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Ecological Applications, 24(8), 2014, pp. 1879–1886

Beyond reducing fire hazard: fuel treatment impacts on overstory tree survival

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Abstract. Fuel treatment implementation in dry forest types throughout the western United States is likely to increase in pace and scale in response to increasing incidence of large wildfires. While it is clear that properly implemented fuel treatments are effective at reducing hazardous fire potential, there are ancillary ecological effects that can impact forest resilience either positively or negatively depending on the specific elements examined, as well as treatment type, timing, and intensity. In this study, we use overstory tree growth responses, measured seven years after the most common fuel treatments, to estimate forest health. Across the five species analyzed, observed mortality and future vulnerability were consistently low in the mechanical-only treatment. Fire-only was similar to the control for all species except Douglas-fir, while mechanical-plus-fire had high observed mortality and future vulnerability for white fir and sugar pine. Given that overstory trees largely dictate the function of forests and services they provide (e.g., wildlife habitat, carbon sequestration, soil stability) these results have implications for understanding longer-term impacts of common fuel treatments on forest resilience.

Key words: forest resilience; frequent-fire forests; large trees; mixed-conifer forest; restoration; Sierra Nevada.

Introduction

Public forest management throughout the western United States currently has a strong emphasis on promoting ecosystem resilience (USDA-FS 2011, Franklin and Johnson 2012). This focus is in response to contemporary disturbance regimes that are considered to be well outside the range of historical variability for certain ecosystems (Stephens et al. 2013), and to concerns over potential vulnerability to climate change (Millar et al. 2007, Williams et al. 2010). Some forests are of particular concern because past management practices, namely fire exclusion and timber harvesting, have already increased the likelihood of uncharacteristic impacts from fire and insects (Brown et al. 2008, Naficy et al. 2010, Taylor et al. 2014). Given this susceptibility, forest managers need information on how their actions affect resilience, particularly over the long term. Here, we define resilience as the ability of an ecosystem to maintain characteristic structure and function in the face of external perturbations (Folke et al. 2004). Furthermore, we focus on the fate of the trees, given their importance to both the structure and function of forest ecosystems (Ellison et al. 2005).

Fuel reduction treatments have been implemented across millions of hectares of forestland throughout the western United States (Schoennagel and Nelson 2011), and are being proposed for millions more (e.g., USDA-FS 2011). These treatments include the use of fire (either prescribed or managed wildland fire), mechanical manipulation (e.g., thinning, mastication, chipping), or a combination of the two to reduce surface and ladder fuels, and to increase tree crown spacing. The primary goal is to modify wildland fire behavior and thereby reduce the probability of uncharacteristically severe fire effects (Agee and Skinner 2005, Stephens et al. 2009). In drier forest types, these treatments may also increase

Manuscript received 21 May 2014; revised 7 August 2014; accepted 11 August 2014. Corresponding Editor: B. P. Wilcox.
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other aspects of resilience (Allen et al. 2002, Franklin and Johnson 2012) by reducing tree densities and retaining larger, more fire-resistant trees (Fulé et al. 1997, North et al. 2009).

Numerous studies on the short-term (1–3 years) impacts of fuel reduction practices indicate that properly designed fuel treatments effectively reduce fire-caused tree mortality under high-fire weather conditions (Fulé et al. 2012, Safford et al. 2012, Martinson and Omi 2013). Additionally, they report few, if any, negative consequences for other forest ecosystem components (e.g., soils, bark beetles, small mammals, songbirds; Boerner et al. 2009, Fettig 2012, Fontaine and Kennedy 2012, Stephens et al. 2012*b*). Collectively, these studies suggest in the short term, treated forests are in a more resilient condition compared to untreated forests.

Longer-term effects (>5 years) of fuel reduction treatments have not been as well studied. In terms of modifying fire behavior, treatments can continue to be effective for up to 15 years (Stephens et al. 2012*a*, Martinson and Omi 2013), but less is known about the impacts on tree growth and mortality. The expectation is that tree density reductions associated with fuel treatments will improve growth and reduce the risk of mortality in the residual trees (Coomes and Allen 2007). However, the most effective treatments for reducing hazardous fire potential involve the use of fire (Stephens et al. 2009), which can injure trees by exposing cambium, live crown, and roots to excessive heat (Lloret et al. 2011). If severe enough, these heat-damaged trees experience "delayed mortality," a phenomenon where trees experience higher rates of mortality up to five years following initial burning (van Mantgem et al. 2011). Even in the absence of outright death, the decreased vigor could impact tree response to drought (Lloret et al. 2011) and other stressors (e.g., air pollution; Takemoto et al. 2001).

If we are truly to assess the effectiveness of fuel treatments in the context of long-term resilience, we need much more information about the effects of these treatments on forest health. Our study aims to help bridge that gap by examining intermediate-term tree mortality and growth responses following the most commonly used fuel reduction/restoration treatments in the mixed-conifer forests of the Sierra Nevada, USA. We use these demographic responses, as measured seven years after treatment, to assess future forest health based on a vulnerability assessment of the surviving trees (Das et al. 2007, 2008). We recognize there are other ecosystem components (e.g., understory vegetation, soil fertility, snags) beyond live trees, which contribute to forest health; however, in this study we primarily focus on tree growth and mortality under the assumption that the tree component, particularly large trees, is the cornerstone of most forest ecosystems (Franklin and Johnson 2012). We illustrate that different treatments appear to have disparate intermediate- and long-term effects on forest health, effects that can differ considerably from their short-term effects on potential fire behavior. These results should help forest managers balance short- and long-term objectives for promoting ecosystem resilience in forests adapted to frequent fire.

Methods

This study was performed at the University of California Blodgett Forest Research Station, which is located in the mixed-conifer zone of the north-central Sierra Nevada (38°54′45″ N, 120°39′27″ W), California, USA. Common tree species include sugar pine (*Pinus lambertiana*), ponderosa pine (*P. ponderosa*), white fir (*Abies concolor*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii* Franco), California black oak (*Quercus kelloggii*), tanoak (*Lithocarpus densiflorus*), bush chinquapin (*Chrysolepis sempervirens*), and Pacific madrone (*Arbutus menziesii*). Three different fuel treatments were tested (Fig. 1): mechanical-only (MECH), mechanical-plus-fire (MECHFIRE), and prescribed-fire-only (FIRE), as well as untreated control (CTRL), which were each randomly applied (complete randomized design) to three of 12 experimental units that varied in size from 14 to 29 ha (Stephens and Moghaddas 2005). See Appendix for more specific descriptions of the treatments.

Overstory and understory vegetation was measured in 20 0.04-ha circular plots, installed in each of the 12 experimental units (240 plots total) in 2001 (pre-treatment), 2003 (post-1-yr), and 2009 (post-7-yr; see Appendix for plot layout, sampling strategy, and specific measurements). In 2010, plots were revisited to extract increment cores from a random subset of trees in each of the 12 experimental units. Two cores were collected for each tree ($n = 496$), one along the contour and one orthogonal to the contour, containing at least the last 30 years of annual growth rings. Ring widths were measured for each core using a digital sliding stage with 0.01-mm precision.

Plot-level tree measurements were used to calculate live tree density and biomass. We used species-specific regional volume equations and wood density estimates to calculate biomass to maintain consistency with long-standing procedures employed by the Forest Inventory and Analysis Program (Zhou and Hemstrom 2009). Repeated-measures analysis was performed to test for differences in live tree density and biomass among time periods (pre-treatment, post-1-yr, post-7-yr) and among treatments (CTRL, MECH, MECHFIRE, and FIRE). Based on diagnostic plots of model residuals, live tree biomass was square-root transformed, which improved compliance with model assumptions. Differences among time periods and treatments were inferred from Tukey-Kramer adjusted P values, with $\alpha = 0.05$.

Mortality was assessed by tracking status of all conifers >25 cm diameter-at-breast-height (dbh) initially assessed as live in 2001 in plots that were re-measured in 2003 and 2009. Harvested and masticated trees in MECH and MECHFIRE treatments were excluded.

FIG. 1. Repeat photographs taken from a field plot in each of the three active treatment types: (A) mechanical only, (B) mechanical-plus-fire, (C) and fire only. Fire hazard and forest regrowth ratings are based on findings reported in Stephens et al. (2012*b*), while understory response ratings are based on shrub cover reported in the Appendix (Table A1).

We calculated annual mortality by species for each experimental unit using methods from Sheil et al. (1995), with confidence intervals determined by profile likelihood (Wyckoff and Clark 2000).

We compared current stand health (as of 2009) among treatments by calculating vulnerability indices for each treatment. A vulnerability index is a relative measure of stand health for each treatment and is indicative of relative future mortality rates. In other words, a treatment with a higher vulnerability index would be expected to have higher future tree mortality rates. Briefly, vulnerability indices were calculated as follows (see Appendix for details): (1) Models that predict individual tree survival probability using tree growth patterns from tree rings were developed using data from a nearby and compositionally similar site. (2) Using these models, we calculated survival probabilities for each tree sampled in our treatments. (3) A resampling procedure was used to create a simulated population that matched the structure and composition of the given treatment (as determined from plot data). An average mortality rate was calculated for this simulated population using another set of simulations. (4) Step 3 was repeated 1000 times to get an average mortality rate for each treatment. This value was defined as the vulnerability index. Importantly, we do not consider the vulnerability index a prediction of absolute future mortality rate, due to uncertainties in the modeling

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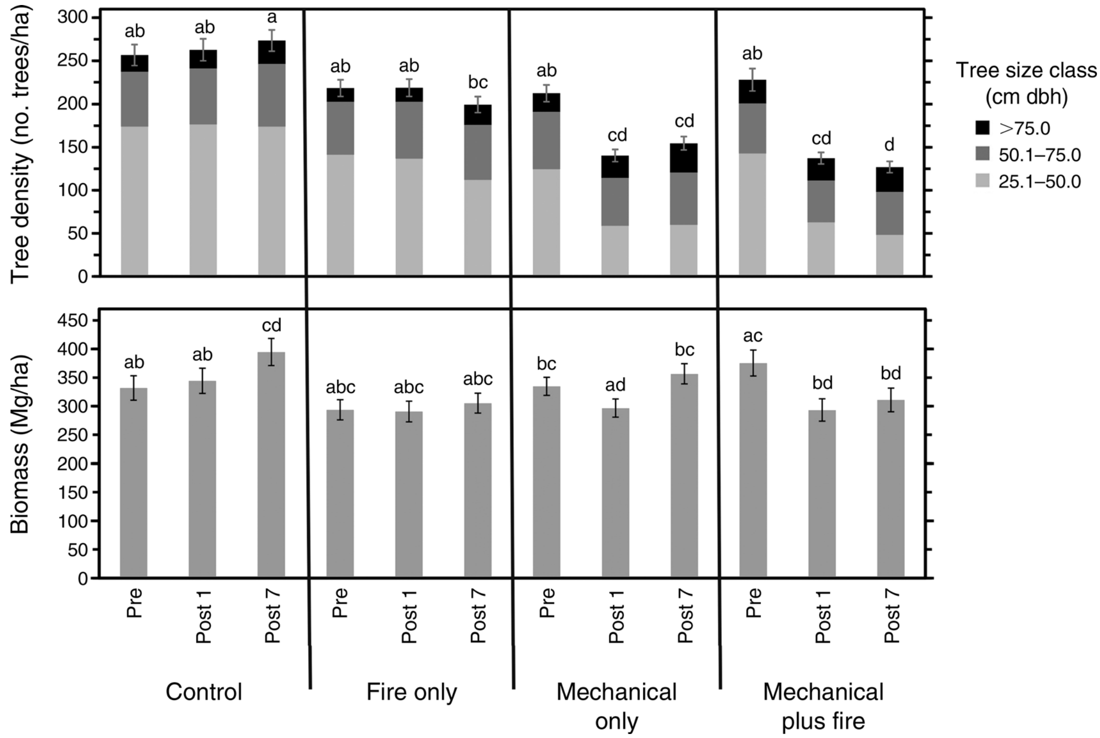

FIG. 2. Average tree density (no. trees >25 cm diameter at breast height [dbh]/ha) and live tree biomass by time period (pre-treatment [pre], one year after treatment [post 1], and seven years after treatment [post 7]) and treatment type. Error bars represent the standard error for each mean. Different letters above bars indicate significantly different time period/treatment estimates based on pairwise comparisons ($n = 66$) using Tukey-Kramer adjusted P values. Comparisons indicated for tree density are for aggregated density (all trees >25 cm dbh).

approach (see Appendix). Instead, we consider it an index of relative tree health.

RESULTS

All three active treatments had a similar initial effect on forest understory conditions and sub-canopy structure, in that live vegetation was considerably reduced (Fig. 1). Initial (post-1-yr) effects on overstory structure, however, differed among treatment types. Overstory live tree density (>25 cm dbh) and live tree biomass were unchanged initially in FIRE, relative to pre-treatment, while both significantly decreased in MECH and MECHFIRE (Fig. 2). Tree density significantly declined by post-7-yr in FIRE, relative to pre-treatment and post-1-yr, while tree biomass was relatively stable over the three measurement periods (Fig. 2). In MECH and MECHFIRE, tree density remained low post-7-yr, however biomass recovery differed between the two (Fig. 2). MECH live tree biomass significantly increased from post-1-yr to post-7-yr and was similar to pre-treatment, while MECHFIRE biomass remained significantly below the pre-treatment level (Fig. 2). CTRL live tree biomass significantly increased post-7-yr, relative to pre-treatment and post-1-yr (Fig. 2). CTRL had greater live tree density post-7-yr than all other treatments. Shrub cover by post-7-yr was greatest in FIRE and MECHFIRE, but was only significantly different between CTRL and MECHFIRE (Appendix: Table A1). Large snag (>50 cm dbh) recruitment (2003–2009) was also greater in the two fire treatments, but differences among treatments were not statistically significant (Appendix: Table A1).

Seven years after treatment, mortality rates (conifers >25 cm dbh) were significantly higher in the treatments with prescribed fire (1.7% per year in FIRE; 1.6% per year in MECHFIRE) compared to CTRL (0.5% per year) and MECH (0.2% per year). This pattern in observed mortality holds for the largest trees (>50 cm dbh; Fig. 3). Given the ecological importance of big trees (Lutz et al. 2012) and the subsequent management priority on maintaining them, we focused our assessment on the large tree component (>50 cm dbh). For treatments as a whole, past mortality rates and future vulnerability were highest in the MECHFIRE treatment (Fig. 3) and lowest in the MECH treatment. Observed mortality was also relatively high in the FIRE treatment compared to the CTRL, though future vulnerability was projected to be similar in those stands. Among species, incense-cedar consistently had the lowest observed mortality and future vulnerability, with the exception of observed mortality in CTRL (Fig. 3). Both white fir and sugar pine had the greatest observed mortality and future vulnerability in MECHFIRE (Fig. 3). There were drastic differences between observed mortality and

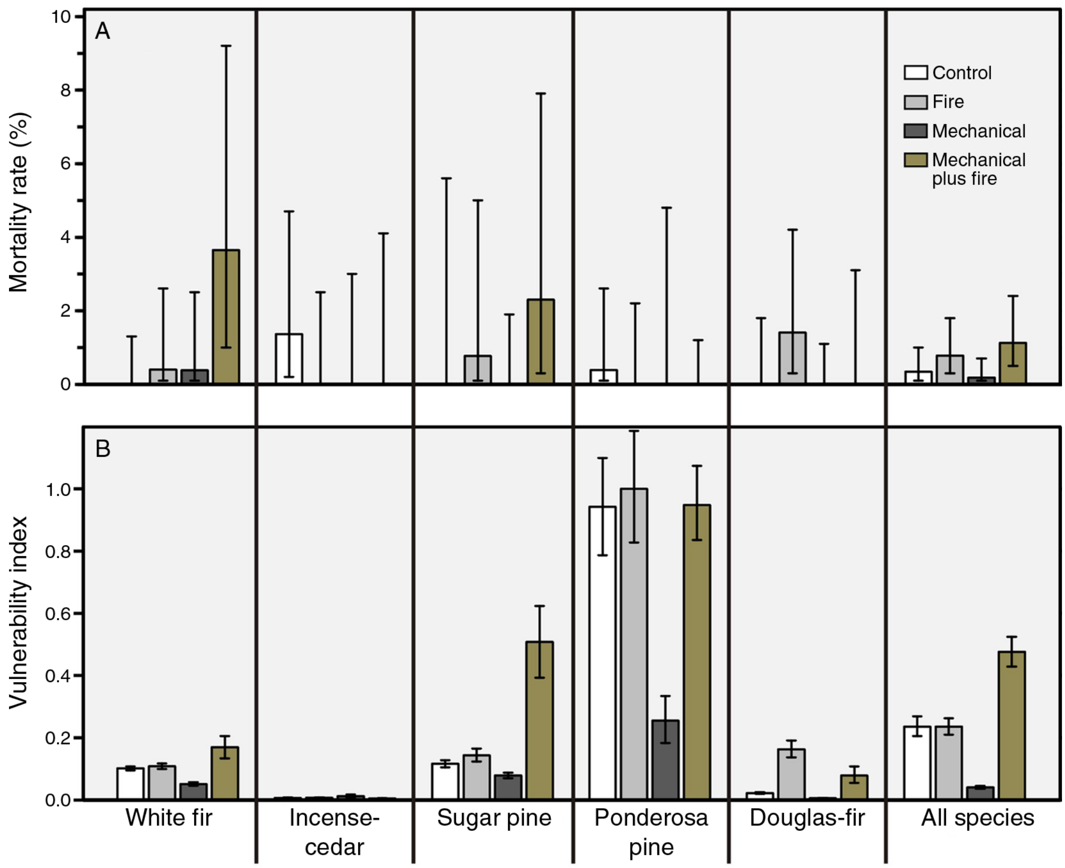

FIG. 3. Large tree (A) observed mortality rate (2003–2009) and (B) projected future vulnerability by treatment type for each of the dominant conifer species and for the stand as a whole. Values are for trees >50 cm dbh. Error bars represent 95% confidence intervals.

future vulnerability for ponderosa pine, with past rates being very low for all treatments and future vulnerability being very high for CTRL, FIRE, and MECHFIRE, and moderately high for MECH (Fig. 3). For Douglas-fir, the greatest observed and future projected mortality rates were in FIRE. Across species, observed and future projected mortality rates were consistently low in MECH, while in the two fire treatments rates were consistently high (Fig. 3).

DISCUSSION

Fuel treatment implementation in dry forest types throughout the western United States is likely to increase in pace and scale in response to increasing incidence of large, uncharacteristically severe wildfires (USDA-FS 2011). While it is clear that properly implemented fuel treatments are effective at reducing hazardous fire potential, there are ancillary ecological effects that can either be positive, neutral, or negative depending on the specific elements examined, as well as treatment type, timing, and intensity. Our analyses of midterm (5–10 years) observed mortality and projected future vulnerability suggest differential impacts of fuel treatments on overstory tree vigor that vary by treatment type, as well as by tree species. Given that overstory trees largely dictate the function of forests and services they provide (e.g., wildlife habitat, carbon sequestration, soil stability), these results have strong implications for understanding longer-term impacts of common fuel treatments on forest resilience.

Fuel reduction treatments that combine thinning-from-below (removing ladder fuels) with prescribed fire have been shown to be most effective at reducing residual overstory tree mortality in modeled and actual fires (Stephens et al. 2009, Safford et al. 2012, Martinson and Omi 2013, Prichard and Kennedy 2014). This efficacy is due to the reduction of both surface fuels (burning) and ladder/canopy fuels (thinning), which limits surface fire intensity as well as the ability of fire to transition into tree canopies (Agee and Skinner 2005). Our results indicating greater observed mortality and future vulnerability for large white fir and sugar pine trees when mechanical thinning and mastication was followed by prescribed fire suggest a tradeoff between reduction in wildfire hazard and reduced tree vigor (for those species; Figs. 1 and 3). With the exception of Douglas-fir, large tree vulnerability in the fire-only

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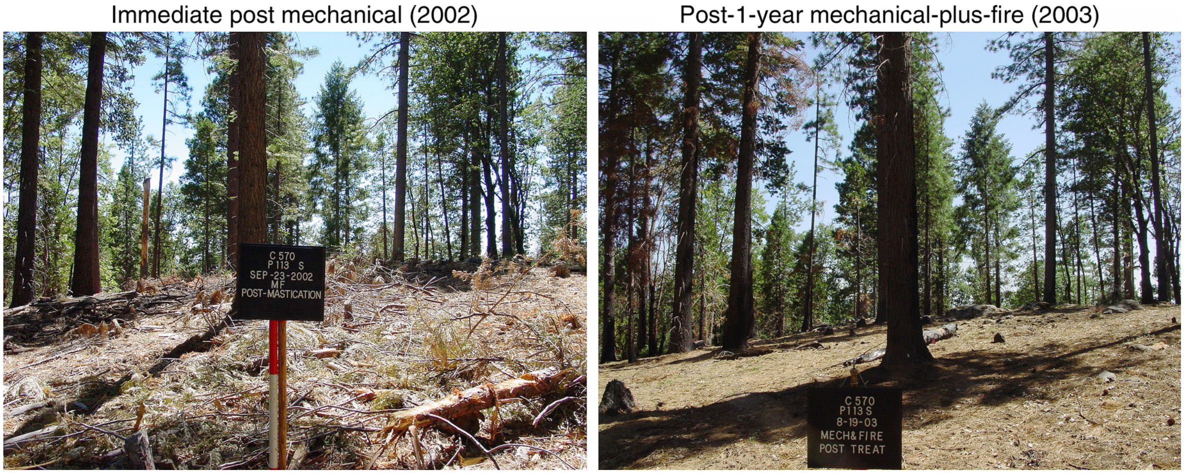

PLATE 1. Repeat photographs of a plot in the mechanical-plus-fire treatment at Blodgett Forest, California, USA. The left photograph shows the augmented surface fuel conditions resulting from the thinning followed by mastication. The right photograph shows the relatively complete surface and ground fuel consumption following a backing prescribed fire. Combustion of this fuel bed most likely contributed to the greater observed mortality and future vulnerability relative to the other treatments examined. Photo credits: Blodgett FFS field crew.

treatment was not different from that projected for the control (Fig. 3). The greater vulnerability in the combined treatment is likely related to the additional surface fuel inputs that were generated from the commercial tree harvest (i.e., tree tops and limbs left in the forest), as well as the mastication of sub-canopy trees and shrubs (see Plate 1). These additional fuel inputs increased fine fuel loads and total fuel depth (Stephens and Moghaddas 2005), which likely resulted in greater fire residence time when burned, thus longer potential exposure of tree cambiums to lethal temperatures. The lack of growth in the combined treatment, as evident by the similarity in tree biomass post-1-yr and post-7-yr, is further evidence of reduced overstory tree vigor (Fig. 2).

There was no such evidence for reduced overstory tree vigor in the mechanical-only treatment. In fact, for most tree species, the observed and projected vulnerability was well below that for the control (Fig. 3), suggesting the mechanical-only treatment improved overstory tree vigor. The significant increase in tree biomass from post-1-yr to post-7-yr (2003–2009) further supports the notion of improved tree vigor in this treatment (Fig. 2). The tradeoff associated with the mechanical-only treatment is that it was initially only moderately effective at reducing hazardous fire potential (Stephens and Moghaddas 2005). As noted, thinning augmented surface fuel loads that in turn increased the potential for severe fire, but ladder fuels were also reduced by thinning (see Plate 1), resulting in slightly lower fire hazards when compared to the controls. However, by post-7-yr, hazardous fire potential decreased, largely due to decomposition of the augmented residues from the mechanical activities (Stephens et al. 2012*a*). In contrast, hazardous fire potential increased in the control over time (Stephens et al. 2012*a*). It is interesting to note that post-7-yr live tree biomass in the mechanical-only and the control was similar, yet live tree density was significantly different (Fig. 2). Clearly, it is possible to achieve live tree carbon levels similar to untreated forests in a lower-density structure, which, based on previous fire modeling and our tree vigor assessments, is likely to be more resilient to disturbance (e.g., fire, bark beetle outbreak) and stressors (e.g., drought; Hurteau and Brooks 2011).

While the mechanical-only treatment accumulated a substantial amount of biomass, had relatively low fire hazard seven years after treatment, and is projected to have the lowest future vulnerability, it lacked some structural elements that were present in the two fire treatments. This is supported by the very low recruitment of large snags (1.3 snag/ha from 2003 to 2009) and the moderately low shrub cover (11.9%) in the mechanical-only treatments, relative to the two fire treatments (Appendix: Table A1). Large snags and shrub cover are important elements for many species of wildlife and contribute to overall heterogeneity in habitat (White et al. 2013). This heterogeneity, which was greater in both fire treatments, is an important aspect of forest restoration, and may be tied to greater resilience (North et al. 2009). These results highlight the critical importance of ecosystem processes (e.g., fire) that are not replicated by mechanical treatments.

The maintenance of tree vigor in the fire-only treatment relative to the control, with the exception of Douglas-fir, is notable (Fig. 3). The last extensive fire recorded in this area was ca. 1900 (Stephens and Collins 2004). This long fire-free period in dry forests is associated with considerable accumulations of surface and ground fuels (Agee and Skinner 2005). A common assumption is that these fuel accumulations contribute to longer heating duration when fire is reintroduced, which can lead to cambial injury even when fire intensity is low (Stephens and Finney 2002). Our results suggest that this potential for greater injury was not realized with respect to altering large tree vigor, relative to no action (control).

Our finding indicating substantially higher future vulnerability for ponderosa pine relative to other species is challenging to explain, especially given its low observed mortality (Fig. 3). It is possible that uncertainties in the modeling (see Appendix) are exaggerating the vulnerability of this species. Regardless, even if our models are overestimating the magnitude of the vulnerability for ponderosa pine, any marked increases could be important, given the existing concern about the loss of large pines relative to historical forest conditions throughout the Sierra Nevada mixed-conifer zone (Collins et al. 2011). In that light, the stark vulnerability increases shown in our results certainly suggest a need for further investigation.

Management Implications

The projected vulnerability for trees in the control is likely to result in comparatively high mortality rates compared to the mechanical treatment. In addition, fire behavior modeling demonstrated increasing hazardous fire potential in the control over time, a hazard which exceeded all active treatment types (Stephens et al. 2012*a*). The combination of anticipated higher mortality and greater fire hazard suggest that the "no action" (with continued fire suppression) management strategy leads to a decrease in resilience. Given that future climate projections indicate a lengthening of the dry season and/or greater drought frequency for California, it seems that both increasing large tree vigor and decreasing potential for hazardous fire will be necessary in order to improve overall forest resilience. The question is, how to balance the two objectives when designing treatments? Our results suggest that treatments involving prescribed fire, which are most effective at reducing hazardous fire potential, may not be improving overstory tree vigor, relative to the mechanical treatment alone. This is problematic given the recent findings from van Mantgem et al. (2013) indicating a positive interaction between drought stress and sensitivity to fire-induced tree injuries. Perhaps the reduced overstory tree vigor we observed following prescribed fire would not be observed in repeat fire applications due to the overall reduction in surface and ground fuels and greater heterogeneity in vegetation structure that resulted from the initial-entry fires.

Based on our results, the mechanical-only treatment may be the best option if improving overstory tree vigor is the sole objective. The fact that hazardous fire potential initially was only slightly reduced, but then improved over time, suggests that if forest managers can tolerate the lack of fire hazard reduction in the short term for potential tree vigor gain over the longer term, mechanical thinning-from-below might achieve both objectives. However, the mechanical-only treatment lacks structural features (i.e., shrubs, large snags) that are associated with other aspects of resilient forests (e.g., wildlife habitat). One potential improvement to the mechanical-only treatment applied in this study is to use whole-tree removal systems, which generally do not result in augmented surface fuels following treatment, and thus an overall improvement in hazardous fire potential relative to untreated forest conditions (Stephens et al. 2009). It is worth noting that effective mechanical treatments include the removal of smaller trees that act as ladder fuels (Agee and Skinner 2005), which often can be costly because many of these trees have limited timber value. Another option, which could be used in addition to whole-tree removal, is to conduct prescribed burning several years (e.g., 5–10) following mechanical treatment. This approach would allow time for residual trees to improve vigor, perhaps allowing the trees to better withstand potential injury from burning, while also substantially extending treatment longevity. To our knowledge, this hypothesis is untested in mixed-conifer forests.

Acknowledgments

We thank Jason Moghaddas, Gary Roller, Zev Balsen, Karla King, Ben Weise, Austin Jones, and John Sanders for their hard work in data collection and processing. Tree cores collected for initial model development were collected as part of the Sierra Nevada Adaptive Management Project.

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Supplemental Material

Ecological Archives

The Appendix is available online: http://dx.doi.org/10.1890/14-0971.1.sm

Data Availability

Data associated with this paper have been deposited in the Forest Service Research Data Archive: http://dx.doi.org/10.2737/RDS-2014-0023