11-2021

Planning for Future Fire: Scenario Analysis of an Accelerated Fuel Reduction Plan for the Western United States

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Citation Details

Ager, A. A., Evers, C. R., Day, M. A., Alcasena, F. J., & Houtman, R. (2021). Planning for future fire: Scenario analysis of an accelerated fuel reduction plan for the western United States. Landscape and Urban Planning, 215, 104212.

Landscape and Urban Planning 215 (2021) 104212

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Planning for future fire: Scenario analysis of an accelerated fuel reduction plan for the western United States

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HIGHLIGHTS

- We modeled a large-scale treatment scenario to reduce wildfire risk to communities.
- The plan treated 77% of the predicted exposure from manageable national forest land.
- Treatments targeted 6.6 million ha scheduled over 10 years.
- Projected wildfire encounters with treated areas was substantial.
- Wildfire was predicted to impact 20% of the planning areas prior to implementation.

ARTICLE INFO

Keywords:
Scenario planning
Wildfire uncertainty
Wildland urban interface
Forest fuel management
Wildfire transmission to WUI

ABSTRACT

Recent fire seasons brought a new fire reality to the western US, and motivated federal agencies to explore scenarios for augmenting current fuel management and forest restoration in areas where fires might threaten critical resources and developed areas. To support this effort, we modeled the scheduling of an accelerated forest and fuel management scenario on 76 western US national forests. Specifically, we modeled a 10-year ramp up of current forest and fuel management that targeted the source of wildfire exposure to developed areas and simulated treatment in areas that accounted for 77% of the predicted exposure. We used a sample of 30 future fire seasons to understand how the plan might be impacted by wildfires and treatment. We found that once fully implemented more than 20% of simulated fires on national forests overlapped fuel treatments, and that roughly 20% of the projects were burned prior to their implementation, suggesting that any plan will undergo significant revision during implementation. Treated areas intersected by wildfire accounted for twice the exposure than non-treated areas that also burned. The study demonstrates the use of scenario planning to design a fuel treatment program that targets wildfire exposure to developed areas, and the methods pave the way for expanded use of scenario planning science to analyze and communicate large scale expansion of current forest and fuel management initiatives.

1. Introduction

Wildfire impacts continue to grow in the western US, driven by social and biophysical processes that include an expanding wildland urban interface (WUI, Radeloff et al., 2018), increasing fire occurrence from human ignitions (Abatzoglou, Balch, Bradley, & Kolden, 2018; Balch et al., 2017; Nagy, Fusco, Bradley, Abatzoglou, & Balch, 2018), changing climate (Abatzoglou & Williams, 2016; Littell, McKenzie, Wan, & Cushman, 2018; McKenzie & Littell, 2017) and fire exclusion policies on national forests (Cohen, 2008). In recent years, regional droughts (Littell, Peterson, Riley, Liu, & Luce, 2016) coupled with high-winds and untimely ignitions (Abatzoglou et al., 2018) increasingly spawned large

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https://doi.org/10.1016/j.landurbplan.2021.104212
Received 17 February 2021; Received in revised form 19 July 2021; Accepted 31 July 2021

and destructive fire events in the western US and in other fire prone regions including Australia (Filkov, Ngo, Matthews, Telfer, & Penman, 2020), Portugal (Ribeiro, Rodrigues, Lucas, & Viegas, 2020) and Greece (Molina-Terrén et al., 2019).

US federal fire initiatives continue to evolve in response to fire impacts and most recently have focused on increasing investments to coordinate fuel management among ownerships (federal, state, local, tribal, NGOs and private) to reduce cross boundary risk transmission from public lands to developed areas (Ager et al., 2021; USDA Forest Service, 2018). The core concept is that coordinating fuel management across boundaries is required to mitigate increasingly large fire events on landscapes fragmented by administrative and ownership boundaries (USDA Forest Service, 2018). Numerous modeling and empirical studies over the past decade have supported the idea that coordinated fuel management can have substantial impacts on fire in terms of reducing spread and intensity, although treatment extent, intensity, time since treatment, and fire weather are all important factors that ultimately determine if treatments are effective (Finney, McHugh, & Grenfell, 2005; Finney et al., 2007; Kalies & Yocom Kent, 2016; Price & Bradstock, 2012; Prichard, Povak, Kennedy, & Peterson, 2020). Despite evidence of treatment effectiveness, widespread implementation over the past 10 – 20 years on US public forests has not reduced losses to developed areas or firefighting costs, leading some to speculate that their density is insufficient to build landscape scale immunity (Barnett, Parks, Miller, & Naughton, 2016; Schoennagel et al., 2017). Fuel management programs face many challenges in terms of logistics and feasibility on western US national forests where substantial area is not targeted for fuel management due to legal, operational, and administrative regulations (Ager, Day, Short, & Evers, 2016; North, Collins, & Stephens, 2012). Evaluating the long-term merits of federal and state fuel management programs under non-stationary fire regimes (Littell et al., 2018) and across large landscapes that include areas where treatments are not implemented complicates the evaluation of existing programs.

Despite uncertainty concerning the science and application of fuel management programs, policy discussions to substantially increase government funding and expand implementation are gaining momentum in the US and elsewhere, especially in locations like California where the 2020 fire season burned a record 1.7 million hectares. As in the broad disaster mitigation literature, these deliberations and development of investment strategies could benefit from scenario planning tools to provide decision support to illustrate, envision, and analyze broad scale management scenarios (Linkevičius et al., 2019), and the future impacts of fire on their implementation (Peterson, Cumming, & Carpenter, 2003; Spies et al., 2014). Specifically, tools are needed that can utilize national scale risk assessments and build provisional scenarios that describe spatiotemporal treatment schedules, with some indication of the risk of planning including variability in wildfire impacts during and after implementation. For public land management agencies, spatially explicit scenarios are the blueprint to communicate conservation and restoration plans to key oversight agencies and stakeholders in policy planning (Eaton et al., 2019; Riddell, van Delden, Maier, & Zecchin, 2019; Xiang & Clarke, 2003), and in the case of wildfire, these scenarios have heretofore been absent from prior major wildfire initiatives (USDA-USDI, 2001; USDA Forest Service, 2015b, 2018). Scenario planning further provides a platform for exploring the effectiveness of large landscape restoration and risk mitigation efforts against a background of highly stochastic events such as wildfire. Although there are numerous small scale studies with forest landscape disturbance models that have simulated fuel management scenarios and wildfires (Spies et al., 2017; Syphard, Scheller, Ward, Spencer, & Strittholt, 2011), their limited scale and scope make them inadequate to inform a national dialogue with policymakers that are interested in ramping up fuel management programs at state, regional, and national scales.

Towards this end, we used a scenario planning model and supporting national data to test a 10-year accelerated large-scale fuel management scenario commensurate with the scale of the wildfire problem across 76 western US national forests (58 million ha). The specific treatment scenario was motivated by discussions with senior agency leaders to support potential revisions to the 2000 National Fire Plan (Babbitt & Glickman, 2000), and address the growing losses from recent wildfires. We examined how a specific priority to reduce wildfire transmission from national forests to developed areas would materialize in terms of a 10-year treatment schedule. We designed the scenario to replicate current practices in terms of the types of fuels and locations where national forests are currently treating, focused on addressing building exposure from fires ignited on national forest lands. We then analyzed how simulated future wildfire scenarios intersected spatially with fuel treatments during and after the 10-year treatment period. The methods are readily extendable to other public and private land mosaics in the US and in other fire prone regions where national scale fuel treatment plans are under development (AGIF, 2020).

2. Methods

2.1. Study area

The study area encompasses the 76 national forests (NF) of the 15 western and central US states (Fig. 1; Forest Service regions 1–6), and the adjacent developed areas as defined below. The national forest land within our study area covers over 58 million ha and contains a diverse array of forest and rangeland ecosystems. About 40 million ha are forested or woodland and 26.8 million ha are fire adapted forests. Protected areas such as wilderness, roadless and nationally designated protected areas make up 50% of the total area. The forests contain a wide array of fire regimes, ranging from fire adapted forests (forested areas with fire return intervals $<$ 35 years), to areas with historical high severity fire, or $>$ 200-year fire return intervals. The national forest network is dissected by numerous mountain ranges including the Rockies, Sierra Nevada, and Cascades, creating pronounced gradients in vegetation, climate, and fire regimes. The Forest Service currently conducts active forest management on around 405 thousand ha per year within the study area.

2.2. Methods overview

The scenario reported here was formulated at several management engagement sessions with senior leaders in the Forest Service during 2020 and 2021. The sessions were conducted to identify specific objectives for an accelerated fuel management program and to use that objective to build, illustrate and communicate a western US treatment scenario for the Forest Service. The engagement session lead to the decision that cross boundary wildfire exposure to developed areas should be the target of forest and fuel management. Accordingly, the treatment scenario used in the study was designed to target treatments to areas predicted to be the source of wildfire exposure to buildings as measured in prior work using wildfire simulation modeling and building footprint data. In brief (detailed methods provided below), the predicted building exposure data were first used to compartmentalize the study area into 10,000 ha project areas that represent implementation units consistent with the current planning processes and conforming to NEPA requirements. We then used the scenario planning model ForSys (Ager, Houtman, Day, Ringo, & Palaiologou, 2019) to apply treatments in each project area until 80% of the total predicted exposure was treated. Note that we did not actually simulate treatments in terms of changing the fuels and vegetation as in previous work (Ager, Vaillant, & McMahan, 2013), and thus the results are framed as exposure treated, not exposure reduced. Current limitations in data and computational capacity preclude modeling fuel treatments and their effect on simulated fire behavior as done in small scale studies. Finally, we analyzed how simulated future wildfires intersected spatially with fuel treatments

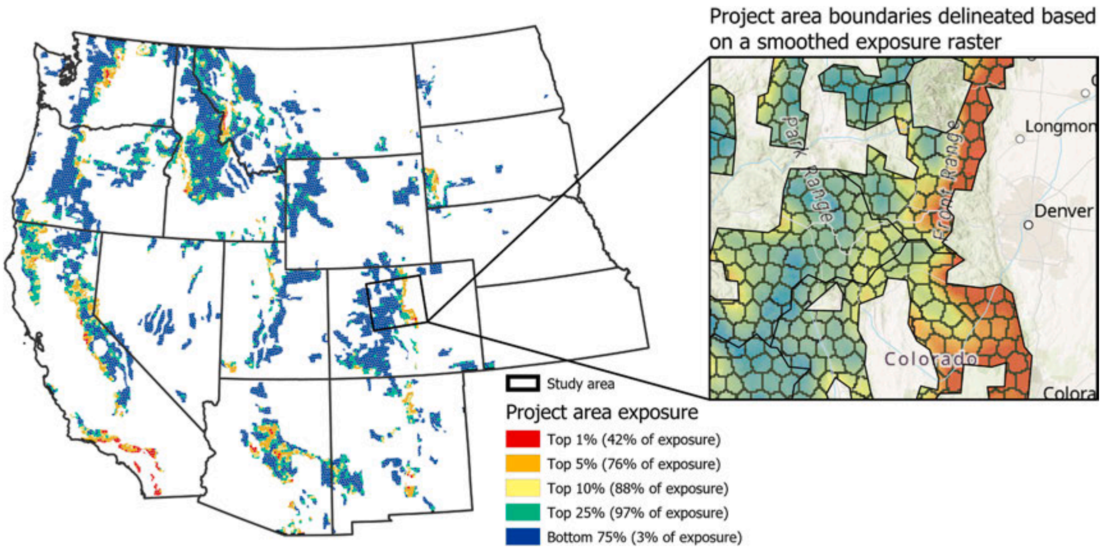

Fig. 1. Project areas and associated building exposure from ignitions within the project areas on national forest lands in the western US. The inset shows project area boundaries delineated using image segmentation of source areas of simulated wildfire exposure to buildings for northcentral Colorado.

during the implementation period and used this information to describe variability in future wildfire-treatment intersections.

2.3. *Estimating wildfire exposure to developed areas*

The process for estimating exposure to buildings from wildfires that ignite on national forests is described in detail in Ager, Palaiologou et al. (2019). Building exposure was mapped using the wildfire simulation data from the national FSim library (Short, Finney, Vogler, Scott, Gilbertson-Day, Julie, & Grenfell, 2020a; fire perimeters not publicly available) with 54 million simulated fires covering the western US and Microsoft building footprint data (Microsoft, 2018). The Short et al. (2020a) wildfire simulations used LANDFIRE 2014 fuel conditions (LANDFIRE, 2017) and the fire season scenarios were based on surface weather data for windspeed and direction, and national gridded weather data from North American Land Data Assimilation System (NLDAS; 1979–2012)(Abatzoglou, 2013). In contrast to prior versions of the library, the newer fire simulations used synchronized Energy Release Component (ERC) streams as described in Grenfell et al. (2010), which retain the spatial covariance structure and temporal auto-correlation of the NLDAS weather inputs. FSim simulates wildfires within large geographic units or “pyromes”, regions of relatively homogenous fire regimes (Short, Grenfell, Riley, &Vogler, 2020). Between 10,000 and 100,000 hypothetical fire season scenarios are simulated for each pyrome depending on the historical large fire frequency. See Appendix A for more details on the FSim model. We created a building centroid point file from individual Microsoft building footprint polygons ($n = 25$ million) (Microsoft, 2018), then intersected FSim fire perimeters with the building footprint data in ArcGIS, to tabulate the total number of buildings within each perimeter. Although FSim models firebrands and thus potential exposure to buildings outside of the fire perimeters, we excluded firebrand exposure due to limitations in the fire modeling system.

The resulting exposure values were attributed to FSim ignition points to predict exposure from ignitions at that location. The attributed ignition dataset was used to create a 90 m smoothed building exposure raster using inverse distance weighting in ArcGIS with a search radius of 2500 m and a power of 0.5, creating a building exposure grid based on the sum total of the ignitions over the 10,000 + fire seasons. To annualize the exposure data an ignition probability raster was created (ignitions/ha/yr) using the ArcGIS point density tool, with a 2500 m circular search radius and the population field set to ignitions per year. The exposure raster and ignition probability raster were then multiplied to create a final smoothed building exposure raster, in which each cell represents the expected annual number of buildings exposed by wildfire igniting in the surrounding hectare per year.

2.4. *Delineating project areas*

Forest and fuel management on US national forests are planned and implemented within planning or project areas, which are typically 12-digit hydrologic unit (USGS and USDA-NRCS, 2013) subwatersheds of size ranging from 5000 to 20,000 ha. We chose to develop an alternative project area configuration based on the exposure map described above to build equally-sized spatial units organized around the main objective of the scenario to treat exposure to buildings. The smoothed building exposure grid was then divided into project areas using an optimized version of Simple Linear Iterative Clustering (SLIC, Achanta et al., 2012). SLIC is an image segmentation algorithm based on a modified form of K-means clustering that includes an adaptive parameter that controls the compactness of the resulting segments. The delineation process resulted in 37,720 project areas each approximately 10,000 ha in size (Fig. 1).

We then created treatment units within each project area generated as hexagons using tessellation in ArcGIS. Small polygons < 5 ha in size were eliminated by merging with neighboring polygons. The resulting 5.2 million stands ranged in area from 5 to 118 ha, with a mean of 81 ha. We filtered the stands to identify suitable targets for forest and fuel management based on: 1) administratively available for mechanical management; 2) conifer forests; and 3) not disturbed by wildfire or past management activities. Availability was determined from protected areas identified using the USGS Protected Areas Database (USGS, 2019), corrected with USFS Roadless and Nationally Designated Areas (USDA Forest Service, 2017a; USDA Forest Service, 2017b). Non-conifer vegetation was removed using the data of Riley, Grenfell, and Finney (2016) processed with the Forest Vegetation Simulator (Crookston & Dixon, 2005; Dixon, 2002 Appendix B). Stands that were recently disturbed either by fire or management activities were flagged in MTBS (MTBS, 2020) and FACTS (USDA Forest Service, 2020), respectively. The disturbance filters removed stands that have been disturbed since the fuels layer used in the simulation layer was created (2015–2020). The resulting filtered stand list was then attributed with the building exposure grid described above to estimate exposure to buildings from fires ignited in that stand in the simulations by summing the exposure grid values for each stand.

Adding these filters for land administration (i.e., manageable) and vegetation (i.e., majority conifer) reduced the amount of exposure to developed areas that was available for management (Fig. 2)(Appendix A Table A1). Note that the initial total exposure was based on simulations completed with 2014 fuels data and we removed lands treated or burned since then to calculate total exposure potentially available to treat. These disturbed lands accounted for 16% of the total estimated exposure. Applying a management filter on the total remaining exposure (considered 100%, inner ring; Fig. 2), showed that removing wilderness and roadless, where only non-mechanical treatments (e.g., fire) are allowed, reduced treatable exposure from 100% to 66% (inner ring to middle ring, Fig. 2). Restricting fuel management to conifer stands reduced treatable exposure by an additional 31%. The resulting 35% of exposure was the land base for treatment (darker green segment of middle ring, Fig. 2).

2.5. Modeling the treatment scenario

We generated the treatment scenario with ForSys, a multi-criteria, hierarchical spatial planning model designed to explore landscape management scenarios for forest restoration and risk reduction. Prior application of the model has been described in a number of case studies in the US and the Mediterranean region (Ager, Houtman, Day, Ringo, & Palaiologou, 2019; Ager, Vogler, Day, & Bailey, 2017; Alcasena, Ager, Salis, Day, & Vega-Garcia, 2018; Botequim et al., 2014; Palaiologou et al., 2021; Salis et al., 2016). The model frames the planning problem as a single or multi-objective maximization with top down activity constraints, and treatment thresholds for each stand. The scenario modeled a 10-year plan, treating 80% of the treatable predicted exposure to buildings from national forests. Projects were prioritized based on the exposure in treatable areas, with preference for stands with the highest predicted exposure (see ForSys parameters in Appendix A Table A2). We assumed the appropriate treatment would be implemented, including thinning and broadcast/pile burning based on silvicultural prescriptions specific to local conditions. As noted above, we did not model changes in fuels or vegetation or post treatment fire behavior due to lack of data and computational limitations.

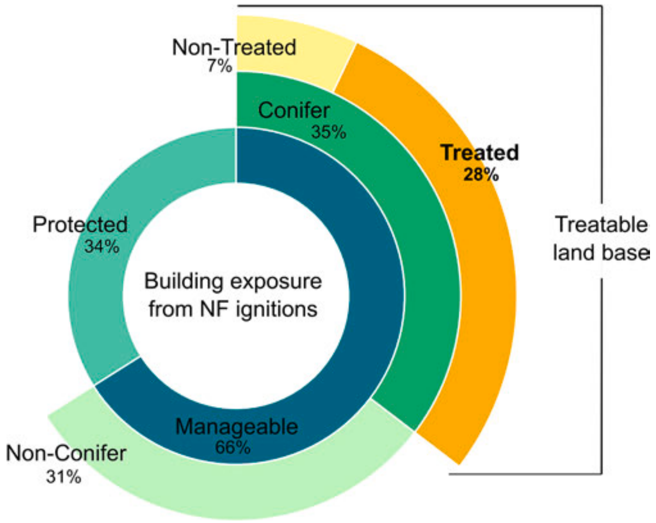

Fig. 2. The area targeted for treatment was built from progressive land base filters on national forest lands in the western US (Appendix A Table A1). Each outer ring is a subset of its inner ring. The final outer ring represents the land base used in the scenario in this study: conifer forest stands available for mechanical treatment (manageable) that have not been recently disturbed by wildfires or treatments (including wildfires as of October 2020), and the dark gold segment is what was treated in the scenario representing 80% of total treatable exposure (yellow segments). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For simplicity, we assumed that the treatment scenario would be implemented independently of the current treatment program (Vaillant & Reinhardt, 2017). Further, the treatment scenario included a hypothetical ramp up period to include time for typical planning required by government entities (e.g., National Environmental Policy Act (NEPA, 1969) in the US), and to build capacity to implement projects. The modeled rate of treatments and other aspects of the scenario in terms of required agency capacity is illustrated in Fig. 3. Follow-up maintenance treatment (primarily broadcast burning) was applied at intervals drawn from a normal distribution with a mean of 15 years and a standard deviation of 5 years, corresponding to an average fire return interval for western forests (e.g., fire regimes 1 and 3). The retreatment was applied over 60 years to illustrate that implementation of the plan will require substantial investment in future decades to maintain fire resilient conditions (Prichard, Stevens-Rumann, & Hessburg, 2017). Note that the specific effect of the treatments on fuels and vegetation was not simulated spatially, but rather tallied as area treated to illustrate a maintenance treatment schedule.

2.6. Analysis

Area and exposure treated were summarized at multiple scales (study area, national forests, project areas) to understand the rate of exposure at different scales. To understand the spatial dynamics of the treatment plan within and among project areas and national forests, the frequency distribution of selected priority project areas among national forests was graphed by implementation year. This analysis illustrates how the program of work shifted spatially among and within forests through the implementation as a consequence of the prioritization schema.

To understand the relative effects of wildfire versus treatments and their intersection during the 10-year treatment implementation and an additional 10 years of re-treatment, we randomly sampled 600 fire seasons from the FSim library (Short et al., 2020a) and randomly assigned these to 20-year wildfire scenarios, resulting in 30 replicate future wildfire scenarios. Thus, each replicate represented a plausible 20-year future wildfire scenario. Boxplots indicated the 30 replicate future fire scenarios exhibited similar inter-replicate variance as larger samples from the fire simulation library, although there were fewer outliers (Appendix A Fig. A2). Additional validation that the 600 fire season sample adequately represented the complete 10,000 fire seasons is described below.

We intersected the fire perimeters with the treatment units as they were implemented over the 10-year period and tallied the area of intersection. The process was completed year by year, such that as treatments accumulated over time, more area was available to intersect with the simulated wildfire footprints. Overlapping wildfire footprints

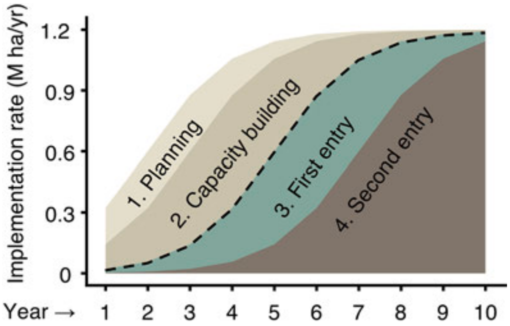

Fig. 3. Hypothetical scenario to accelerate forest and fuel management in the western US showing a ramp up period to account for NEPA planning, workforce capacity, project sale layout, and contracting.

were eliminated under the assumption that the earlier fire burned first and did not re-burn. From the fire and fuel treatment intersects we quantified the area and timing of overlap during the implementation period and 10 years following implementation. These outputs were used to measure: 1) the number of project areas affected by fire before they were scheduled to be implemented; 2) the area burned within scheduled treatments before they were treated; 3) the area treated before the stand experienced a wildfire; and 4) the total area burned that was not part of the scheduled treatments. These comparisons were examined for both the land base that was available to treat as defined in this study (outer yellow ring, Fig. 2) and all national forest lands. The latter included wilderness and roadless areas that cover almost 50% of the national forest land and for that reason substantially dilute the estimates of wildfire treatment overlap (#2 above).

To ascertain whether the sample size was sufficient to represent the parent 10,000 fire seasons in the entire FSim library, we used the annual burn probability grids generated by FSim simulations to calculate the expected wildfire-treatment overlap. Note that this alternative method does not allow estimation of inter-scenario variability which was a key output in the assessment of future fire impacts, nor does it account for the self-limiting effect of multiple large fires burning in short sequence within the same area. We calculated the annual expected area burned according to prior work (Scott, Helmbrecht, Thompson, Calkin, & Marcille, 2012) for each FSim 270 m pixel as:

$$\text{Annual expected area burned} = \text{BP}^{*}\text{Area} \tag{1}$$

where BP = the burn probability of the pixel. The average expected annual area burned for each stand was calculated as the average of the 270 m gridded outputs and then summed over a 10-year total. We then calculated the area of overlap between the simulated area burned and the implemented treatments over 10 years as done for the 30-replicate sample.

3. Results

3.1. Implementation schedule

The 10-year initial treatment phase treated 6.6 million ha of high-exposure conifer forests available for active management within 3,475 project areas (Appendix A Table A3). The rate at which exposure was treated under the scenario was highly non-linear with 66% of the exposure treated within the first six years at the scale of the study area (Fig. 4A, B). The number of projects implemented increased over time, especially after year four. The increase in the annual number of projects was a function both of the ramp up in area treated over time, but also the decrease in the average area treated within each project, which required more projects to meet the annual target (Fig. 4). The area treated per project was highest at the start of the scenario, where high exposure stands were selected initially, then declined as successive project areas had either less exposure or an increasing number of constraints that limited the extent of management (Fig. 4B, D). Over time these constraints included (a) a decrease in the amount of national forest within the project area, (b) an increase in the portion of the project where equipment access is limited or banned, and (c) an increase in the portion of non-forested or non-conifer stands (Appendix A Fig. A6). Retreatment peaked approximately 20 years after initial treatment, and as the first round of maintenance treatments began to ebb around year 25, the second round began to ramp up, resulting in sustained maintenance at about 2.6 million ha per year (Fig. 5).

At the national forest (NF) scale, the response in terms of exposure treated varied substantially with area treated (Appendix A Fig. A3), as did the total area requiring treatment corresponding to 77% of the exposure. The San Bernardino and Prescott NFs had the highest rate of exposure treated per hectare although not the highest total amount of exposure to treat (exposure was relatively more concentrated), whereas the Shasta-Trinity shows one of the least efficient treatment effects on exposure per hectare despite receiving 141,640 ha of treatment. All of the top 10 NFs (in terms of exposure treated) except the San Bernardino had projects implemented in all 10 years (with the exception of year 1 reserved for planning). However, seven NFs showed similar treatment rates where about 3% of the total exposure is treated on the first 16,000 ha. The remaining three NFs showed widely different treatment efficiencies (Appendix A Fig. A3).

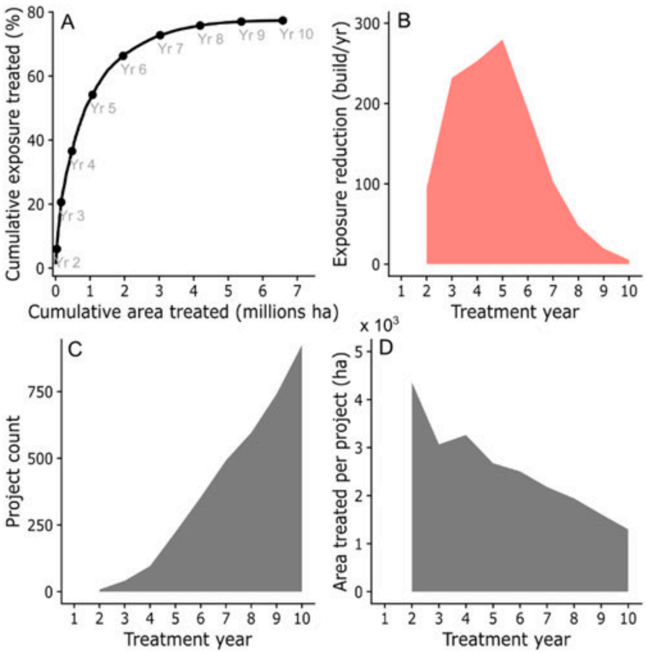

Fig. 4. Schedule of treatment implementation and the resulting treatment rate on A) cumulative building exposure treated, B) exposure treated per treatment year, C) project count, and D) area treated per project.

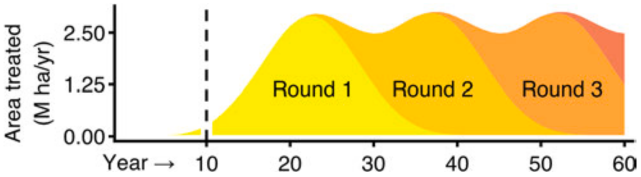

Fig. 5. Hypothetical 60-year schedule of maintenance re-treatments after the initial 10-year implementation to maintain fire resilient conditions. Fuel treatment scenarios need to consider a long-term strategy rather than a single treatment since their effectiveness decays over time (Kalies & Yocom Kent, 2016). Re-treatment assumed every 10 years with dithering to account for the fact that re-treatment schedules are not implemented on precise timeframes due to uncertainties in burning windows and other operational factors. Although not explicitly simulated, re-treatments are primarily broadcast burning in fire adapted forests, which constitute the majority of the treated area in the scenario (Jain, Battaglia, Han, Graham, Keyes, Fried, & Sandquist, 2012).

3.2. Spatial dynamics among and within national forests

Treatment occured over five years for 70% of the forests (Fig. 6A), and over 75% of forests would need to implement > 5 projects per year (Fig. 6B). The total number of projects implemented within a national forest was > 64 for 75% of forests (Fig. 6C). In general, the treatment area in forests that were treated over multiple years was greater than those with shorter implementation horizons (Fig. 6D). Thus the space–time schedule realized from the prioritization can be characterized as 8 project areas treated per forest in a given year, on average about 46 project areas treated within the 10-year time frame, implemented in 5–6

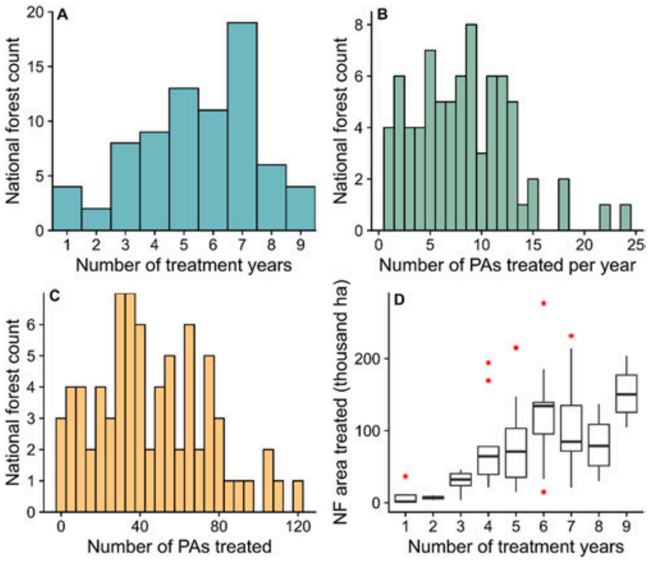

Fig. 6. Distribution of priority project areas (PA) among national forests (NF) and by implementation year. A) Number of years a national forest contained an implemented project; B) number of project areas treated on national forests in a given year; C) number of project areas treated within a national forest; and D) area treated on national forests versus number of years projects were implemented within the national forests.

years.

Mapping the ten-year treatment plan (Fig. 7) shows concentrated areas of treatments located in central Washington, southwestern Oregon, the Sierra Nevada, and the Colorado Front Range. Note that entire project areas are symbolized, which represents a larger area than the stands that were actually treated. On average, 44% of the available land base area received treatments within each project area. The map shows that in general, a larger number of project areas are implemented in the later years of the simulations, a finding that is investigated further below. Example maps of the selected planning areas at a finer scale (Appendix A Fig. A4), using California as an example, show the distribution of priority project areas was also highly clustered around the northern, central, and southern Sierras. Treatments for a single project area (Appendix A Fig. A5) showed a clustering of selected stands that treated the area responsible for 80% of the exposure on 4,905 ha (63 stands).

Across all Forest Service regions, the 10-year treatment plan led to large shifts in area treated among the NFs in each region (Fig. 8) illustrating that a dynamic workforce would be needed to implement the scenario. Forests that were allocated treatments in earlier years generally had the highest predicted building exposure values, but in many cases had relatively few treatable hectares. This resulted in treatments being concentrated in the early part of the plan followed by a steady decrease (e.g., Okanogan-Wenatchee, Region 6). In other cases, the treated area for NFs increased over the implementation window (e.g., Kootenai, Region 1), which given the ramp up in area treated over time, represents a multiplicative increase in actual area treated. These different treatment allocation patterns were the consequence of how project areas were prioritized among the NFs, which were based on the amount of exposure that could be addressed through treatment.

3.3. Treatments versus wildfire during implementation

A total of 6.6 million ha of treatments were implemented over a 10-year implementation period, which was then followed by the 10-year assessment period during which treatments were maintained and fires continued. The geographic overlap between treatment and wildfire activity varied widely among the replicates. Over the entire 20-year period, area burned on national forests ranged from 0.04 to 1.99 million ha per year among the 30 replicates (mean = 0.40 million ha per year, CV = 64%). During this period, between 10% and 62% burned within the targeted land base for treatments (i.e., outer ring Fig. 2), which included stands that were both manageable and majority conifer (mean = 31%, CV = 23%).

To assess overlap between wildfire and treatments we first determined whether areas burned more than once during the 20-year fire season scenarios. On average, <1% of annual fire perimeters fell in areas that had previously burned (range: 0.6% − 12%; CV = 9%). Re-burned areas were excluded from the subsequent estimates of treatment effects. Across the 30 replicates, over the ten year period, between 3% and 7% of the 6.6 million ha of scheduled treatment burned before being implemented (mean = 5%, CV = 21%), which represents up to 20% of the projects. Once fully implemented (i.e., wildfires occurring between years 10 and 20), between 2% and 34% of the total annual area burned on all national forest land was within areas that had received treatments (i.e., wildfire after treatment) (mean = 15%, CV = 27%). When considering fire that burned only on manageable, majority conifer stands (i.e., the targeted land-base), this range increased to between 27% and 62% (mean = 46%, CV = 13%) (Fig. 9A). The effectiveness of treatments was greater when evaluated in terms of building exposure. The 6.6 million ha of treatment intersected between 2% and 59% of annual predicted exposure originating on western national forests in a given year (i.e., wildfire before treatment)(mean = 24%, CV = 52%), and between 23% and 88% of that portion of annual exposure specific to fire on manageable, majority conifer stands (mean = 67%, CV = 14%) (Fig. 9B).

Validation of wildfire and treatment overlap with the complete 10,000 fire seasons using burn probability as described in section 2.6 showed that the estimated overlap between simulated wildfires and treated areas from the 30 replicate sample on lands targeted for treatments was within 0.7% of the entire FSim sample (15% versus 14.3%; Appendix A Table A4). On the larger land base (all national forest lands) the estimated overlap from the 30-replicate sample on lands targeted for treatments was within 9% of the entire FSim sample (46% versus 54%; Appendix A Table A4). We expected a slightly larger estimate from the burn probability analysis given overlapping fire perimeters were excluded in the 30 replicate scenarios.

Wildfire-treatment intersections were further investigated by examining the relationship between fire frequency and degree of overlap between area burned and area treated (Fig. 10). As detailed in the methods, this process was implemented in a sequential process where the fires were overlayed with treatments as both disturbances occurred year by year during the implementation. Overlap between successive fires was eliminated with preference given to the earlier fire in terms of burned area. The annual percent was calculated separately for fires on the entire national forest versus only targeted lands. The results showed that nearly 60% of fires overlapped at least some treated area (Fig. 10, labeled a), that more than half of these fires had at least 50% overlap with treatments (Fig. 10, labeled b) and about 20% of fires on the treatable or target national forest land base had 100% overlap with treatments (Fig. 10, labeled c). When looking at the proportion of annual fires on the entire national forest (including wilderness), these numbers are 25%, 15% and 2% respectively (Fig. 10, a-c on red line).

4. Discussion

The multiple US federal initiatives to scale-up fuel management to protect communities from wildfire (Charnley, Spies, Barros, White, & Olsen, 2017; USDA Forest Service, 2015a, 2018) can benefit from scenario analyses to design, test, and communicate policy options and describe how future wildfire regimes might impact policy implementation. The key findings of the study include: 1) up to 20% of the project areas scheduled over a 10-year period were affected by fire before being implemented, meaning that the planning analysis in the project could

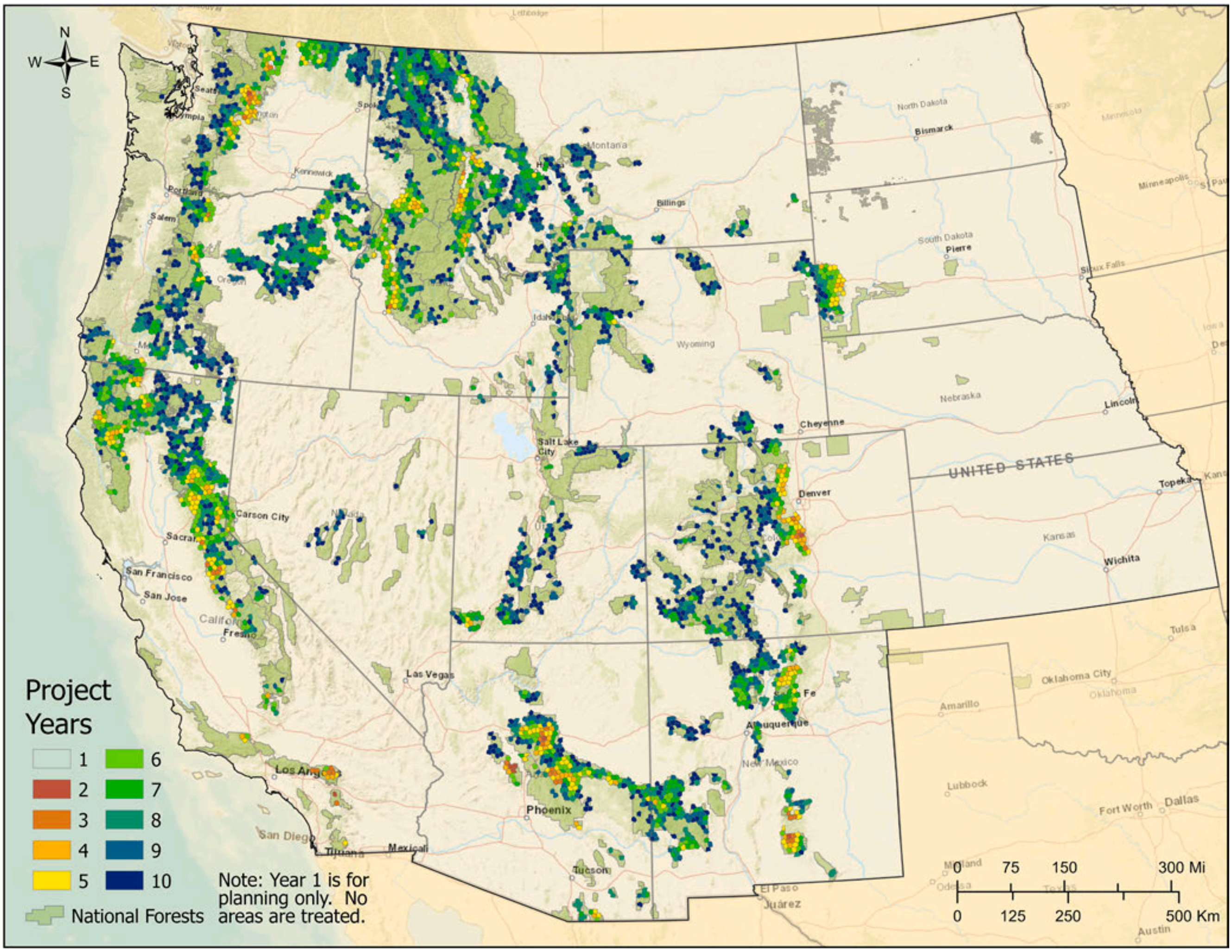

Fig. 7. Map of ten-year western US national forest treatment plan with projects symbolized by treatment year, with highest priority projects implemented in year 2 and year 1 reserved for planning (Fig. 3). Note that entire project areas are symbolized rather than the individual stands treated. See Appendix A Fig. A4 for finer scaled map of California.

potentially be voided by wildfire disturbance and the project delayed or cancelled; 2) wildfire affected a substantial portion outside of the planned treatments, suggesting that wildfire will contribute to loss during the plan implementation; 3) annual area burned and resulting building exposure varied widely among replicate future fire scenarios; and 4) on lands targeted for treatments, fires intersected substantial treated area. Note that our estimate of the effect of fire on planning is underestimated since we assumed a 1-year implementation period for a given project area, whereas in practice treatments are carried out over longer (2–7 year) timeframes.

Results from this study contrast with other studies that have concluded that treatments rarely encounter wildfires (Barnett et al., 2016; Boer, Price, & Bradstock, 2015; Dunn et al., 2020; Schoennagel et al., 2017; Thompson, Riley, Loeffler, & Haas, 2017), and therefore are ineffective as a general mitigation strategy (Schoennagel et al., 2017). Rather, we found that between $< 0.01\%$ and 3.5% of treatments were burned by wildfire each year once treatments were fully implemented (mean $= 0.5\%$). Over a 10-year period, 5% to 13% of treatments burned (mean $= 9\%$). However, an alternative way to examine the issue is to quantify wildfire encounters with fuel treatments (Syphard et al., 2011), versus treatments with wildfires as in the studies cited above. Evidence from the Agency Fuel Treatment Effectiveness Monitoring database (IFTDSS, 2021) where actual wildfire encounters with hazardous fuel treatments are recorded during wildfire incidents shows, for example, that between 2018 and 2020 over 2000 fires either intersected with USFS fuel treatments and/or were used by management, and changed wildfire behavior and/or helped control wildfire. Moreover, in the simulated treatment scenario, we found about 60% of fires each year encounter some treatment and 40% of fires burn where treatments accounted for over 50% of the burned area. Perhaps the low relative frequency of treatments encountering wildfires reported in the cited studies is because of their cumulative effect at slowing fire on landscapes with a high density of treatment units. In addition to these observations it is important to recognize that there are manifold objectives for restoration treatments in fire frequent forests, even if they do not burn (Stephens et al., 2021), and fuel management is a strategic precursor on fire-excluded landscapes to return low cost, large-scale prescribed and resource objective fire. Bioregional variation in encounter rates range from near 0% for coastal forests (fire return intervals exceed 500–700 years) in the Pacific Northwest, to $> 25\%$ in more fire prone regions, and thus national averages (Barnett et al., 2016; Schoennagel et al., 2017) obscure local situations where wildfires regularly burn into treated areas (IFTDSS, 2021).

As part of the scenario we analyzed the spatial schedule of project areas and found that over the implementation period, projects became increasingly complex in terms of land ownership, management restrictions, vegetation states, and fire regimes (Appendix A Fig. A6). This suggests that the highest exposure to communities occurs in a fairly

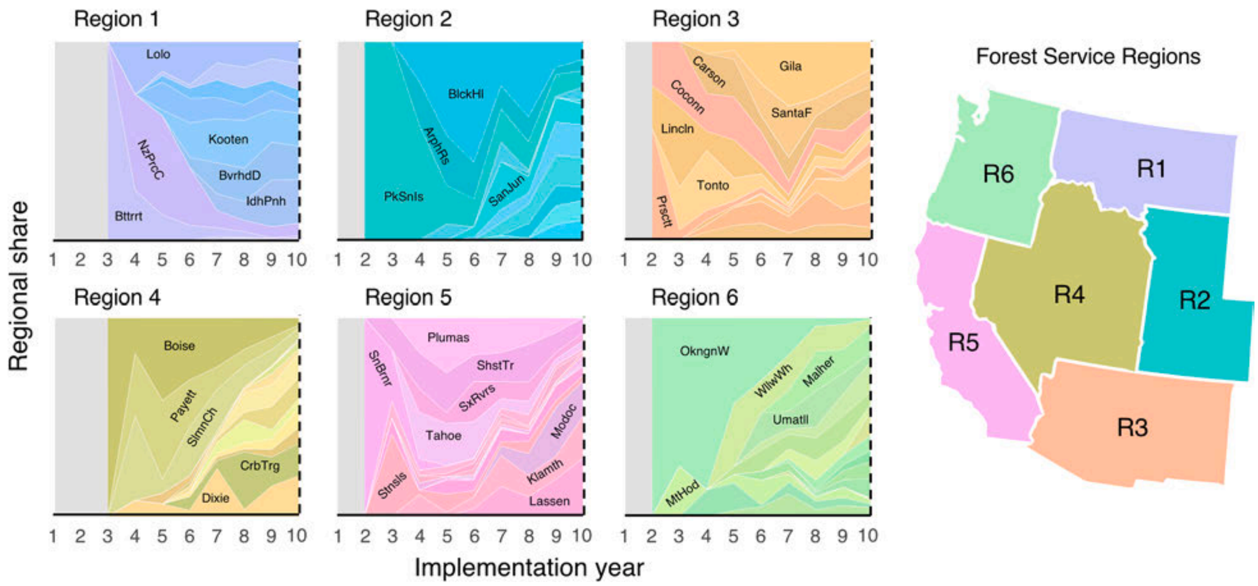

Fig. 8. Variation among national forests in percentage of area treated over the ten-year management plan in the western US. Data show the relative proportion of treatments allocated to the different national forests within each Region over the planning cycle. Note that no regions received treatments in year 1 and only some regions received treatment in year 2.

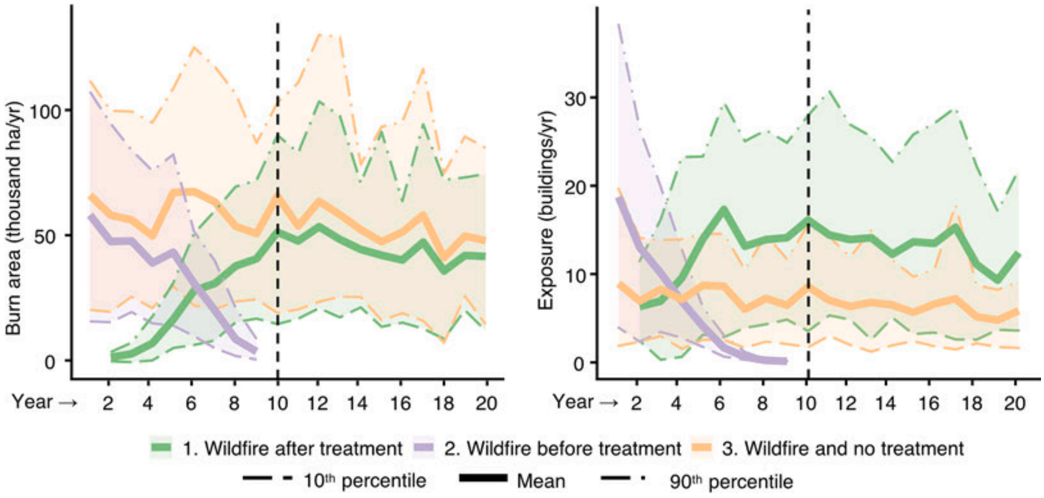

Fig. 9. The projected intersection between wildfire and treatment on the treatable land base (Fig. 2) is shown over the 20-year scenario as measured by A) area burned and B) annual building exposure. Trends (mean, 10th and 90th percentiles) are shown for: 1) wildfire that occurred after treatments (green), 2) wildfire that occurred before scheduled treatments (purple), and 3) wildfire that did not intersect treatments (orange). Year 10 is indicated in both panels as a dashed vertical line when treatments are fully implemented. The left panel illustrates that on average an equal area of treated (green solid line) and untreated (orange solid line) area burns each year after year 10. By contrast, the right panel illustrates that more than twice as much exposure is treated vs untreated, although treated exposure varies substantially among fire scenarios (transparent green ribbon). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

narrow physiographic and ecological setting, one that will need to be expanded to treat a larger proportion of the exposure. Expanding to all lands (Charnley et al., 2017) would lead to a different priority map (Ager, Palaiologou et al., 2019), and the potential to use cross boundary authorizing environments created in recent legislated initiatives (USDA Forest Service, 2018). The spatial schedule also revealed that the top-down application of a specific priority creates a plan that includes substantial shifting of investments for treatments among national forests during implementation (Fig. 8). While the model used in this study has the capacity to pro-rate specific treatment levels to geographic subunits and thus eliminate irregularities in the schedule, our objective was to apply a benchmark treatment scenario to optimize the application of treatments to reduce exposure to developed areas, and then observe the resulting shift in the spatial schedule.

Our treatment scenario focused on forest fuel reduction (Reinhardt, Keane, Calkin, & Cohen, 2008), which is the primary silvicultural method for reducing wildfire risk as part of the expansive restoration programs on western US national forests (Stephens et al., 2021; USDA Forest Service, 2015a). Fuel management programs can restore fire on fire-excluded landscapes, improve control, reduce building loss and generate positive ecosystem benefits (Kalies & Yocom Kent, 2016). However, fuel management scenarios are one part of a multifaceted solution to the fire problem in the western US, and treating fuels to solve the wildfire problem is ultimately an exercise in futility without concomitant policies to harness naturally occurring, resource objective wildfires (Huffman, Roccaforte, Springer, & Crouse, 2020) to simultaneously treat fuels, restore fire resiliency, and reduce the fire deficit. Since about 50% of national forest land is in wilderness and roadless areas where mechanical fuel management is either prohibited or infeasible, resource objective fire will play a role in any significant solution to the fire problem.

Treatments in our scenario were narrowly focused on reducing

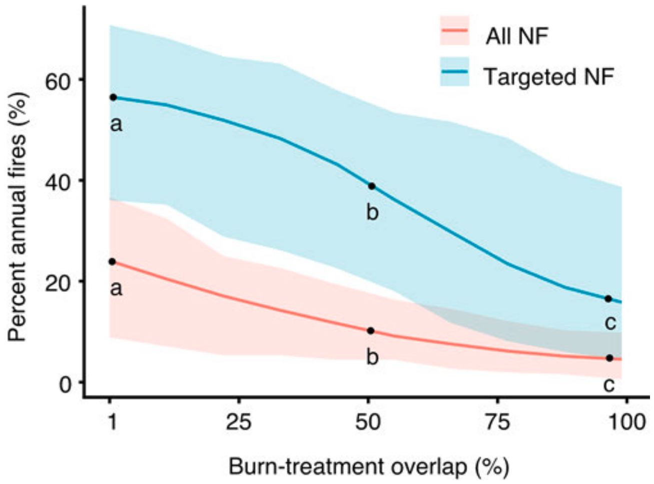

Fig. 10. Overlap between simulated wildfires and treated areas versus percentage of annual fires. Graphs shows the frequency that treatment and wildfires overlapped for a given level of overlap. For example, just under half of all annual fires will have at least 50% overlap with treatments (b) for the targeted national forest (NF) land base. The target NF land base = national forest stands that are manageable (excludes wilderness etc.), majority conifer and not recently disturbed by wildfire or fuel treatments (outer ring in Fig. 2). The shaded area represents the 10th and 90th percentiles among the 30 replicate wildfire scenarios.

uncontrolled fire spread into developed areas, where risk to people, smoke, and other constraints require scheduled mechanical fuel management and prescribed fire rather than unplanned ignitions. Treatment in these situations is driven by risk reduction, rather than achieving a reference condition within the historic range of variability (Stephens et al., 2021). Fine scale studies of treatment needs on national forests suggest that treating to manage fuels and forest health according to current practices in the field leads to substantially higher estimates of treatment need compared to those generated from studies of historical range of variation (Belavenutti, 2021). Although the modeled treatment scenario has many implementation challenges not addressed in the study, including workforce capacity, and NEPA planning and funding as outlined in Fig. 3, the work provides a dialogue with funding agencies to build strategic plans to garner support to change laws and land management practices in response to catastrophic wildfires. Most of the exposure to buildings in the western US originates from lands other than national forests (79% from non-national forest lands (Ager, Palaiologou et al.. 2019)) underscoring the importance of an all lands approach for future fuel management strategies (USDA Forest Service, 2018).

Spatial planning models as described here are widely applied to understand and resolve conflicts in multi-objective forest management and restoration systems (Schroder, Tóth, Deal, & Ettl, 2016; Triviño et al., 2017), especially tradeoffs between financial and ecological objectives (Ager et al., 2017; Pohjanmies, Eyvindson, & Mönkkönen, 2019). While the current application is focused on fuel management to protect developed areas from wildfires (versus ecological restoration (Stephens et al., 2021)), prior application of the ForSys model investigated multicriteria objectives and tradeoffs among a range of ecological and economic values and management tradeoffs at different scales (Ager et al., 2019). Multiscale scenario analysis can reveal scale mismatches between ecological processes and proposed solutions to environmental problems (Biggs et al., 2007; Star et al., 2016), and help resolve conflicts between economic and conservation objectives in forest management (Pohjanmies et al., 2019). The current application advances prior work by introducing stochastic wildfire to quantify risk in conservation and disaster mitigation planning risk (Avin & Goodspeed, 2020; Langford, Gordon, & Bastin, 2009) that heretofore has received little attention in the realm of wildfire policy planning in the US and in other countries that are developing wildfire disaster mitigation strategies (AGIF, 2020; Palaiologou et al., 2021).

Scenario planning is a well-established technology in industry and government and is widely used to illustrate alternative futures and their evolution under a clear set of assumptions, rather than providing one specific forecast (Bunn & Salo, 1993; Peterson et al., 2003; Trammell, Thomas, Mouat, Korbulic, & Bassett, 2018; Xiang & Clarke, 2003). Despite wide use elsewhere, scenario planning to examine alternative futures is not widely practiced in federal land management planning (Trammell et al., 2018). In our study, we acknowledge the significant administrative and other constraints that would need to be overcome to implement the simulated treatment scenario, but point out that quantifying and exposing management barriers is one purpose of conducting these exercises (Peterson et al., 2003; Trammell et al., 2018; Xiang & Clarke, 2003). This study focused on a single treatment plan based on a simple set of assumptions with the primary focus being the assessment of interannual variability in treatment-fire intersects. Future research could assess different treatment scenarios or interactions between treatments and wildfire, including those managed for resource objectives (Huffman et al., 2020).

We acknowledge several limitations in methods, in particular using intersections as a proxy for spatial interactions between fires and treated areas. Thus our estimates of future wildfire impacts (area burned, exposure and treatment overlap) are an indicator of the potential for fire-treatment interactions, rather than an estimate of the reduction in area burned (Kalies & Yocom Kent, 2016). We measured the area that would have burned if the treatments were not implemented or had no effect on fire spread. Re-simulating wildfires on the treated landscape across the 36 million ha study area for each year of the plan would be a significant undertaking and beyond the scope of this study. Although forest landscape management models with wildfire disturbance (e.g., Envision, LANDIS, LSim) (Ager et al., 2018; Ager, Barros, Houtman, Seli, & Day, 2020; Liang, Hurteau, & Westerling, 2017) can integrate fuel treatments and wildfire, technical and computational limits preclude their application to even a small fraction of the network of 76 western US national forests. The effects of treatment on wildfire are highly variable, but simulation research suggests that strategically treating 30 – 50% of landscapes as in the current study results in a reduction in area burned by wildfire by > 50% across a variety of forested landscapes, and also provides many paths to manage fire to protect values at risk due to lower fire spread rates, and improved fire control (Kalies & Yocom Kent, 2016; Stephens et al., 2012). Most importantly, variation among the 30 replicate fire scenarios in burned area as generated from the FSim model (CV = 67%) suggests that variability in future fire seasons can obscure effects of fuel treatments on reducing exposure when examined over large scales and short time frames (e.g., 2–5 years), despite treatments that are effective at local scales (IFTDSS, 2021). To our knowledge, estimates of future wildfire variability have not been incorporated into prior large scale assessments (Calkin, Ager, Gilbertson-Day, Scott, Finney, Schrader-Patton, Quigley, Strittholt, & Kaiden, 2010; Cleland et al., 2017; Dillon, 2015; USDA Forest Service, 2011) or in federal forest planning (IFTDSS, 2021; NFMA, 1976; Trammell et al., 2018).

5. Conclusions

Our study demonstrated a top down approach to develop a large-scale prioritization to address wildfire risk to developed areas, and an approach to coarsely assess potential wildfire impacts and spatial intersections with treatments during implementation. The results of the study are being used by the Forest Service to communicate a strategy to ramp up current levels of hazardous fuel treatments to the legislative branches that oversee the agency. The methods can be used by other national scale wildfire management agencies to develop strategic plans, including the assessment of planning risk (Mentis, 2015), i.e., the range of potential wildfire impacts on implementation of strategic risk reduction programs. Future work can explore the effect of climate change as part of scenario analyses (Star et al., 2016) including assessment of planning risk for fuel treatment and restoration programs (Peterson et al., 2003). For instance, will extreme variability in future wildfire make the use of risk assessment ineffective as a prioritization method for 5–10-year restoration and risk reduction plans? Wider use of scenario planning models by land management agencies is consistent with systems thinking, data analytics, and prescriptive intervention (National Academies of Sciences, 2019), as a way to enhance foresight into natural resource management outcomes, and as part of addressing wildfire challenges in the near term future.

6. Author statement

This study addresses a significant landscape planning issue, the protection of developed areas adjacent to large areas of fire excluded national forests that are increasingly experiencing large and severe wildfire events. We examine how forest and fuel management can be prioritized to target wildfire transmission to developed areas and simulate treatment scheduling and implementation on over 6 million ha and 76 national forests. We then explore how future wildfires might spatially intersect treated areas using a library of fire simulation perimeters. The study was conducted to support proposals within the USDA Forest Service to substantially increase the scale of current fuel management activities on western US national forests.

Acknowledgements

This work was funded by the USDA Forest Service, Rocky Mountain Research Station and the National Fire Decision Support Center. The scenario analyzed in this paper were motivated by numerous discussions with John Phipps, former Forest Service Deputy Chief. We thank Ken Bunzel and Chris Ringo for geospatial processing and analysis. We also thank Jim Menakis for assistance with the Forest Service Fuel Treatment Effectiveness Monitoring database.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104212.

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