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Large-scale restoration increases carbon stability under projected climate and wildfire regimes

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Changing climate and increasing area burned pose a challenge to forest carbon (C) storage, which is compounded by an elevated risk of high-severity wildfire due to long-term fire suppression in the western US. Restoration treatments that reduce tree density and reintroduce surface fire are effective at moderating fire effects and may help build adaptive capacity to changing environmental conditions. However, treatment implementation has been slow and spatially limited relative to the extent of the area affected by fire suppression. Using model simulations, we quantified how large-scale restoration treatments in frequent-fire forest types would influence C outcomes in the Sierra Nevada mountain range under projected climate–wildfire interactions. Our results indicate that large-scale restoration treatments are an effective means of reducing fire hazard and increasing C storage and stability under future climate and wildfire conditions. The effects of implementation timing suggest that accelerated implementation of large-scale restoration treatments may confer greater C-storage benefits, supporting California’s efforts to combat climate change.

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Methods

Study area

This study encompassed approximately $3.4 \times 10^6$ ha of forest land in the Sierra Nevada mountain range of California and Nevada (Figure 1) and covered a substantial elevation gradient (165–4230 m). The climate is Mediterranean with dry summers and wet winters; most of the annual precipitation occurs in the form of snowfall (Fites-Kaufman et al. 2007), and snow cover persists into summer, depending on elevation. Temperature and total precipitation vary as a function of elevation and latitude, and influence fire activity, with wildfire events primarily occurring during the dry months (Syphard et al. 2011).

The Sierra Nevada range supports a diversity of tree species and forest types that sort by elevation, with low-elevation forests and woodlands generally composed of conifer and broadleaved species, and mid- and high-elevation forests primarily composed of conifer species (Liang et al. 2017a; see WebPanel 1 for additional details). Historically, fire events were frequent (fire return interval: 5–20 years) at lower elevations and frequency decreased with increasing elevation due to shorter snow-free seasons (Van de Water and Safford 2011). Selective timber harvest and subsequent fire suppression beginning in the early 20th century disrupted historical fire regimes at low and mid-elevations, and led to an increase in tree density and forest fuel loads, as well as a shift in composition toward more fire-intolerant species (Taylor et al. 2016). Conversely, fuel loads have not markedly deviated from historical conditions in high-elevation forests, where fires were infrequent (Mallek et al. 2013).

Simulation model description and development

We used LANDIS-II (www.landis-ii.org/home) – a spatially explicit landscape model with a core-extension structure – to simulate forest C dynamics in response to different treatment scenarios under projected climate–wildfire interactions. In conjunction with the LANDIS-II core, we used four extensions, consisting of Century Succession, which simulates C pools and fluxes; Dynamic Fire and Fuels (two distinct extensions), which simulate stochastic wildfire behavior/effects and classify the landscape by generalized fuel types, respectively; and Leaf Biomass Harvest, which simulates management (Scheller et al. 2011; see WebPanel 1). We leveraged previous model parameterization, calibration, and validation efforts, which are described in detail in Liang et al. (2017a), for this study.

The Century Succession extension drives simulations with monthly climate distributions created from means and standard deviations of monthly temperature and precipitation. Consistent with prior work (Liang et al. 2017a), we used downscaled (12-km) climate projections from three regionally representative general circulation models (GFDL, CCSM3, and CNRM) under the A2 emissions scenario to develop monthly climate distributions.

The Dynamic Fire and Fuels extension assigns fuel types based on tree species and age cohorts, and re-classifies fuel types at each time-step to account for succession, disturbance, and management activity. Wildfire fire size is determined by user-defined fire size distributions, fire weather conditions (eg wind speed, fine fuel moisture), topography, and fuels (eg amount, composition, distribution). Most of our study area maintains adequate fuel to carry large fires throughout the simulation period (Liang et al. 2017b). Fire severity class is scaled from 1 to 5, with
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severity classes 1 and 2 being surface fires, 3 and 4 involving some torching of overstory trees, and 5 being stand-replacing. To simulate area burned, we derived decadal fire size distributions based on the climate-model–specific projections of area burned by large wildfires (>200 ha) developed by Westerling et al. (2011) (see WebPanel 1).

Fuel treatment implementation

We used the Leaf Biomass Harvest extension to simulate not only thinning from below but also prescribed fire treatments that are commonly practiced in low- and mid-elevation forests to reduce fire hazard in the Sierra Nevada, following Syphard et al. (2011) and Krofcheck et al. (2017). The thinning and prescribed fire treatments were designed to remove a greater proportion of the youngest cohorts and shift the age distribution toward older cohorts. Across the landscape, treatments were implemented in fire-prone forests that currently have a greater risk of high-severity fire (Figure 1). The potential treatment area accounted for 57% of the total study area and excluded federally designated wilderness, riparian conservation areas, and infrequent-fire forest types (e.g., high-elevation forests).

We developed two scenarios for implementing large-scale restoration treatments: distributed and accelerated. The distributed scenario allocated thinning treatments at a rate of 12% of potential treatment area per decade, whereas the accelerated scenario implemented treatments at a faster rate of 25% per decade, with thinning completed by mid-century. Stands with higher fire hazard were treated first. Following each thinning treatment, prescribed fire treatments were successively applied on a 10–30-year return interval as a function of elevation band to reflect the fact that historical fire frequency generally decreased with increasing elevation (see WebTable 1 and WebPanel 1 for details). Because prescribed fire was only implemented after thinning treatments in low- and mid-elevation forests, the accelerated scenario had a greater number of prescribed fire intervals.

Simulation experiment

We simulated three treatment scenarios (control, accelerated, distributed) with three climate–wildfire scenarios, for a total of nine different scenarios over a 90-year simulation period (2010–2100) using a 10-year time-step. We ran 10 replicate simulations of each scenario to capture climate and wildfire stochasticity. Results for each treatment scenario were averaged over 30 simulations (10 replicates for each of three climate–wildfire scenarios) to summarize effects of different treatments on wildfire behavior and C balance for the entire study area (WebPanel 1).

Results

While cumulative area burned by wildfire was consistent across treatment scenarios, widespread application of restoration treatments gradually reduced the proportion of landscape burned by high-severity wildfires, with an increasingly greater proportion of the landscape burned by low-severity surface fires relative to the control (Figure 2). The reduction in wildfire severity occurred more rapidly in the accelerated scenario than in the distributed scenario, with the ratio of area burned by higher severity fires (severity class ≥ 3) to area burned by lower severity fires (severity class < 3) decreasing from 1.59 to 0.66 in the accelerated scenario and 0.87 in the distributed scenario.

Although C loss was initially higher in the restoration treatments, treatment effects on fire severity led to an
immediate reduction in wildfire emissions and lowered cumulative C emissions and losses (Figure 3). There was little difference in total C loss between the accelerated and distributed scenarios for the first half-century, but cumulative C losses were significantly lower \((P < 0.001)\) in the accelerated scenario by late-century (Figure 3b). The timing of treatment implementation had significant effects on both wildfire emissions and aboveground C (AGC). The accelerated and distributed scenarios reduced cumulative wildfire emissions by 42% and 31%, respectively. Although late-century mean AGC differences were small on a per unit area basis (accelerated = 156 megagrams of carbon per hectare \([\text{Mg C ha}^{-1}]\), standard deviation \([\text{SD}] = 1.5\); distributed = 154 Mg C ha\(^{-1}\), SD = 2.0; \(P < 0.001\)), by 2100 the accelerated scenario stored 6 teragrams \((\text{Tg})\) more C across the Sierra Nevada than the distributed scenario. Because of the timing of treatments and the stochastic nature of wildfire, C losses resulting from thinning and prescribed burning were larger in the accelerated scenario than in the distributed scenario (Figure 3b), but because the accelerated scenario rapidly restored surface fire regimes in low- and mid-elevation forests and reduced burn severity, total cumulative losses across the Sierra Nevada were significantly lower (Figure 3b).

The influence of treatments on burn severity also led to greater AGC accumulation across the landscape relative to the control. The proportion of the landscape in which C accumulation was greatest \((\Delta \text{AGC} > 60 \text{ Mg C ha}^{-1})\) over the simulation period increased from 8% in the control to 17% in the distributed scenario and 20% in the accelerated scenario, generally tracking the spatial distribution of restoration treatments (WebFigures 2 and 3). In addition, both the distributed and accelerated scenarios had lower late-century AGC coefficients of variation over the landscape, indicating more stable C storage (WebFigure 4). Because of the effects of treatments on moderating tree mortality from wildfire, the accelerated scenario substantially reduced the area that had no forest cover in 2100 due to climatic limitations on post-fire recovery (WebFigure 5).

**Discussion**

Reducing the risk of high-severity fire always involves short-term C costs (Campbell et al. 2012), which our results confirm (Figure 3). Wildfire C emissions in California are projected to increase by 19–101% in response to future changes in climate (Hurteau et al. 2014b). Although reducing wildfire emissions requires repeated atmospheric C emissions from more frequent prescribed fires (Hurteau 2017; Krofcheck et al. 2017), prescribed fire emissions are smaller and we found support for our hypothesis that large-scale treatments will lower fire severity and reduce wildfire emissions relative to the control (Figures 2 and 3). Inclusive of emissions from repeated prescribed fire, our large-scale restoration treatments reduced fire emissions...
by an average of 0.07–0.09 Mg C ha\(^{-1}\) yr\(^{-1}\) over the
90-year simulation, with the cumulative amount of avoided
C emissions across the entire Sierra Nevada equaling
24% of California’s 2020 emission limit (116 Tg; California
Assembly Bill 32).

Given the stochastic nature of wildfire and the effects of
treatments on reducing large C releases (Hurteau et al.
2018), we hypothesized that the accelerated scenario
would incur larger C losses as a result of treatment but
lower cumulative losses than would the distributed sce-
nario. In the distributed scenario, more untreated area
was burned by wildfire before treatments could be im-
plemented, leading to a larger area being affected by high-
severity wildfire. In contrast, the accelerated scenario
reduced cumulative C losses over the long term as a result
of the trade-off between substantial C losses from wildfire
and moderate C losses from treatments. These different C
outcomes emphasize the necessity of weighing trade-offs
between the C costs of treatments and the long-term C
benefits when planning large-scale treatment implemen-

While the effects of treatments can yield disparate
responses in forest C over time (Campbell et al. 2012;
Krofcheck et al. 2018), we found that by moderating fire
effects under changing climate and increased burned area,
the treatment scenarios had higher late-century AGC
than the control (WebFigure 2). Previous studies have
demonstrated that restoration treatments that focus on
removing smaller trees and restoring surface fire can sub-
stantially increase canopy base height while at the same
time minimizing reductions in live tree C and increasing
The temporal distribution of C losses demonstrated that large-
scale restoration treatments may initially incur greater C
loss from the system, with the size of this near-term C cost
being a function of implementation timing (Figure 3).
However, because the accelerated scenario rapidly reduced
the risk of tree mortality from canopy fires, the remaining
C was held in a more stable form and a greater fraction of
the landscape retained forest cover as compared to the
distributed scenario (WebFigures 2, 4, and 5). Given that
climate change is expected to facilitate severe wildfire
occurrence and drought-induced tree mortality (Allen
et al. 2015; Jones et al. 2016), large-scale treatments may
become more C cost-efficient in stabilizing forest C than
our simulations indicate, and accelerating treatment
deployment may help confer greater C benefits.

Our treatment results are conservative with respect to
C losses from the system due to thinning because we
treated all thinned biomass as a loss and applied treat-
ments to all low- and mid-elevation forests. Previous
research has suggested that a portion of this biomass can
be converted to long-lived wood products, which reduces
total C loss (North et al. 2009). In addition, developing
treatment networks and strategically siting treatments
may increase the efficacy of treatments in reducing wild-
fire spread and intensity (Collins et al. 2013), and can
also facilitate the reintroduction of surface fire in areas
where harvesting is limited and surface fire alone can
reduce fire hazard (North et al. 2012). Furthermore, our
results are conservative because we held fire weather con-
ditions constant throughout the simulations. Warmer
and drier conditions, as well as higher wind speeds,
enhance fire behavior and can increase the probability of
high-severity wildfire in untreated forests (Krofcheck
et al. 2017), and severe fire weather conditions are
becoming increasingly common in the Sierra Nevada
(Collins 2014). However, treatment efficacy with respect
to fire severity has been demonstrated under both current
and projected extreme fire weather when surface fire
regimes are restored (Krofcheck et al. 2017, 2018).

Other operational considerations are left unaccounted
for by our simulations. Large-scale treatment implemen-
tation may be restricted by the cost of thinning small,
non-merchantable trees. However, a large-scale, long-
term treatment plan with an incremental deployment
of treatments may form a steady and predictable flow of
biomass, which could help diversify the wood products
industry and improve the economics of removing small
trees (Hampton et al. 2011; North et al. 2012). Although
widespread prescribed fire application would contribute
to degraded air quality, prescribed fire emissions can be
substantially lower than those from large, severe wildfires,
and management prescriptions can reduce exposure by
prioritizing treatments when wind conditions are condu-
cive to transporting emissions away from population
centers (Wiedinmyer and Hurteau 2010). Moreover,
restoring forests to achieve long-term C gains may require
trade-offs with other management objectives (eg wildlife
protection), but large wildfires also pose a major impedi-
ment to achieving these objectives (Jones et al. 2016;
Stephens et al. 2016). Large-scale treatment planning
therefore requires a degree of flexibility to accommodate
other goals.

By accounting for climate–wildfire–vegetation interac-
tions, our results suggest that large-scale restoration
treatments in historically frequent-fire forests can be an
effective strategy to moderate fire effects, as well as to
manage for higher C storage and stability under projected
climate change and increasing area burned. A more rapid
treatment implementation schedule could confer a
greater long-term C benefit and sustain more forest cover
than delayed treatment implementation, with ecological
and societal benefits.

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References


Supporting Information

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