphasis on guidance for managers. We focused the remaining funds provided through PSWRS on Objective 1a (vegetation and fuels development using remotely sensed data) and Objective 2 (synthesis of findings for management). We were able to partially address the other research objectives and questions through collaborations with colleagues. Despite those constraints, we were able to deliver a substantial number of publications and presentations.

Objective 1: Understand relationships between high-severity patches and novel ecological conditions

1a) Fuel Development and Potential for Uncharacteristic Effects of Reburn

Research Question #1a-1: How does fuel type and continuity in high-severity patches vary with patch size, time-since-fire, pre-fire vegetation type and structure, and landform characteristics (e.g., aspect, elevation, slope, and moisture availability)?
Hypothesis: Larger high-severity patches are more likely to develop more homogeneous fuelbeds with greater continuity. Fuel continuity will be positively influenced by pre-fire tree density, time-since-fire, and site productivity.

Research Question #1a-2: How do post-fire management actions (e.g., salvage harvest, site prep) alter fuel development and vegetation growth, composition and structure?

Hypothesis: Post-fire management activities will alter fuel types and reduce fuel continuity initially, but continuity will increase with time, and may ultimately exceed that in untreated areas.

We addressed both questions and hypotheses through the analysis of vegetation development on public and private-industrial forest lands in the 2007 Moonlight Fire on the Plumas NF and large private land inholdings. We were fortunate to forge the relationship with the private landowner to access data and history of treatments. Because the level of active post-fire management strongly differed between ownerships, we were able to address the research questions. Much of the private land experienced intensive salvage harvesting and reforestation (including repeated applications of herbicides to control competing vegetation), while a majority of the public land experienced limited salvage and reforestation. The analysis examined the potential for shifts to different vegetation types reflecting different fuelbeds, composition, and structure. We were not able to develop a system for evaluating downed logs using remotely sensed data; however, the high-resolution aerial photography used by collaborators in another JFSP project (16-1-05-13) appears to provide a solution to that challenge. Our results were limited to these pilot studies because of limitations on access to data from different ownerships, challenges in developing a workable methodology, and the overall reduction in scope of the project. However, Moonlight is a particularly important study area, as it had one of the two lowest mean densities of conifer seedlings and saplings of fires evaluated for regeneration (Welch et al. 2016).

Objective 1b: Regeneration and Plant Community Composition

Research Question 1b-1: Does tree regeneration (by species) decrease with distance to green (including partially scorched or torched) forest edge, and is there a threshold high severity patch size where tree regeneration failure occurs?

Hypothesis: Tree regeneration will decline nonlinearly with distance to green trees and high-severity patch size, with threshold responses at distances exceeding 250 m and patches greater than 25 ha.

Through engagement with partnerships, we partially addressed this hypothesis in our synthesis products. Graduate students overseen by collaborator Safford conducted analyses of regeneration data they collected along with co-PI Meyer and other Region 5 staff. Those analyses led to two publications and associated tools for evaluating the need for active revegetation. The findings from those studies and guidance on how to apply the tools were incorporated into the post-fire restoration framework synthesis report.

We did not find a consistent threshold response for distance to seed trees or patch size that would apply to the entire region; instead, researchers have suggested a gradation of declining regeneration based upon a variety of factors, and proposed different thresholds to represent
different ecological contexts as well as risk tolerance. We noted where managers and research scientists have adopted rules of thumb for prioritizing areas that are likely to require interventions based upon expected seed rain from surviving green trees, as well as patch size metrics relative to NRV. We summarize the results of the data analysis and synthesis in the results. We incorporated those findings into the synthesis reports, and discussed the resulting tools in Appendix B to Meyer et al. (In press) as well as in a book chapter (Williams et al. In review).

Research Question 1b-2: How does this pattern vary among shade-tolerant versus shade-intolerant conifers, and between conifers and hardwoods (including both seedlings and resprouts)?

Hypotheses: Declines in tree regeneration with distance to green trees and high-severity patch size will be more pronounced in shade-intolerant conifers than shade-tolerant conifers and hardwoods. Hardwood resprouts will be unaffected by distance to green hardwood trees and high-severity patch size. Post-fire conifer survival will be higher in shade-intolerant than shade-tolerant conifers.

We partially addressed this hypothesis. The regeneration analysis found higher post-fire survival in shade-tolerant conifers (white fir, red fir, Douglas fir, and incense cedar) than in pines. That regeneration analyses did not look at hardwoods, although co-PIs examined survival and regeneration of California black oak (one of the most important hardwoods in YPMC forests of the Sierra Nevada) in a companion analysis from the Rim and King Fires that is discussed in the results.

Research Question 1b-3: How does post-fire salvage logging and tree planting influence these relationships?

Hypothesis: Post-fire salvage logging in combination with tree planting will reduce the potential for regeneration failure in high severity patches exceeding 25 ha, especially in shade-intolerant pines.

We partially addressed this hypothesis through the analysis of vegetation development on public and private lands in the Moonlight Fire, combined with the analyses of regeneration in untreated areas. We had to limit our analysis of salvage and planting to that single case study fire; however, the two of the analyses demonstrated why concerns might be particularly high in the Moonlight Fire. Furthermore, Co-PI Meyer completed an analysis that found that replanting reduced the potential for regeneration failure in shade-intolerant pines (see results).

Research Question 1b-4: How do climate (e.g., annual precipitation), topography, and understory shrub cover affect tree regeneration in post-fire landscapes?

Hypothesis: Tree regeneration will be greatest in forest patches characterized by higher annual precipitation, north-facing slopes, and lower understory shrub cover.

We addressed these hypotheses; specifically, the regeneration analyses led by Welch et al. (2016) and Shive et al. (2018) supported them (see Table 1 in the results).
Objective 1c: Wildlife module

The formal meta-analysis of wildlife studies originally proposed under this task was dropped due to the loss of funding. Our efforts regarding wildlife instead consisted of integration of synthesized findings from studies into publications in support of the larger framework, including two journal articles (Jager et al. In review, White and Long 2019).

Objective 2: Synthesis and Management Publications

Research Question: How can post-fire harvest/fuel reduction and replanting be designed to effectively reduce and break up patterns of fuel loads and best support wildlife communities?

We addressed this question by synthesizing existing science and findings from analyses. Specifically, we developed restoration guidance for post-fire landscapes, including lower versus upper montane, forest vs. chaparral, and moister (west-side Sierra Nevada) versus drier (east-side Sierra Nevada) contexts. Through General Technical Reports, journal articles and workshops we explained how management strategies can reduce/break up patterns of fuel loads and support wildlife communities as part of landscape restoration.

Research Question: How does survival, growth and potential future fire resistance of different tree species seedlings compare between variable and regular spacing planting patterns?

We found very limited information from field studies on this question and so we unable to obtain definitive answers. We presented the rationale for this approach in the North et al. (2019) journal article, and we also considered the limited amount of science in the second draft GTR.

Research Question: Under what post-fire circumstances (distance to green forest, high-severity patch size, topography, and expected climate) will forests maintain resilience to stand-replacing fire and where natural regeneration is insufficient to promote future forests?

This question was addressed and was the focus of the two general technical reports, journal article, and presentations.

Background

Our project grew out of a broader synthesis on forest management in the Sierra Nevada and Southern Cascade Range of California (Long et al. 2014), where fires have experienced increasingly large fires with patches of high severity that exceed the natural range of variation. This trend had posed a key challenge for National Forest management, since large high severity patches promote ecologically novel conditions, including the loss of mature trees over extensive areas, limited seed sources for tree regeneration, and creation of uncharacteristic fuel beds that could feed future fires. Post-fire logging to remove dead trees has been a contentious issue as there have been several studies demonstrating negative impacts to various wildlife species, and a key question is how such treatments might help or hinder ecological recovery. Consequently, some observers have criticized post-fire interventions as being insufficiently informed by scientific frameworks (Chen et al. 2013).

Materials and Methods
Objective 1a: Fuels module, including patch size analysis

In order to study fuel development within high severity patches, we first developed a method to define high severity patches using readily available fire severity maps and the PatchMorph tool in ArcMap. The settings for delineating high severity patches were optimized using several fires, including the Cub Fire, Moonlight Fire, Power Fire, Angora Fire, Rim Fire, King Fire and Rough Fire. We visually examined which settings appeared to yield the most sensible results for delineating patch boundaries without excluding significant high severity areas or creating highly complex shapes (Figure 1). These were:

1. minimum patch width (spur setting) of 90 m;
2. minimum width of lower severity area allowed within a patch (gap setting) of 90 m; and
3. minimum amount of high severity within a patch of 90%.
4. minimum patch area set to 5000 m² so that minimum patch size would be dictated by the spur setting; and
5. a smoothing window of 2 pixels.

![Figure 1](image_url)

**Figure 1.** Example of delineated patch boundary (blue line) relative to high severity patch boundary using a 30 m classified fire severity map. Red is high severity, yellow is moderate severity and green is low severity.

To consider fuel development, we analyzed National Agriculture Imagery Program (NAIP) 1-meter aerial photos to characterize fuel type (e.g., shrub, small trees, coarse woody, etc.), fractional cover, and distribution within high-severity patches. We were interested in analyzing how fuel continuity in high-severity patches varies with patch size, time-since-fire, pre-fire vegetation type and structure, landform characteristics, and management actions. We began by looking at live fuels, using a greenness index to represent the presence of live fuels. Preliminary work looking at live fuel progression was done using NDVI change over time in the Moonlight
and Antelope Fires. Initially, several greenness indices (see http://www.harrisgeospatial.com/docs/broadbandgreenness.html for helpful descriptions) were calculated from the Image Analysis window in ArcMap, including NDVI, SAVI and MSAVI, using the band arithmetic function (see http://resources.arcgis.com/en/help/main/10.1/index.html#/009t000001z4000000 and red and infrared bands in the NAIP imagery.

While all NAIP images were collected in summer, the collection dates as well as seasonal conditions varied by year leading to variation in greenness not necessarily related to fuel accumulation (e.g., from annual plants), so a different source of red and infrared imagery was needed. It was determined that a fall acquisition would be preferable so that the phenology could be better synchronized between years and most of the signal would be due to perennial rather than annual plant growth.

NDVI has been calculated for the eDaRT (Ecosystem Disturbance and Recovery Tracker) program operated by the US Forest Service Region 5 Remote Sensing Lab using Landsat data. Data was available at 2 week intervals going back to 2009 (Landsat data is available prior to this, but 2009 was the earliest record that was already processed for eDaRT, which was developed to track forest mortality). NDVI calculated from Landsat data has the advantage of more frequent collection dates (including data in the fall) but the resolution is much more coarse than NAIP imagery (30 m compared to 0.6-1 m). Another limitation of Landsat data is that there are bands of missing data (gaps) in some acquisitions. Using NDVI available through the Remote Sensing lab, imagery collected on a day closest to October 1st was chosen to compare between years.

Differences between Treatments on Public and Private Lands
We encountered challenges in attempts to compare private land treatments to those on public lands. Initially, we worked to develop methods for evaluating live vegetation amount/presence from remote sensing. In addition, treatment boundaries and descriptions are available through the FACTS database for Forest Service lands (although the reliability of data on post-fire treatments may need to be investigated), but treatment histories are generally not available on private lands.

However, we were able to compare treatments in the Moonlight Fire through a collaboration with a private landowner that was adjacent to national forest lands and was willing to share data. To track and compare the rates of vegetative regeneration across land ownership, multispectral data collected by the Landsat-5 TM and Landsat-7 ETM+ sensors were used to perform an annual linear spectral unmixing time series analysis. To provide context on changes in forest structural characteristics, the Random Forest ensemble classification algorithm was used to create classified images of land-cover for immediate pre-fire (2007) and 11 year post fire (2018) forest conditions. Land-cover was classified into the following categories: “Forb/Soil/Rock”, “Shrub”, “Young Forest”, “Mature Forests-Closed Canopy”, and “Mature Forest-Open Canopy”. These categories were selected as they were the most generalized representation of forest structure attainable that also preserved critical indicators of forest succession. These land-cover maps were compared using cross-tabulation to evaluate for transitions in land-cover type that occurred 11 years post-fire. To perform map validation, 300 ground control points (60/class) were systematically selected and excluded from use in classification for use in accuracy assessment. Accuracy assessment was performed through the comparison of digitized ground control point land-cover class assignment to land-cover class assignment generated during
classification analysis. As all ground control points were digitized for use in the 2018 land-cover classification, this method of classification accuracy could only be applied to the results of the 2018 land-cover classification. Due to this limitation, it was assumed that the results of the 2018 land-cover classification accuracy assessment are generally applicable to that of the 2007 (pre-fire) classification as the model was calibrated using the same ground control points/datasets, albeit collected at a different time. Accuracy assessment of the linear spectral unmixing time series analysis was conducted by averaging unmixed residuals by property ownership type for each time point, and then averaged across all time points to produce summary statistics. Each landownership type’s average residual value was then compared across time points to evaluate relative unmixing accuracy.

Objective 1b: Revegetation module

Project collaborators examined detailed and extensive post-fire vegetation inventories using a combination of tree regeneration plots (60 m²) installed every 4 ha (10 acres) and common stand exam (CSE) plots (0.04 ha) every 16 ha (40 acres) (>1800 plots total). The analysis by Welch et al. (2016) used data from 14 fires and Shive et al. (2018) used data from 24 fires, all in yellow pine and mixed conifer forests (YPMC). They did not analyze areas that were actively treated, so the analysis considers only trajectories in the absence of planting. They analyzed the data using a combination of statistical procedures to evaluate responses of tree regeneration (total and by species) to green tree distance and high severity patch size and other landscape factors. Shive et al. built a spatially-explicit habitat suitability model for forecasting post-fire forest regeneration. In response to expectations from the JFSP support for this project, the underlying data from these analyses were entered into the data archive (see Appendix C).

PIs Long and White also studied responses of California black oaks to the Rim Fire of 2013 and the King Fire of 2014 within patches of different burn severity through field sampling.

Objective 2: Synthesis and Management Publications

The investigators led collaborative groups involving NFS managers (R5 Ecology Program staff and silviculturists from individual National Forests) in developing two coproduced science reports to inform post-fire interventions. Our team organized and conducted a post-fire management workshop to inform the first GTR with silviculturists from Region 5 on March 6, 2017. The lead PI then convened a smaller team of researchers and managers to develop a second GTR on post-fire restoration strategies and tactics for forested areas. The team included FS silviculturists, regional ecology staff, and a cooperative extension forester, who engaged in team meetings beginning in 2019 to develop the scope, outline, and initial draft, which is currently being revised. These efforts were broadened out to several other publications (journal articles and a book chapter) following presentations.

To inform treatment strategies, PIs Long and North also initiated two field studies in coordination with the Eldorado National Forest on the Power Fire. The first focused on thinning oak resprouts and using prescribed fire. Preliminary findings from the latter study are being incorporated into the second GTR.
Results and Discussion

1a: Fuel development analysis including patch severity analysis

Findings from the patch size analysis highlighted that the Rim and American fires stood out in terms of the very high amounts of contiguous high severity patches, in contrast with the Rough Fire. Based on a simple summary of pixel values, 20% of the Rough Fire burned at high severity (Figure 2A), based on simple classification thresholds (Miller and Thode 2007). To define high severity patches, we used spur and gap settings of 90 m (295 ft.), a minimum patch area of 5000 m² (1.24 ac) and a smoothing tolerance of 90% within a 2-pixel window. For this example, we had no reason to restrict the minimum patch size and used 5000 m² because it is lower than the smallest area that would be possible within the specified spur distance, so that the spur and gap settings alone would determine the spatial configuration of patches. The smoothing tolerance setting was chosen to create a patch perimeter entirely within high severity pixels (i.e., no slivers of other pixels along the inside of patch edges). Smaller spur settings resulted in patches that were more interconnected, as well as the creation of a greater number of smaller patches. Smaller gap settings also increased the interconnectivity of patches, and allowed for larger patches with a lower shape complexity. Based on these parameters, high severity patches identified by PatchMorph within the Rough Fire accounted for 15% of the total area burned (Figure 2B). The difference between this proportion and that from the simple summary is mainly due to smaller, more isolated areas of high severity area not meeting the patch delineation criteria.

Considering additional factors when analyzing patch configuration, such as pre-fire vegetation type, can help to distinguish between different kinds of fire effects. Vegetation type is a particularly relevant consideration when there are strong differences in regeneration responses following high severity fire across types. To illustrate how this might be done, we performed a second patch delineation that included high severity patches within conifer vegetation only, based on the California Wildlife Habitat Relationships attribute in the Forest Service Region 5 2000–2014 Existing Vegetation spatial dataset (see Appendix A). While conifer forest was most prevalent at higher elevations within the Rough Fire footprint, other vegetation types such as shrub and oak woodland were common at lower elevations. Forty two percent of the area burned was in conifer forest (Figure 2C). Using the same settings for the PatchMorph algorithm on a raster that included both fire severity and vegetation type to delineate patches resulted in 7% of the fire area in patches of pre-fire conifer forest that burned at high severity (Figure 2D).

In addition to simply defining patches, this approach can be used to gain insight into processes such as expected vegetation recovery within patches. Regeneration of conifer species is typically reliant on wind dispersed seeds, and is therefore limited by distance to the nearest mature trees. This is a concern for large patches with greater interior, or core, area. For this example, we assessed patch interior area greater than 120 m from remaining conifer forest. This is a common dispersal distance threshold in conifer forests (Collins et al. 2017), and is twice the expected dispersal distance used by Welch et al. (2016), which found a steep decrease in regeneration with distance to nearest seed tree [such thresholds are discussed again later in the report]. Such areas accounted for 3% of the Rough Fire area (Figure 2E).
Figure 2: Spatial patterns of high severity fire for the 2015 Rough Fire based upon (A) high severity, contiguous patches of high severity (B), high severity burned in coniferous vegetation (C), contiguous patches of high severity in coniferous vegetation (D), and conifer-dominated areas in high severity patches that were >120 m from live conifers.

The patch analysis was applied to a number of recent wildfires to illustrate how particular wildfires have resulted in extreme departures from NRV (Figure 3). While high severity patch size is a critical indicator of departure, other considerations, including impacts to high value resources, may not be captured by that metric. Findings from the analysis of patch size were incorporated into the first GTR (Meyer et al. In press).
Figure 3: Percent area in high severity patches by size class from several recent large wildfires (2007 to 2015) in dry mixed-conifer forests of California.

Fuel development using satellite remote sensing data
Preliminary comparisons were made between plantations and unmanaged areas that had burned at high severity. We attempted to use both NAIP (Figure 4) and Landsat NDVI (Figure 5). NDVI was similar 2 years post-fire between plantations and untreated areas (Figure 6). In untreated areas NDVI continued to increase until 2011 (approximately 4 years post-fire) in the untreated areas, while it remained the same within the plantations. NDVI appeared relatively stable from 2011-2016, but note that 2012-2016 coincided with an extreme drought in the Sierra Nevada that may have limited vegetation growth.
Figure 4: Planted areas (orange) within high severity patches that burned in the 2007 Moonlight Fire, shown in 2016 NAIP imagery.

Figure 5: Untreated areas (purple outline) within high severity patches that burned in the 2007 Moonlight Fire with NDVI calculated from Landsat data (lower panel, brown lines correspond to data gaps).
Our original intent was to summarize fuel development within high severity patches. However, using individual patches as the unit of analysis proved to be problematic for two main reasons. First, when summarizing by patch the large patches are counted equally with the small patches, so most of the data come from many smaller patches while most of the high severity area is in one or two large patches. Second, large patches have a wider range in NDVI than small patches, particularly as time since fire increases. As such, a single average value for large patches contained more noise than smaller patches, resulting in little differentiation between the two. This was counter to our own observations on the ground. Beyond these issues we encountered problems using NDVI or other greenness indices to look at spatial patterns of fuel continuity. Doing so first required establishing a minimum threshold NDVI value for a pixel to be considered “vegetated” (e.g., classify NDVI raster into 2 classes of vegetated or not to look at spatial patterns). This was difficult because due to the subjectivity in determining when a 30 m pixel reached a point of being continuously “vegetated”.

In completing the imagery analysis, we found that our ability to detect changes in post-fire vegetation/fuel development was hampered by differences in timing of NAIP collection and phenology of vegetation across successive post-fire images. We could not attribute trends over time or differences in post-fire management to actual differences in vegetation/fuel development. After considering alternative imagery sources, we settled on Landsat given its availability prior to and following contemporary wildfires. We focused on the normalized difference vegetation index (NDVI) and closely related indices. For areas burned at high-severity we detected subtle differences in NDVI between untreated vs. intensively reforested stands over the first 3-4 years. After 5-7 years post-fire NDVI values (and other related indices) were similar across these obviously different vegetation/fuel complexes. Following these findings, we refined our analysis of Landsat imagery to incorporate an advanced remote sensing technique called linear spectral unmixing (results reported below).

**Figure 6**: NDVI values (as calculated for eDaRT) within preliminary plantation and untreated high severity burn areas within the 2007 Moonlight Fire.
Comparison of post-fire vegetation/fuel development on private and public lands in the Moonlight Fire

Using the post-fire vegetation classes listed previously, the team detected significant differences in forest vegetation recovery between public (USFS managed) and private timberland following the 2007 Moonlight Fire. Vegetation establishment on publicly owned lands occurred at twice the rate of their privately owned counterpart. However, by 2018 over half (53.9% or 10,062 ha) of publicly owned lands converted from forest (pre-fire) to a shrub-dominated land-cover type while only 2.2% (122 ha) of privately owned lands did so. Additionally, only 1% (249 ha) of publicly owned lands were characterized by young regenerating forests in contrast to 72.8% (3,875 ha) of privately owned lands (Figure 7). Private lands in the study relied on salvage (89%), replanting of conifers (90.7%), and herbicide to limit competition from shrubs (99.6%). In contrast, public lands relied much less on salvage (23%), replanting (22.5%), and herbicide (none on a large scale). This strong contrast in post-fire vegetation regeneration will likely persist for many decades and impact ecosystem services and future disturbance potential.
Figure 7: Flow diagram representing the transitions in land-cover classes that have occurred on privately managed lands (top panel) and publicly managed lands (bottom panel) impacted by the Moonlight Fire over the 11 years post-fire (2007-2018).

Solid lines indicate a transition equaling 5% or greater of ownership extent. Dotted lines indicate the largest transition experienced by a given class if no transitions achieved this criterion. All values are defined as % of ownership extent.

Figure 8: Contrasting conditions on private lands (left) that were salvaged, replanted, and treated with herbicide to reduce shrubs, compared to untreated public lands (right) seven years after the Moonlight fire.
Aerial remote sensing data
After seeing the limitations of NAIP imagery, we also explored use of high resolution (0.3 m by 0.3 m) aerial photography and LiDAR data. This work was supported by JFSP project (16-1-05-13). It involved quantifying standing snags, logs and shrub cover over large aerial photo plots nine years after high severity fire. Additionally, this work assessed how these photo-interpreted fuel levels varied by topographic setting, and how fuel levels influenced subsequent wildfire severity when reburned 12 years after the initial fire. This work was summarized in a recent publication (Lydersen et al. 2019).

1b: Regeneration
Landscape influences on potential for state shifts
The analysis of regeneration data by Welch et al. (2016) found zero recruitment in 43% of their plots, sub-par seedling densities (by agency standards) on most of the fires. Similar findings have been found in a recent review of studies in the western U.S. (Stevens-Rumann and Morgan 2019).

The analysis also found a negative relationship between seedling presence and shrub cover. They specifically reported that shade-tolerant white fir, red fir, Douglas-fir, and incense cedar outnumbered pines on eight of the 14 fires included in the analysis.

The analysis also found that that natural regeneration in areas with basal area mortality <75% was often sufficient to meet stocking guidelines. Important landscape factors in this analysis were precipitation regime (distinguishing dry from moist types).

Distance to seed trees:
The Welch et al. (2016) analysis employed distance categories of 0-30 m, >30-60 m, >60-200 m, and >200 m. That analysis used 60 m and 120 m as thresholds as break points mostly based on the old forester rule of thumb for seed dispersal to approximate two tree heights; and the field crew’s sampling methodology was limited by the ~200 m maximum range of the laser range finger. This meant that actual mean distance to a viable seed tree was underestimated for high severity plots, where 19% of the plots had no visible seed trees. Their resulting field tool for predicting regeneration adopted a threshold of 60 m to distinguish regeneration probabilities.

The results did indicate a nonlinear relationship, as increasing distance to seed tree by one distance category resulted in 62% less regenerating conifers (95% confidence interval 49–72%). They also found that mean distance to seed trees in plots with no conifer regeneration to be 68.8 m, far below our hypothesized threshold of 250 m. They considered a density of 200 trees/acre to be the minimum required stocking rate for successful regeneration in dry mixed-conifer areas (although that figure is higher than long-term stocking rates (North et al. 2019), which account for probable mortality). They found that plots lacking live basal area in cool aspects below about 40% slope could experience successful regeneration, but that areas in warm aspects or on steeper slopes would likely not.

Several threshold values for distance to seed trees have been suggested for mixed-conifer forests in recent publications, including 60 m, 120 m, and 200 m. The 120 m range seems to have become a rule of thumb for managers based on various sources. It was cited in an example we
included from the King Fire (North et al. 2019), and was also used in an analysis of the Rough fire in the first GTR. Our review paper (North et al. 2019) referenced a 200 m threshold as a high-end rule of thumb to capture any natural regeneration. That value was informed by research by David Greene, whose publication, Greene and Johnson (1996) included a figure suggesting that 200 m was an upper limit for spruce species. Other work supported the 120 m threshold as a basis for likely distance of seed dispersal based upon the tallest height of mixed conifer trees in the area (McDonald 1980; Clark et al. 1999).” Clark et al. (1999) presented figures suggesting that 100 m was a threshold for wind dispersal of seed in mixed-conifer forests. McDonald (1980) found that >90% of conifer seed fell within an area 1½ times the height of the average dominant tree (200 feet or 60 m), which suggests a threshold above 90 m. He added that “at least some seeds of ponderosa pine and white fir reach the center of 10-acre clearcuttings, however. Wind gusts, eddies, and possibly convectional lifting, aid in transporting them there” [Note that the radius of a 10 acre circular patch is 113 m.]. Furthermore, animal dispersal could also contribute to regeneration at greater distances. The field study did find some regeneration in places where potential seed source distance exceeded 200 m (K. Welch, pers. communication).

Co-PI Meyer has led a separate analysis of addition regeneration data that were collected for the Inyo National Forest using the R5 Ecology Program post-fire regeneration protocol (which was streamlined from the protocol used to generate the data analyzed by Welch et al. 2016). That analysis (Meyer and Vane 2020) has examined post-fire conifer regeneration patterns within drier coniferous (Jeffrey pine) forests located in the eastern Sierra Nevada. It has found similar patterns to more mesic west-side mixed conifer forests, but with some notable differences. Similar to mixed conifer forests, the probability of successful conifer regeneration was strongly and nonlinearly related to distance to seed tree and fire severity, with the highest regeneration densities observed in moderate burned stands located in close proximity to seed trees. In severely burned Jeffrey pine stands, they found threshold values for distance to seed trees tended to occur at the lower range observed for mixed-conifer forests (i.e., 50 to 60 m), especially on steeper, south-facing slopes. The effect of shrub cover on Jeffrey pine regeneration was dependent on regeneration size class, with positive effects observed in saplings but not seedlings. And artificial regeneration increased median sapling densities of Jeffrey pine by 20-fold and median sapling height by 60% in severely burned areas.

Distance to seed trees measured in the field does not precisely translate to analysis of high severity burn patches that have been mapped based upon remote sensing, since there are often some surviving trees within those patches, and there are not necessarily seed trees at the edges. However, both managers and researchers have adopted the Euclidean distance to the nearest “lesser burned” edge as a proxy measure (Shive et al. 2018). The different thresholds for distance to seed trees would translate to relatively small patch sizes: 60 m \(\rightarrow\) 2.8 acres (1.13 hectares), 120 m \(\rightarrow\) 10 acres, and 200 m \(\rightarrow\) 31 acres. Those values are all considerably smaller than suggested NRV references of 200-250 acres (80-100 ha).

The collaborators’ analyses highlight the importance of slope, moisture, and shrubs in modulating these effects, which suggests that these numerical thresholds should be limited to serving as rules of thumb to guide prioritization. Managers noted that they would conduct interventions in areas closer to green trees to meet other objectives, such as promoting desired species composition.
Landscape effects on conifer regeneration

The collaborators’ analysis found that increases in precipitation and north-facing aspect, along with decreases in slope and shrub competition, all tended to increase conifer regeneration (Table 1).

Table 1: The influence of various landscape factors on conifer regeneration (Welch et al. 2016).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Effect on conifer regeneration (number of seedlings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (10 m increase)</td>
<td>+3% (95% CI: 1–4%)</td>
</tr>
<tr>
<td>Slope (5% increase)</td>
<td>-6% (95% CI: 3–10%)</td>
</tr>
<tr>
<td>North-facing aspect (10° shift to the North)</td>
<td>+5% (95% CI: 3–7%)</td>
</tr>
<tr>
<td>Shrub cover (10% increase)</td>
<td>-10% (95% CI 6–15%).</td>
</tr>
</tbody>
</table>

A second team, Shive et al. (2018), expanded on these datasets in building the Post-fire Spatial Conifer Regeneration Prediction Tool, or POSCRPT. Rather than relying strictly on patch size, they developed a “seed availability proxy,” or SAP, by inferring seed production within a 150 m neighborhood area based upon an estimate of post-fire basal area derived from a combination of remote sensing and FIA data. They found that the best model of conifer regeneration included climate variables (annual precipitation, climatic water deficit, actual evapotranspiration, and snowpack), topographic variables (aspect and slope), burn variables (number of years post-fire and continuous burn severity based upon RdNBR), and SAP. Annual precipitation was particularly important, as locations with precipitation levels above 2,000 mm had seven times greater odds of regeneration than those with average precipitation (~1,200 mm). Burn severity was also very important, with strong negative effects on regeneration in high severity areas (above 700 RdNBR). Burn severity was strongly correlated with SAP, although the inclusion of SAP added to the predictive value of the model more than the landscape variables. Accordingly, their final tool predicts regeneration based upon 30-yr average annual precipitation, burn severity, and SAP.

Comparing the results of the POSCRPT tool (Figure 9) with a simpler analysis of high severity patches modified with a 120 m buffer (Figure 10) illustrates how the former provides more detailed probabilities to inform decisions, although the end treatment plan for a fire like King with enormous patches of high severity might not necessarily look that different when based upon the simpler analysis. Note also that the POSCRPT tool also identifies areas (such as a 400 hectare patch in the southern end of the King Fire) that have low likelihood of conifer regeneration because of low precipitation. Such areas may have been historically or even recently shrub-dominated (as shown by the pink color in Figure 10), and therefore not an appropriate target for reforestation from a strict restoration perspective.
Figure 9: Results from applying the POSCRPT tool to the King Fire (figure 5 in Shive et al. 2018).

Figure 10: Analysis based upon burn severity modified with 120 m buffer (left) and the treatment plan within high burn severity patches on federal lands (right) (figure 4 from North et al. 2019).

*Hardwood survival and regeneration*

We found that only 1% and 10% of oak trees had surviving crowns within high-severity patches in the Rim and King Fires, respectively. Meanwhile, 6% and 20% of black oaks appeared to be
fully killed, and the remaining 93% and 70% were top-killed with basal resprouts (Figure 11). By contrast, oaks had 53% top-survival in low-severity patches in the Rim Fire, with the remaining 47% resprouting from the base. The rates of top-kill in the Rim Fire was higher than reported from previous fires. These findings suggest potential for a structural, rather than a largely compositional, shift away from mature trees and the ecological services that they provide. This issue has been augmented by an recent analyses of trends in oak condition following reburns (Hammett et al. 2017) and a study of trends in biomass in large hardwoods in California forests (Long et al. 2018).

**Figure 11:** Within the Rim Fire of 2013, young conifer trees had encroached on these California black oaks; two years later, the top-killed oaks on the left had resprouted only from the base (the predominant condition in high severity patches), while the oak on the right was able to resprout from the crown (a rare condition in high severity patches).

**Objective 1c: Wildlife**

Our review and synthesis highlighted that different species will benefit from different post-fire treatments, noting that shrub-associated species, such as the fox sparrow, will avoid mature forest and instead attain their highest abundance in the interior of patches. Other wildlife and plant species may depend upon or thrive upon early-successional conditions, including black-backed woodpeckers, although these can be supported by retaining patches of snags and mosaic of shrub habitats within the landscape. On the other hand, large conifers are important to sustain habitat for the long term for other species including California spotted owl habitat (North et al. 2017), so interventions such as conifer planting may be important to sustain their populations over the long-term (Stephens et al. 2016).

**Objective 2: Synthesis and Management Publications**
We completed a major general technical report to guide post-fire restoration (Meyer et al. In press). Because we worked with such a large team of contributions, and because the work touched on important policy issues, the entire process of writing, technical review, revision, and policy review took longer than expected, so we have long anticipated getting it finally published. We also initiated a second technical report to illustrate more specific landscape-based strategies and tactics for mixed conifer forests, and we look forward to completing that over the next few months. Key findings from the synthesis products are discussed in the following section.

We delivered and received feedback on our findings at a variety of workshops and conferences during each year of the project. We delivered information to groups of scientists and managers not only through the main technical reports, but also through a range of peer-reviewed journal articles and a book chapter, several of which were invited following presentations at scientific conferences. See Appendix B for the list of publications, presentations and workshops.

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

The multiple components of this project collectively provide a deeper understanding of the factors that contribute to state shifts and offer a framework upon which to guide both active interventions and passive deferrals. We first summarize key findings regarding indicators of state shifts, and then present implications of the results for management.

The regeneration analyses indicate that distance to live conifer trees is a key factor influencing short-term revegetation. In particular, analyses by our collaborators indicate that relatively small distances to surviving live trees are associated with high probabilities of insufficient natural regeneration for several years following wildfires. The analyses suggest that some recent wildfire events in California have been particularly problematic, with the size of many high severity patches far exceeding the natural range of variation for frequent-fire yellow pine/mixed-conifer forest areas. The post-fire development study in the Moonlight Fire showed that passive management in large, high severity patches will likely result in a shift to a persistent shrub-dominated state. Furthermore, the fuel complex associated with this shifted state (high continuity of live fuels interspersed with high loads of coarse wood) can result in repeated high severity fires in relatively short intervals (Lydersen et al. 2019). While the analysis of the Moonlight Fire only considered conditions 11 years post-fire, other work (Bohlman et al. 2016) has found that increases in shrubs, along with shade-tolerant conifers, within untreated areas persisted within fires that were two and four decades old. The ecological significance of these changes depends upon their extent, arrangement, and historical references. For that reason, an analysis of patch size and arrangement (rather than more simplified statistics such as area burned or percent of area burned at different severities) is important for evaluating whether fire outcomes have promoted or discouraged ecological restoration. Different measures pertaining to high severity patches can be winnowed to hone in on areas of highest risk for state shift. In an example from the Rough Fire, while 20% of total area burned at high severity, only 3% of the area was in high severity patches in former conifer-dominated areas that were more than 120 m from unburned areas.

Implications of the results for management/policy
1. **Overall conclusions**

1.1. High-severity fire can be both **restorative** and **degradative** within in areas that historically evolved with regimes dominated by frequent, predominantly low-moderate severity fire regimes.

1.2. As outlined in the post-fire restoration framework, a systematic analysis of data can help evaluate departure and expected post-fire trajectories.

1.3. These evaluations depend heavily on landscape-scale consideration of patch size and arrangement in order to maintain appropriate structural and compositional diversity, while facilitating restoration of fire regimes.

2. **Recognizing and actively responding to degradation**

2.1. Degradation may occur when wildfires shifts areas that were historically dominated by conifer forest and frequent fire regimes into uncharacteristically large and persistent non-conifer communities (shrubs and hardwoods).

2.2. Such degradation may indicate reduced system resilience and a loss of ecosystem services afforded by mature conifer forest, including habitat for wildlife, seed production, carbon storage, and wood production.

2.3. Because many factors and objectives inform post-fire interventions, it is difficult to specify thresholds for intervention based upon the size of high severity patches and levels of fuel accumulation.

2.3.1. We have tools to predict reforestation probability based upon distance to green trees and climate.

2.3.2. From a landscape restoration perspective, it would be appropriate to evaluate conditions according to an overall distribution relative to a reference time and area rather than on a patch-by-patch basis. However, managers often need to consider relatively fixed thresholds within a treatment area in order to make pragmatic choices.

2.3.3. Preliminary thresholds were suggested in the first GTR; for example, a threshold of 100 ha for high severity patches in areas of yellow pine/mixed-conifer forest based upon NRV evaluations.

2.3.4. Several wildfires in California stand out in terms of departure based upon patch size metrics, including Rim, American, Moonlight and King.

2.3.5. From a cross-boundary perspective, it may be important to consider the overall representation of these different conditions across ownerships.

2.4. Some publications prior to our work had recommending limiting post-fire salvage and replanting to areas of high severity. Restricting treatments to areas of high burn severity
could be counter-productive to restoration objectives for reducing fuels and restoring desired species composition (e.g., pine dominance). In our collaborations, including the research study piloted to apply prescribed fire in previously burned areas of the Power Fire, managers expressed trepidation about using prescribed fire in areas of moderate burn severity due to high fuel levels.

2.5. Active treatment strategies:

2.5.1. Post-fire treatments including “salvage” or thinning of dead and surviving trees, and use of managed fire may be important for both reducing future fire risks and for facilitating active reforestation by aiding growth of planted trees or natural regeneration.

2.5.2. Where management objectives are tied to rapidly reestablishing conifer trees, then active reforestation (planting seedlings typically with control of competing vegetation) remain a critical tool.

2.5.3. To simultaneously address revegetation goals while minimizing impacts to wildlife use, managers can prioritize harvesting and replanting projects within the interior of uncharacteristically large patches.

2.5.3.1. Because patches of high severity are becoming so much larger, applying post-fire interventions uniformly across such patches would promote a different kind of homogeneity, associated with potential loss of biodiversity and high fire hazards posed by young forest.

2.5.3.2. Deferring salvage from some of the high severity patches also serves as a mitigation for black-blacked woodpecker and other birds that tend to specialize on dead trees.

2.5.3.3. Because distance to green trees is a constraint on regeneration, while post-fire wildlife use decreases with distance from green edges, targeting the interior of large high severity patches can help reconcile objectives for reforestation, promoting heterogeneity, and sustaining wildlife.

2.5.3.4. Similarly, removal of dead trees in riparian areas might be calibrated by favoring retention in areas that may be in a deficit for large woody debris, and favoring reductions in areas that are more likely to contribute to failure of downstream culverts and bridges.

3. Recognizing and supporting passive restoration

3.1. High severity burn effects may be restorative in many parts of the landscape where conifers have increased due to the legacy of fire suppression, potentially including drier slopes as well as wetter areas, such as riparian bottomlands; stands of aspen, oaks, and other hardwoods; and meadows.
3.2. Such communities may reflect persistent, edaphically-based conditions. However, other non-conifer types, including areas dominated by shrubs and young trees with a legacy of dead snags, may reflect ephemeral stages that occurred in a variable mosaic over time.

3.3. Deferring replanting in these areas may facilitate passive restoration.

3.4. Applying a combination of various active interventions and deferral can encourage a diversity of patch characteristics that promotes landscape resilience.

4. Recognizing and supporting opportunities to restore fire regimes through strategic fuel reductions and use of managed wildland fire.

4.1. Rather than focusing exclusively on the “black” areas of high tree mortality, the surrounding “green” forests that were unburned or burned at low severity warrant attention particularly for prescribed burning, possibly in conjunction with thinning to reduce fuels where needed to safely apply fire.

4.2. Large patches of high severity may represent opportunities to disrupt the potential impacts of future reburns by using them in the short-term to contain managed fires in the surrounding green forests.

4.3. Post-fire restoration strategies can promote natural fire containment features; for example, ridgelines may be treated not only to maintain areas of low fuels and low-density, fire-resistant species including oaks and sugar pine, which also have high cultural value for many tribes in California.

5. Uncertainty in decision-making

5.1. The data that are immediately available in the wake of a disturbance may not provide the level of detail needed to effectively evaluate ecological departure. For example, short-term assessment often relies on indicators that are easily measured after the fire (such as change in vegetation cover and size of high severity patches), while longer term indicators (such as areas supporting natural regeneration) may be difficult to obtain without sufficient time, resources, and field verification.

5.2. Decisions about whether to invest in interventions need to be informed by data on effectiveness, rather than assuming that interventions are either destined to fail or critical to the success of overarching restoration goals. Adaptive management is needed in these contexts to facilitate learning and improve post-fire planning and restoration.

5.3. Because changes in climate may affect ecological site potentials, it may be important to modify restoration targets from the historical range of variation. However, research may be needed to determine whether high levels of moisture stress would render interventions futile or important for increasing the chance of recovery?
Literature Cited


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

Technical reports


Articles in peer-reviewed journals

Primary publications


Secondary publications


**Text books or book chapters**


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


**Conference or symposium abstracts**


Long, J.W. “When wildfires warrant interventions for ecosystem conservation and restoration in Western U.S. montane ecosystems.” Oral presentation at the Symposium on Fire Resilience: Can Fish, Wildlife, and Humans Adapt to Shifts in Wildfire Disturbance? AFS/TWS joint conference, Reno, NV. 1 October 2019. This presentation led to inclusion of findings in a draft manuscript (Jager et al. above).

Long, J.W.; Williams, J. After the Fire Conference and Workshop hosted by the Nature Conservancy, Tahoe City, California. Scheduled for April 7, 2020 but postponed due to coronavirus travel restrictions.

Posters


Workshop materials and outcome reports


Long, J.W.; Lydersen, J.; Welch, K.; Estes, B.; Meyer, M.; Gross, S.; Wuenschel, A.; Coppoletta, M. and Tompkins, R. 2017. Long-term restoration of forest ecosystems following severe wildfires. Workshop 45 at the Ecological Society of America Annual Conference, Portland, August 8, 2017. The workshop featured presentations by PIs and key collaborators from USFS Region 5, the Plumas National Forest, UC Berkeley and UC Davis, along with discussion with the audience of several dozen participants:

1) Long, J.W. Overview of contexts in which interventions are important
2) Lydersen, J. Size of stand-replacing burns and fuel development in California wildfires Jamie Lydersen
3) Welch, K. and Estes, B. Revegetation and prediction tools
4) Discussion about effects
5) Meyer, M. Decision framework, need and principles
6) Gross, S. Spatial assessment
7) Wuenschel, A. Spatial assessment tools

Topics in Reforestation Summit, UC Davis – January 25 2018, held in collaboration with PSWRS, R5 Ecology Program, and UC Davis, with researchers from those institutions and others (UC Berkeley, National Park Service). Organized by co-PI North, with Long, Meyer, and Safford presenting and participating. Outcomes included a publication (North et al. 2019).

Field demonstration/tour summaries

White, A.M. and Safford, H.D. Angora Fire 10 Years Later Field Trip & Symposium organized by the California Fire Science Consortium, June 22-23, 2017, South Lake Tahoe, CA.

Meyer, M. Fire Science Retreat at Sequoia-Kings Canyon National Park. August 2017. Featured field trips to the Rough Fire, which was featured as a case study for the assessment GTR. Organized by Co-PI North.


Presentations/webinars/other outreach/science delivery materials.

Appendix C: Metadata

Data used in the revegetation analysis are being uploaded to the USDA Forest Service R&D National Research Data Archive (https://www.fs.usda.gov/rds/archive/) by collaborator Kevin Welch. He expects to complete that within three months.