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Key Points:
- Forests provide a range of ecosystem services, including climate regulation, that are dependent on ecosystem structure and function.
- Fire-exclusion has altered the structure of frequent-fire forests, and climate change is exacerbating the risk of uncharacteristic wildfires.
- Optimizing management can reduce high-severity fire risk and increase climate change mitigation by stabilizing forest carbon.

Supporting Information:
- Supporting Information

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Optimizing Forest Management Stabilizes Carbon Under Projected Climate and Wildfires

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Abstract Forests provide a broad set of ecosystem services, including climate regulation. Other ecosystem services can be ecosystem dependent and are in part regulated by local-scale decision-making. In the southwestern United States, ongoing climate change is exacerbating a legacy of fire-exclusion that has altered forest structure and increased high-severity wildfire risk. Management can mitigate this risk by reducing forest density and restoring frequent surface fires, but at the cost of reduced carbon stocks. We sought to quantify the role of management in building adaptive capacity to projected climate and wildfires and the carbon consequences in a forested watershed. We simulated carbon dynamics under projected climate and wildfires and two management scenarios: prioritized and optimized. The prioritized scenario involved thinning and prescribed burning in areas selected by stakeholders to mitigate high-severity wildfire risk. The optimized scenario used the probability of high-severity wildfires to locate thinning treatments and increased prescribed fire area burned relative to the prioritized scenario. Both scenarios reduced wildfire severity and significantly increased net photosynthesis relative to no-management. However, the optimized scenario decreased management-related losses by 2.4 Mg • C • ha^{-1} and wildfire emissions by 2.9 Mg • C • ha^{-1} relative to the prioritized scenario. By decreasing the area thinned and increasing the area burned relative to the prioritized scenario, the optimized scenario halved the time to realize a net carbon benefit relative to no-management. Given the increasing climatic and disturbance pressures impacting southwestern forests, management will play a critical role in building adaptive capacity and ensuring the continued provision of ecosystem services.

Plain Language Summary Forests provide a range of services to society, including carbon storage, which helps regulate the climate. Wildfires impact a forest's contribution to climate regulation by releasing carbon to the atmosphere through combustion and by killing trees, which reduces the amount of carbon removed from the atmosphere. In forests that historically experienced frequent-fire, fire-exclusion has increased tree density and the amount of biomass available to burn. These changes have increased the risk of stand-replacing wildfires, and ongoing climate change is making forests more flammable. Management to reduce stand-replacing fire risk typically involves thinning small trees and prescribed burning, both of which reduce the amount of carbon stored in the forest. We sought to determine how management would influence wildfire behavior and carbon dynamics for two different scenarios under projected climate for a municipal watershed in the Sangre de Cristo Mountains of New Mexico. The prioritized scenario-placed thinning and burning treatments based on stakeholder and manager input. The optimized scenario-placed thinning treatments based on the chance of stand-replacing wildfires and applied prescribed burning to all frequent-fire forest types in the watershed. Both scenarios reduced the occurrence of stand-replacing fire. However, the optimized scenario stored more carbon because 54% less of the watershed was thinned. This reduced carbon losses from management and halved the time it took the watershed carbon storage to surpass that of the no-management scenario. Informing management based on risk helps build adaptive capacity to changing climate and maintains the climate regulation benefits of forests.

1. Introduction

Forests provide a wide range of ecosystem services, including biomass production, habitat, climate regulation, and the provision and purification of water for society (Brockerhoff et al., 2017; Mori et al., 2017). The quantity and quality of these services is dependent on ecosystem structure and function (Mace et al., 2012), both of which can be compromised by land-use history and climatic change (Millennium Ecosystem Assessment, 2005). Since the 1950s, anthropogenic influence on the Earth system has resulted in rates of change to the climate system and ecosystem disturbance regimes that are without precedent

(IPCC, 2013; Ribes et al., 2017), causing ecosystem reorganization and altering the provision of ecosystem services.

The influence of changing climate on forests varies spatially as a function of abiotic stressors, directly causing a range of ecosystem responses (Allen et al., 2010). Climatic perturbations can also intensify disturbance processes creating an indirect pathway for changing climate to alter forest systems (Seidl et al., 2017; Vilà-Cabrera et al., 2018). The combination of these direct and indirect pathways may result in increased vulnerability to disturbance and disturbance intensity, placing many forested ecosystems at risk of significant reductions in productivity (Seppälä, 2009). Further, for those forests which already experience frequent water limitations, the potential outcomes of climate-related disturbance trend toward widespread tree mortality (Allen et al., 2015, Williams et al., 2013).

In seasonally dry forests, longer and hotter droughts have resulted in significant mortality events over the past 2 decades with hotspots in Australia (Brouwers et al., 2013; Semple et al., 2010), Europe (Čater, 2015), and more recently in the western United States (Anderegg et al., 2015; Asner et al., 2016; Hicke et al., 2015). These shifts in drought intensity and duration have amplified seasonal trends in fuels aridity in seasonally dry forests, increasing ecosystem flammability (Abatzoglou & Williams, 2016). In the semiarid southwestern United States, landscapes have been subject to a significant drought since the turn of the century, resulting in extensive and severe subsurface soil moisture anomalies due to the warming climate and snow pack reduction, resulting in increases in area burned across the region (Abatzoglou & Williams, 2016; Westerling, 2016).

The direct and indirect effects of changing climate interact with ecosystems shaped by over a century of fire-exclusion. The suppression of wildfires has transformed frequent-fire-adapted forests from systems historically characterized by open understories shaded by fewer, older trees, into high stem density conditions with nearly continuous forest canopy (Hagmann et al., 2013, 2014; Johnston et al., 2017). These shifts in ecosystem structure increase forest vulnerability to drought, as competition for water increases with tree density (Voelker et al., 2019). Further, the legacy of fire-exclusion has resulted in a forest and fuels structure that increases the probability that ignitions result in high-severity wildfires torching mature trees and significantly impacting the structure of the forest (Singleton et al., 2019). These structural vulnerabilities, combined with increased extent, duration, and intensity of climate change-type drought events (Seager et al., 2007; Williams et al., 2015), and a lengthening of the fire season (Jolly et al., 2015), set the stage for larger, hotter wildfires to impact the vulnerable forests of the southwestern United States. The severity of fire weather events (Collins, 2014), area burned (Westerling, 2016), and the frequency of high-severity fire (Singleton et al., 2019) continue to increase, suggesting that these trends will continue on a similar trajectory. Cessation of the increase of high-severity fire ultimately depends on the contemporary structure of forest and fuels distributions equilibrating with current climate and wildfire regimes (Liang et al., 2017), reducing the likelihood of uncharacteristic wildfires once the majority of forests either have experienced severe wildfires or have been influenced by management activities (Parks et al., 2016).

Management intervention at the local scale can result in immediate reductions in high-severity fire risk through changes in forest structure and in the distribution and quantity of fuels (Ager et al., 2014; Finney et al., 2005; Lydersen et al., 2017). In the frequent-fire-adapted forests of the southwestern United States, the management influence on fire behavior involves reducing tree density by mechanically thinning younger and shade-tolerant trees that can carry surface fire into the crowns of mature trees followed by prescribed burning on a regular interval to maintain forest structure (Agee & Skinner, 2005; Hurteau et al., 2016). Consequently, fuels reduction treatments initially remove carbon from the landscape, yet over time the compensatory growth attributed to the release of the remaining trees from competition, combined with the reduced likelihood of high-severity, stand-replacing wildfires can result in a net carbon gain across the landscape and facilitate climate regulation (Hurteau et al., 2016; Hurteau & North, 2010; Krofcheck et al., 2018).

The net ecosystem carbon balance (NECB), defined as the summation of the carbon inputs (i.e., net photosynthesis) and losses (e.g., management and wildfires) from the ecosystem, is a useful metric to understand the trajectory and stability of the forest from a growth and carbon accumulation perspective (Chapin et al., 2006). Further, because NECB incorporates changes to ecosystem structure from wildfires and management and ecosystem function from net photosynthesis, changes in NECB directly impact ecosystem services beyond climate regulation by affecting the quantity and quality of habitat, wood production, and so forth. The initial NECB cost of management, for example, through mechanical thinning to reduce tree density, is required to establish a forest structural condition that is capable of reducing losses from high-severity wildfires and subsequent post-fire reductions in net photosynthesis (Hurteau et al., 2016; North & Hurteau, 2011). Yet, decision-making with respect to how and where these treatments are placed and what type of treatments are implemented can help maximize treatment benefit while minimizing the landscape carbon losses from management and therefore decrease the time to a net carbon benefit (Krofcheck et al., 2018; Wiechmann et al., 2015). Given the extent of frequent-fire forest that has deviated from its fire-maintained condition is large, and the pace at which treatments are being implemented is slow (North et al., 2012), treatment placement optimization can help balance the need to mitigate high-severity wildfire risk, the climate-regulating role of forests, and the economic costs of management.

Here we used a process-based model of vegetation function at the landscape-scale to investigate how management intervention can build ecosystem adaptive capacity to projected climate and wildfires. We quantified the components of NECB to understand how treatment placement and carbon costs influenced the trajectory of net photosynthesis and wildfire carbon emissions. Specifically, we asked (1) how are net photosynthesis, management, and wildfire emissions related in terms of their contribution to landscape NECB? And (2) how does treatment optimization affect the time required to achieve a positive NECB?

2. Materials and Methods

2.1. Site Description

We chose to investigate the role of fuels reduction treatment placement in mitigating NECB losses in a fireshed (defined as an area where the social and ecological concerns regarding wildfire overlap) in northern New Mexico. The Santa Fe fireshed encompasses the city of Santa Fe's approximately 7,000 ha municipal watershed and has drawn considerable attention from managers and stakeholders because of the risk of high-severity wildfires and the threat it poses to the provision of municipal water supply. The Greater Santa Fe Fireshed Coalition (http://www.santafefireshed.org/), a group of federal, state, tribal, and nongovernmental organizations, has been using a collaborative process to develop a management strategy to mitigate the risk of high-severity wildfires within the Fireshed, including treatment type and placement. The Fireshed is approximately 45,000 ha and is located in the Sangre de Cristo Mountains, east of Santa Fe, New Mexico (Figure 1). The Fireshed spans an elevation range of 1,900–3,700 m and contains vegetation ranging from piñon-juniper woodlands (*Pinus edulis, Juniperus monosperma*) in the low-elevation foothills, transitioning to ponderosa pine (*P. ponderosa*) in the mid elevations, and with mixed-conifer forest and spruce-fir (*Picea engelmanii, Abies lasiocarpa*) at higher elevations, with some scattered stands of Gambel oak (*Quercus gambelii*) and quaking aspen (*Populus tremuloides*) occupying recently disturbed regions in the mid and high elevations. The soils range from silty clay skeletal mixture Sobordoro soils in the low to mid elevations, transitioning to more loam-dominated mixtures at higher elevations. For the period 1980–2015, mean annual temperature is 9.4 °C, and mean annual precipitation is 360 mm, with a larger fraction of precipitation falling as snow in the winter months at higher elevations (Thornton et al., 2012).

2.2. Model Description and Model Region Generation

We conducted landscape-scale simulations of forest growth, succession, and disturbance across the Santa Fe Fireshed at a spatial resolution of 1 ha using landscape disturbance and succession II (LANDIS-II; v6.2), a forest landscape disturbance and succession model with additional processes represented via modular extensions. The core LANDIS-II model simulates demography in terms of species-specific age cohorts, each with a unique set of parameters that govern their growth, succession, dispersal, and mortality across a spatially explicit landscape (Scheller et al., 2007). To increase the coupling between abiotic drivers and ecophysiology, we used the photosynthesis and evapotranspiration (PnET)-Succession extension (v2.0; de Bruijn et al., 2014) for LANDIS-II, which is based on elements of the PnET-II model (Aber et al., 1995) and affords the model the ability to drive succession and biomass accumulation based on an additional set of species-specific physiological parameters. We used the Dynamic Fuels and Fire extension (v2.1) to simulate wildfires and fuels interactions (Sturtevant et al., 2009) and the Biomass Harvest extension (v3.0) to simulate management (Gustafson et al., 2000). The Dynamic Fuels and Fire extension simulates stochastic wildfires, and the effects on the ecosystem are a function of the fuels, weather, and forest conditions when the fire occurs. The model calculates wildfire severity (the effects of fire on the vegetation) based on the proportion of tree cohorts that are killed. Severity classes range from 1–5, with classes 1 and 2 being surface fire and no, or low, tree

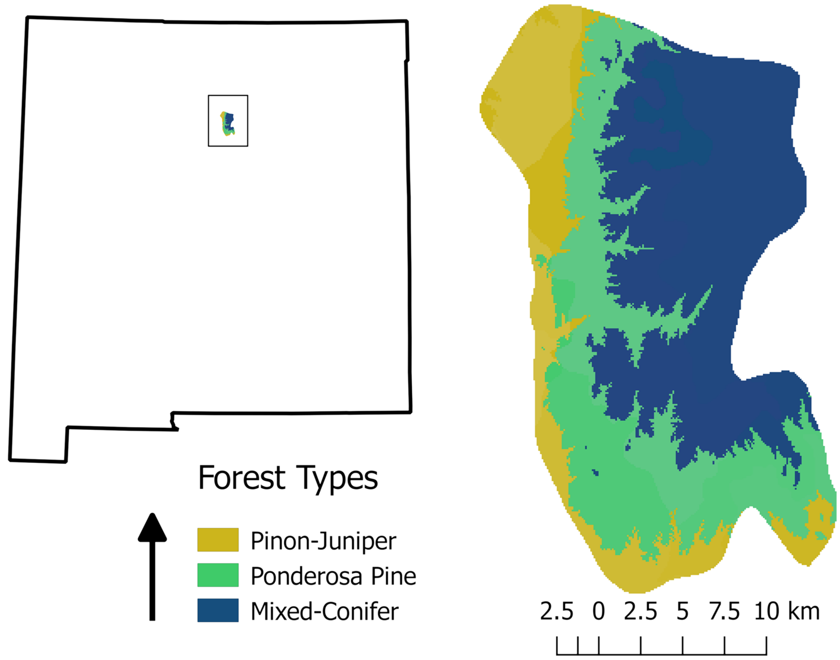

Figure 1. The Santa Fe Fireshed, located in Northern New Mexico, United States, is composed of three distinct vegetation types roughly ordered by increasing elevation: piñon-juniper woodlands (tan), ponderosa pine forest (green), and mixed-conifer forests (blue).

mortality; class 3 being mixed-severity fire that includes surface fire and some overstory tree torching that causes mortality; and classes 4 and 5 that include torching and crowning, resulting in a larger fraction of the overstory trees being killed by fire (see Supporting Information S1).

The LANDIS-II core and PnET-Succession extensions require the landscape to be separated into distinct "ecoregions," hereafter referred to as model regions. The model regions are defined by unique edaphic and climatic zones. For the growth and succession parts of the model, we chose to intersect elevation data (https://datagateway.nrcs.usda.gov/) roughly corresponding to the broad vegetation transitions determined by the Southwest Regional Gap Analysis (http://swregap.nmsu.edu/) with soil data (State Soil Geographic dataset, https://datagateway.nrcs.usda.gov/) across the Fireshed, resulting in the 18 unique model regions that resulted from the combination of three elevation bands and six soil types. The fuels and fire parts of the model require the landscape be divided into fire regions, which are areas with similar fire weather, fire size distributions, and ignition frequencies. We used the same three elevation bands to create three distinct fire regions.

2.3. Climate Data

The LANDIS-II core model and the PnET-Succession extension require climate inputs at a monthly timestep. We drove the model with climate projections from the Localized Constructed Analogs statistically downscaled climate projection from five climate models forced with Representative Concentration Pathway 8.5 from the Coupled Model Inter-comparison Project Phase 5. Specifically, we chose Community Climate System Model (CCSM), Centre National de Recherches Météorologiques (CNRM), Flexible Global Ocean-Atmosphere-Land System Model (FGOALS), Geophysical Fluid Dynamics Laboratory (GFDL), and Model for Interdisciplinary Research on Climate (MIROC5-ESM 2) given their projections represent the range of outcomes for the region. The Localized Constructed Analogs product is a daily, 1/16th degree resolution-downscaled product that has been shown to track local variability in precipitation better than the coarser resolution parent models (Pierce et al., 2014). The projections include data from 1950 to 2100, and we used data from 1950 to 2000 for model spin-up. We downloaded the data using the U.S. Geological Survey Geo Data Portal (http://cida.usgs.gov/gdp/), and computed weighted area grid statistics on a per-model region basis using the export service in the data portal.

Table 1
Total treatment area and rates for thinning and prescribed burning

Scenario	Thin area (ha)	Thin rate (ha yr^{-1})	Prescribed fire area (ha)	Prescribed fire rate (ha yr^{-1})
Prioritized	13,273	1,327	16,531	1,657
Optimized	6,006	1,201	21,054	1,958

The PnET extension also requires radiation and atmospheric carbon dioxide concentrations as inputs to the model. We downloaded spatially explicit shortwave radiation from Daymet using the U.S. Geological Survey Geo Data Portal, and created a distribution of mean monthly shortwave radiation on a per-model region basis (Thornton et al., 2012). We then converted the shortwave radiation to photosynthetically active radiation following Britton and Dodd (1976). We used historic CO_2 concentrations for model spin-up (https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html) and concentrations from the Representative Concentration Pathway 8.5 for model projections (Riahi et al., 2007).

2.4. Model Parameterization and Validation

We developed the initial communities layer, which is the spatial distribution of species-specific age cohorts, using U.S. Forest Service Forest Inventory and Analysis data and Southwest Regional Gap Analysis data (see Supporting Information S1). We parameterized the Dynamic Fire and Fuels extension using regional fire size data from Geospatial Multi-Agency Coordination, previously published fuels data, and climate projections from the Multivariate Adaptive Constructed Analogs v2 collection to develop fire weather distributions (see Supporting Information S1). We obtained species-specific parameters for the PnET ecosystem succession extension from previously published data and the TRY database, then validated the model against eddy-covariance tower data (Gustafson et al., 2015, Kattage et al., 2011, Remy et al., 2019, see Supporting Information S1).

2.5. Management Treatment and Scenario Development

We developed management treatments for the Biomass Harvest extension to approximate common thinning and prescribed burning treatments implemented in the region. We simulated thinning-from-below by removing approximately 30% of the biomass from each pixel identified for treatment (Hurteau et al., 2011; Hurteau et al., 2016). Thinning treatments preferentially removed biomass from the youngest cohorts. Prescribed fires were simulated such that initial-entry burns were implemented in the year following mechanical treatments and were simulated using a fire return interval consistent with the historical data, ranging from 10–17 years depending on whether the forest types were ponderosa pine or higher elevation stands co-dominated by ponderosa pine or Douglas-fir. Thinning treatments were only applied to forest types that historically burned at high frequency (i.e., ponderosa pine-dominated stands).

To answer our questions, we developed three different scenarios (no-management, prioritized, and optimized). Prior to this analysis, the Santa Fe Fireshed Coalition used a collaborative process to develop a proposed fuels treatment plan for the fireshed. We based our prioritized treatment scenario on implemented, planned, and potential treatment locations provided by the Fireshed Coalition. Given the Fireshed Coalition's objective of mitigating the risk of high-severity wildfires, we used a procedure similar to Krofcheck et al. (2017, 2018) to develop an optimized treatment placement scenario. To develop the optimized scenario, we used the initial vegetation community representing the dominant vegetation types, the operational constraints to mechanical thinning of vegetation (slope >30%), and the probability of high-severity fire under progressive fire weather (see the supporting information, Figure S1). We then used the calculated probability of high-severity fire across the Fireshed to determine the treatment priority for the landscape (see Supporting Information S1). The areas identified for thinning in the optimized scenario are a subset of those identified for thinning in the prioritized scenario. Additionally, the optimized scenario includes a larger area identified for prescribed burning because prior research has demonstrated widespread prescribed burning, coupled with targeted thinning treatments, can modify the risk of high-severity wildfires (Krofcheck et al., 2018, 2019).

The resulting treatment areas and rates for mechanical thinning and prescribed burning are described in Table 1. The area treated by prescribed fire is larger than the thinned area because prescribed fire treatments were not limited by slope (Figure S1). In both scenarios, mechanical thinning was constrained to ponderosa pine-dominated areas.

2.6. Simulation Experiment Description and Analysis

We ran 25 replicates of each of the three scenarios (no-management, prioritized, and optimized) using five climate projections for years 2000–2050. Fire weather distributions tracked projected climate and were updated each decade to account for changes in temperature and precipitation (see Supporting Information S1). We calculated the mean fire severity of all three scenarios by using annual raster outputs of fire severity from all replicate simulations for each of the five climate projections used in our modeling environment. Similarly, we calculated the cumulative sums of landscape net photosynthesis, carbon removed due to management, and carbon lost due to wildfires. We compared these outputs between treatments by subtracting each management output from the no-management scenario. Because we compared all the model outputs for the management scenarios to the no-management scenario, cumulative net photosynthesis differences that are negative indicate the management scenario sequestered more carbon relative to the no-management scenario. We calculated the cumulative NECB for each management scenario by subtracting the carbon losses from the system (management and wildfires) from cumulative net photosynthesis and subtracted no-management cumulative NECB to obtain the difference from no-management. Positive cumulative NECB values indicate that the management scenario cumulative NECB was higher than the no-management cumulative NECB. We conducted data processing, statistical analysis, and figure generation in Python 3.6.

We compared mean fire severity by treatment scenario using annual raster outputs of fire severity from all replicate simulations for each of the five climate projections used to drive each management scenario. We compared cumulative photosynthesis between the management scenarios by subtracting cumulative photosynthesis from the prioritized and optimized scenarios from the no-management scenario. The differencing of the management scenarios from the no-management scenario means that a negative cumulative photosynthesis value means the management scenario is taking up more carbon than the no-management scenario. We calculated the cumulative NECB for all scenarios by subtracting carbon losses from the system (management and wildfires from net photosynthesis. We then differenced cumulative NECB by subtracting the no-management scenario from the two management scenarios. Positive cumulative NECB values indicate that the management scenario cumulative NECB was higher than the no-management cumulative NECB. We conducted data processing, statistical analysis, and figure generation in Python 3.6.

3. Results

Combinations of mechanical thinning and prescribed burning in both management scenarios resulted in large and significant reductions to landscape-scale fire severity (Figure 2). As expected, the largest reductions in fire severity occurred where treatments were implemented. The optimized scenario resulted in 29% more of the landscape having reductions in mean wildfire severity greater than 20% relative to the prioritized scenario due to the additional 4,523 ha that received prescribed fire (Table 1). However, the prioritized and optimized treatment scenarios did not significantly differ from each other in terms of the proportion of wildfires that burned at high-severity. There were no significant differences in the total number of fires or the wildfire size distribution across scenarios, because we held those distributions constant for all simulations.

The implementation of thinning treatments caused the cumulative *Psn* to decrease relative to no-management during the first decade when thinning treatments were implemented (Figure 3). Between 3 and 5 years following completion of the thinning treatments, both management scenarios had increased the cumulative landscape Psn relative to no-management because of reduced resource competition and decreased disturbance pressure, a trend that persisted throughout the 50 year simulation period (Figure 3). The cumulative difference in the landscape Psn of both treatment scenarios was significantly higher in the prioritized (6.6 ± 0.08 Mg • C • ha^{-1}) and optimized (6.8 ± 0.08 Mg • C • ha^{-1}) scenarios than in the no-management scenario. At the landscape-scale, this is equivalent to 0.32 Tg C for the prioritized and 0.33 Tg C for the optimized scenarios (Figure 3).

By the end of the simulation period, both treatments resulted in significant reductions in carbon (C) losses due to wildfires relative to no-management (prioritized 3.0 Mg • C • ha^{-1}, optimized 5.9 Mg • C • ha^{-1}), equivalent to 0.15 Tg C for the prioritized and 0.33 Tg C for the optimized scenarios across the landscape (Figure 4). The total C removed due to thinning and prescribed burning was higher for the prioritized scenario (8.4 Mg • C • ha^{-1}) than the optimized scenario (6.8 Mg • C • ha^{-1}, Figure 4), due to the combined

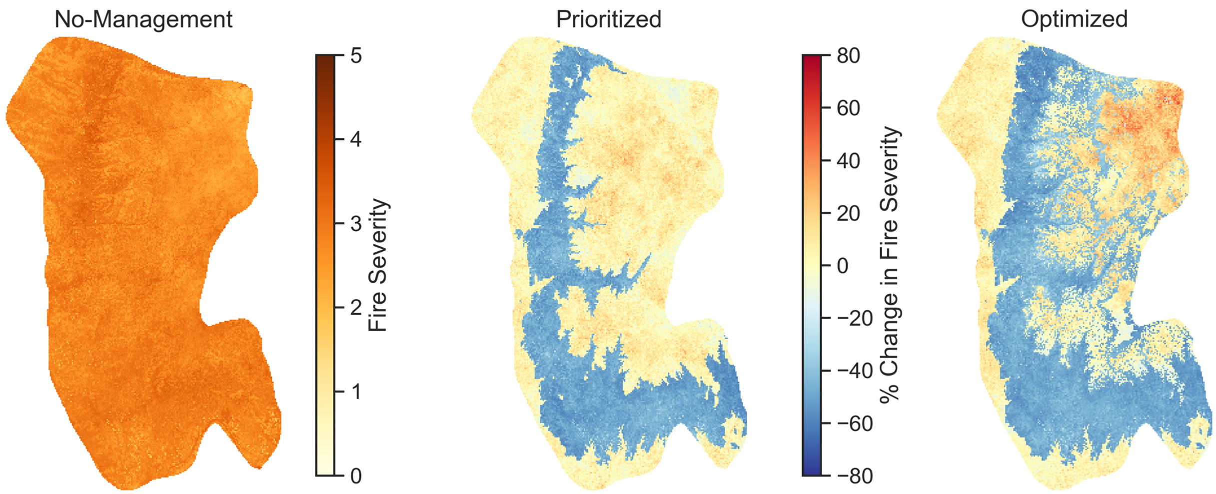

Figure 2. Mean wildfire severity across the Santa Fe Fireshed for the no-management scenario (left) and the percent reduction in mean wildfire severity from no-management for the prioritized (center) and optimized (right) scenarios. Fire severity ranges from 1 to 5, with 1 and 2 being surface fire, 3 being surface fire and some overstory tree torching, and 4 and 5 including crowning and high overstory tree mortality.

impact of a reduction in mechanical thinning of 7,267 ha and an increase in prescribed burning of 4,523 ha under the optimized scenario (Table 1).

At the end of the 50 year simulations, the cumulative NECB benefit relative to no-management was 1.2 Mg • C • ha^{-1} for the prioritized scenario and 5.9 Mg • C • ha^{-1} for the optimized scenario, equivalent to 0.06 Tg C for the prioritized and 0.29 Tg C for the optimized scenarios across the landscape (Figure 5). Throughout the simulation period, this relative benefit was dynamic in both treatments as a function of stochastic wildfire, climate and fire weather projections, and management prescriptions, with the mean time to net benefit for the prioritized scenario occurring at simulation year 45, and at year 24 for the optimized scenario.

4. Discussion

Forest management in fire-prone, semiarid ecosystems is an exercise in mitigating the potential loss of ecosystem services that can occur from high-severity wildfires. A legacy of fire-exclusion, which has increased the sensitivity of frequent-fire-adapted forests to climatic change and climate-driven disturbance, presents a significant challenge for many forests in the western United States. Maintaining these fire-prone forests and the broad suite of ecosystem services they provide hinges on restoring forest structural heterogeneity and reducing fuels, the maintenance of which is dependent upon restoring frequent-fire regimes (Hurteau

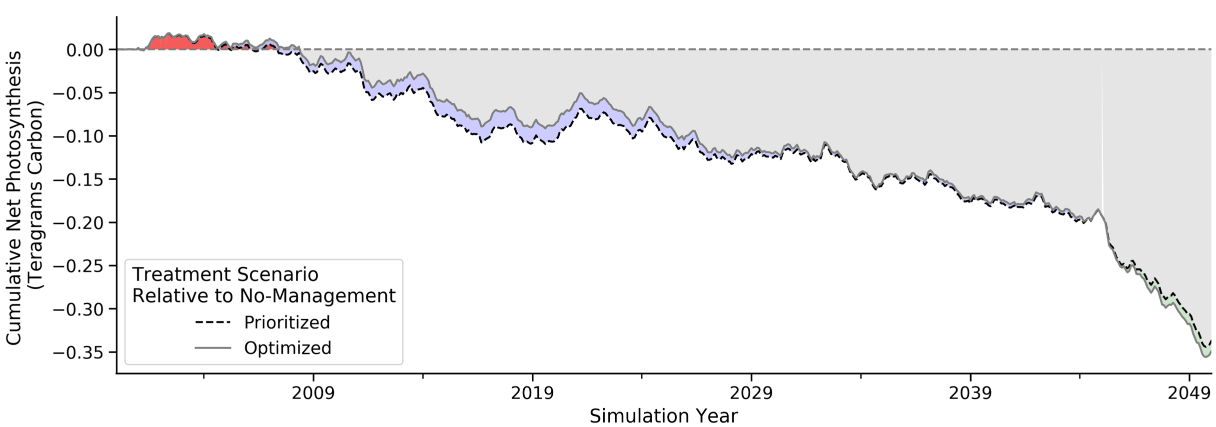

Figure 3. Net photosynthesis integrated across the Fireshed over time, relative to the no-management scenario (0 line) for both the prioritized (dashed black) and optimized (solid gray) scenarios. Positive values indicate the no-management scenario sequestered more carbon than the management scenario (red shading).

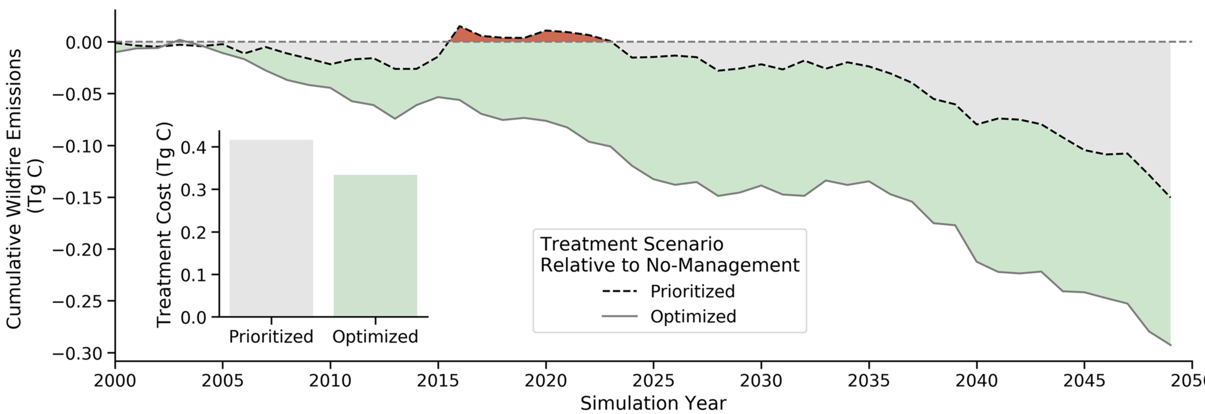

Figure 4. Differences in carbon (C) loss due to wildfires integrated across the Fireshed over time, relative to the no-management scenario (0 line) for both the prioritized (dashed black) and optimized (solid gray) scenarios. Positive values indicate the management scenario had higher wildfire C emissions relative to the no-management scenario. The total C removed by mechanical thinning and prescribed burning associated with each treatment scenario is shown in the inset bar graph.

et al., 2014). Further, the contemporary record of drought and wildfire impacts on forested ecosystems in the semiarid southwestern United States suggests that the ecosystem instability borne from combinations of fire-exclusion and climatic change will result in large structural changes and reductions in ecosystem function (Allen et al., 2015; Hurteau, 2017).

While mitigating human impacts on the climate system requires a global effort, mitigating the impacts of changing climate and disturbance regimes on forests is inherently a local process. These intervention strategies require an upfront carbon cost, an initial detriment to NECB, but can help stabilize forest carbon and contribute to global climate change mitigation efforts. Our results demonstrate that informing management decisions by optimizing treatment locations can provide the same reduction in high-severity wildfire risk as prioritizing treatment using a nonquantitative approach (Figure 2) and do so with reduced upfront carbon costs (Figures 4 and 5). Focusing thinning treatments in areas that have the highest probability of high-severity fire allows for a large reduction in the area thinned (7,267 ha reduction in the optimized scenario). However, achieving the reduction in mean fire severity (Figure 2) requires an additional area be treated with prescribed burning (4,523 ha) over the prioritized scenario. Treating the additional area with regular prescribed burning has the effect of reducing surface fuels and maintaining a lower density of small trees that facilitate the movement of fire from the surface into the canopy. This yielded a mean net reduction in the carbon costs associated with treatment of 1.6 Mg • C • ha^{-1}. While the carbon costs of treatment will vary by geographic location and ecosystem type, identifying areas where the most carbon costly treatments

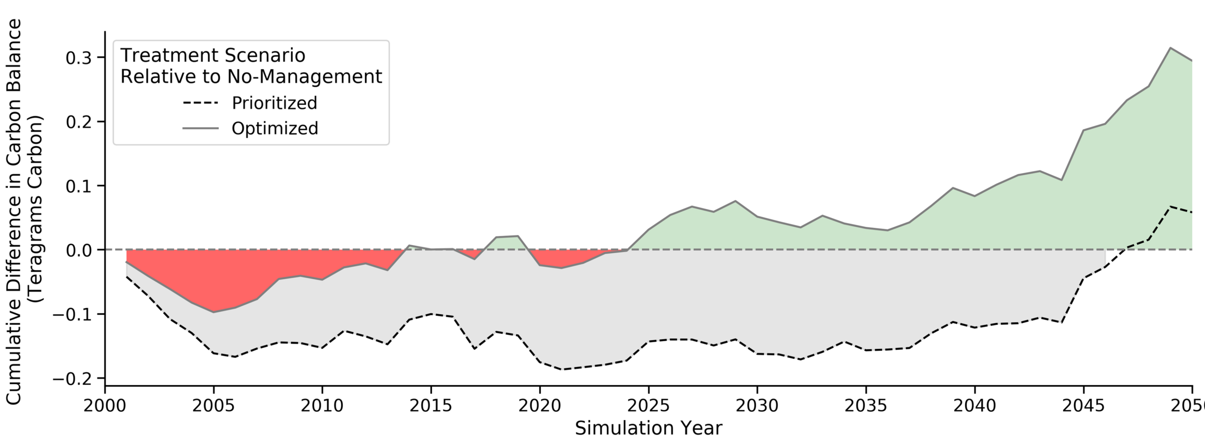

Figure 5. Cumulative net ecosystem carbon balance (NECB) of the prioritized (dashed black) and optimized (solid gray) scenarios, relative to the no-management scenario (0 line), for the entire Santa Fe Fireshed. Positive values indicate the management scenario landscape a had greater NECB relative to the no-management scenario due to the balance of carbon (C) into the ecosystem from photosynthesis and C lost from the system due to thinning, prescribed burning, and wildfires.

(e.g., thinning) will yield the greatest benefit in terms of reducing high-severity wildfire risk, and augmenting these with additional prescribed burning will help reduce the upfront carbon costs of treatment.

Management at local scales is constrained by a range of biotic, abiotic, and human factors and objectives. In our simulations, we used the probability of high-severity fire as the only objective function to minimize, and executed the mechanical thinning of the landscape over the shortest feasible time frame, with regular maintenance using prescribed fire. This rapid transition toward an ecosystem structure resembling historical fire-maintained conditions resulted in increased carbon uptake efficiency and carbon stock accumulations at the scale of the landscape, relative to our no-management scenario (Figures 3 and 5). When operating in our dramatically simplified decision space, we found that optimally placing mechanical treatments to minimize the risk of high-severity wildfires accounted for nearly a three-fold increase in the overall net carbon benefit and cut the time to realize that benefit in half (Figure 5). When optimizing forest management activities to meet a single objective, research in other geographic locations has also demonstrated that fewer management inputs are required when the treatment locations are determined using a quantitative approach (Barros et al., 2019; Chung et al., 2013; Krofcheck et al., 2018, 2019). However, working within place-based abiotic, biotic, and human constraints to achieve societally desirable objectives oftentimes requires balancing competing objectives.

The multivariate decision-making space for forest management in the western United States includes minimizing wildfire hazard for communities, habitat provision for protected species, and water quality and quantity, among others. In the case of the Santa Fe Fireshed and other forested watersheds of the southwestern United States, a century of fire-exclusion, nearly 2 decades of extreme drought, and warming have increased high-severity wildfire risk (Hurteau et al., 2014; Singleton et al., 2019; Swetnam & Brown, 2011). In this water-limited region, streamflow invariably increases following high-severity wildfires due to decreased infiltration and decreased vegetation water use (Bart, 2016; Wine et al., 2018; Wine & Cadol, 2016). However, the measured increase in water yield from severely burned watersheds following precipitation events is paired with a significant detriment to water quality, which has cascading negative impacts on wildlife, riparian biodiversity, and ultimately the provision of municipal water from forested landscapes (Cooper et al., 2015; Jackson et al., 2012; Jones et al., 2016; Murphy et al., 2018).

Thinning treatments and the reintroduction of frequent surface fires help restore a more heterogeneous forest structure and reduce the probability of high-severity wildfires (Figure 2). These forest conditions are correlated broadly with increased forest productivity and biodiversity (Barros et al., 2017; Spies et al., 2017). Yet, a restored forest structure beneficially affects nearly every aspect of ecosystem function and the corresponding services that forests provide. Forests that experience fire on an interval close to the historic norm tend to show increased productivity over time, in part as a result of the increased tolerance to biotic and abiotic disturbance afforded by size, age, and species heterogeneity (Kerhoulas et al., 2013; Voelker et al., 2019). At the scale of the landscape, this can result in greater water use efficiency, increased carbon sequestration, and increased water availability (North & Hurteau, 2011; Roche et al., 2018). Thus, the opportunity exists to manage for a suite of ecosystem services and meet a range of societal objectives by a priori evaluation of the factors that pose the largest risk to ecosystem services in frequent-fire forests across the western United States.

Encouragingly, our simulation results suggest the potential for management to stabilize the provision of ecosystem services even in semiarid landscapes that have an increased likelihood of high-severity fire. Further, when treatments are optimally placed, the carbon losses from treatment can be minimized, and the NECB maximized under projected climate change (Figures 3 and 5). While management decision-making is rarely univariate, understanding the carbon consequences of forest management is important as society seeks to mitigate climate change and begins to price these activities (Fargione et al., 2018; Griscom et al., 2017; Verdone & Seidl, 2017).

The work we present here suggests the potential for collaborative fuels and fire management efforts to leverage simulation modeling to build on or optimize the impact of place-based fuels treatment strategies. Here, we incorporated a modeled probability of high-severity fire risk to both determine the location of treatments and to broaden the extent of prescribed burning to restore ecologically appropriate fire into areas that otherwise were not planned to be treated. Given the increasing use of collaborative planning to implement forest management activities that meet a suite of societal objectives (Schultz et al., 2012), this approach can help inform decision-making by providing insight into the potential for planned activities to meet desired goals.

Our approach can be applied in other ecosystems that have seen a departure from their historic fire regime. Prior research in a Sierran mixed-conifer forest has demonstrated the value of integrating existing management plans with modeling to ask specific questions about the impacts of using mechanical thinning or prescribed burning in isolation or in combination (Krofcheck et al., 2017) and has shown that constant application of prescribed burning is required to maintain the initial gains in reducing high-severity fire risk. Similarly, the utility of using a risk-based approach to efficiently allocate treatments has been demonstrated in a range of forest types, from pine plantations in the southeastern United States to conifer forests in Oregon (Ager et al., 2014; Krofcheck et al., 2018). Consequently, whereas the specific insights from this study broadly relate to southwestern frequent-fire-adapted landscapes, the strategic pairing of proposed management decision-making strategies with simulation modeling efforts can be used to ask specific questions regarding the potential for proposed treatments to interact with future climate, and may shed light on ways to maximize the impact of management while reducing the associated costs.

Our results should be considered in the context of the limitations of our simulation approach. The factors influencing the probability of high-severity fire in our study are ignition locations, fire weather, and vegetation. While we used random ignitions to develop the probability of a high-severity fire layer that informed the optimized scenario, human ignitions are a large contribution to the total number of fires and tend not to occur randomly on the landscape (Balch et al., 2017). Developing the probability surface with local fire start data would likely better inform the result. We developed our fire weather distributions using projected climate data to account for the projected increase in temperature and its effect on fuel moisture. However, extreme weather events (e.g., high winds, severe drought, etc.) can influence fire behavior and spread, and these are unaccounted in our fire weather distributions because of the resolution of the projected climate data and the influence that local topography has on wind. The distribution of vegetation on our simulated landscape is interpolated from remotely sensed and forest inventory data. As a result, the vegetation conditions, which influence fire behavior, at a given location on our simulated landscape likely deviate from reality. Improving the probability of the high-severity fire layer would require a more intensive field plot network in order to identify the exact locations that have the highest risk of high-severity fire. Further, simulated landscapes are much simpler than their natural counterparts and do not incorporate many of the real world and societal complications inherent to natural systems. Our simulation environment operated at the scale of 1 ha, and while this is spatially very highly resolved compared to most land surface modeling studies, the implications for how management activities are planned and executed needs to be considered. As an example, our simulations assumed that specific hectares of the landscape could be treated, either in isolation or in aggregate, and ignored the strategic usage of roads or importance of structures in placement of treatments and management of wildfires. While accounting for these additional factors would likely change the geographic location of some areas with a high probability of high-severity fire within a particular fireshed, the concept of using a risk-based approach to locating forest treatments will retain utility.

5. Conclusions

The current structure of forested landscapes of the southwestern United States have been shaped by a legacy of fire-exclusion, increasing the likelihood that changing climate and wildfires will significantly impact the ecosystem services these forests provide. Management activities to restore forest structural heterogeneity and ecologically appropriate fire regimes can help build forest adaptive capacity for dealing with ongoing climate change and help ensure the continued provision of ecosystem services. A data-informed approach to allocating management activities across a landscape provides the opportunity to minimize the costs and tradeoffs that are inherent in forest management. Further, building adaptive capacity into these systems facilitates their continued contribution to climate regulation through carbon uptake and storage.

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