Forest Ecology and Management 434 (2019) 99–109

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Tradeoffs between US national forest harvest targets and fuel management to reduce wildfire transmission to the wildland urban interface

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ABSTRACT

US public land management agencies are faced with multiple, often conflicting objectives to meet management targets and produce a wide range of ecosystem services expected from public lands. One example is managing the growing wildfire risk to human and ecological values while meeting programmatic harvest targets for economic outputs mandated in agency budgets. Studies examining strategic management tradeoffs on federal lands and program efficiencies are rare. In this study we used the 79 western US national forests to examine tradeoffs between forest management scenarios targeting wildfire risk to the wildland urban interface (WUI) and those meeting agency convertible volume production targets. We quantified production frontiers to measure how the efficiency of meeting harvest volume targets is affected by prioritizing treatments to areas that transmit fire to the WUI. The results showed strong tradeoffs and scale effects on production frontiers, and more importantly substantial variation among planning areas and national forests. Prioritizing treatments to reduce fire transmission to the WUI resulted in an average harvest volume reduction of about 248 m^3 per ha treated. The analysis also identified opportunities where both management objectives can be achieved. This work represents the first large-scale tradeoff analysis for key management goals in forest and fuel management programs on national forests.

1. Introduction

An ongoing wildfire management challenge in the US and elsewhere concerns the multiple ecological and social objectives on fire-prone public wildlands where catastrophic wildfire events are occurring with increasing frequency (Fischer et al., 2016; Steelman, 2016). In the 2017 fire season alone, over 9000 structures were destroyed or damaged by fire in the western US (Insurance Information Institute, 2018), with a significant proportion of these affected by fires starting on national forest lands. Current forest management programs on these forests emphasize fuels reduction and restoration of fire adapted forests, and treat an estimated 655 thousand ha annually (Vaillant and Reinhardt, 2017), well short of the estimated 32 million ha backlog determined from ecological assessments (USDA Forest Service, 2017a). Destructive wildfire events that increasingly plague much of the western US have brought close scrutiny over the effectiveness of federal forest management programs, especially those aimed at reducing wildfire risk to the wildland urban interface (WUI) adjacent to national forests (Kalies and Yocom Kent, 2016). Multiple factors complicate the assessment of progress and effectiveness, including impacts from highly stochastic wildfire and increasingly severe weather anomalies driving mega fire events in the western US (McKenzie and Littell, 2017; Schoennagel et al., 2017). The fact that fuel management programs have the dual objective of restoring fire and protecting communities from it, depending on fire ecology context and location, complicates monitoring and demonstrating progress and outcomes (Vaillant and Reinhardt, 2017). Recent assessments have suggested that treatment programs are, in fact, targeting appropriate locations as specified in national policy (USDA-USDI, 2001), but limitations in data describing treatment locations and purpose make it difficult to precisely understand project scale priorities across expansive fire-prone national forests (Vaillant and Reinhardt, 2017).

The scrutiny over fuel management programs begs for a broader understanding of how the myriad of often conflicting management objectives concerning conservation, restoration of fire adapted forests, and agency wood production targets (USDA Forest Service, 2017a) influences the process of prioritizing limited budgets to conduct forest management activities on the 67 million ha national forest network. Quantifying conflicts among on-the-ground management objectives is not well described except for some relatively small study areas in the western US (e.g. Ager et al., 2017c; Vogler et al., 2015). Much of the prior work is focused on risk tradeoffs between long-term benefits to reduce fire risk and short-term adverse impacts to wildlife habitat (Scheller et al., 2011; Spies et al., 2017) and carbon (Kline et al., 2016;

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https://doi.org/10.1016/j.foreco.2018.12.003
Received 29 June 2018; Received in revised form 2 November 2018; Accepted 2 December 2018

Chiono et al., 2017; Creutzburg et al., 2017). These studies highlight how assumptions about future wildfire can change the outcome of risk tradeoff analyses, and generally support the role of management to reduce wildfire risk to various ecological values. They do not, however, consider the wider array of management goals that typical public land managers (i.e. Forest Service District Rangers) encounter in the process of selecting planning areas and stands to treat within them. In previous work (Vogler et al., 2015; Ager et al., 2016; Ager et al., 2017c) we addressed this gap and examined an array of management goals and tradeoffs in the Blue Mountains in northeast Oregon and found one of the sharpest tradeoffs was between net revenue from forest management activities and implementing projects that treat areas likely to contribute fire to the surrounding WUI. However, the extent to which these trends might persist or vary at the scale of the western US national forests is not known, despite the fact that both WUI protection and timber outputs are important national forest management goals and have specific annual targets (USDA Forest Service, 2017a). The wood products derived from harvesting on national forests are a significant source of revenue in rural US economies. For instance, revenue generated from national forest timber sales are currently valued by the agency in the range of 79 million USD per year. At the same time, numerous policy documents direct treatments for other purposes, including terrestrial and aquatic restoration and protection of key forests and habitat for fire sensitive species (USDA-USDI, 2001; Butler et al., 2015; USDA Forest Service, 2015b; Steelman, 2016; Stephens et al., 2016; Cleland et al., 2017).

In this paper we examine tradeoffs and outcomes between forest management policies that address wildfire risk to the WUI originating from wildfires on national forests versus achieving harvest targets that the US Forest Service allocates to the national forest system. The former objective is one of the primary fire control goals of the national fire plan (USDA-USDI, 2001) and the federal wildland cohesive strategy (USDA-USDI, 2013), while the latter is an important agency mission to sustain rural economies and provide wood supply to the forest products industry. The results document tradeoffs among forest management priorities among and within national forests in the western US. The results further document scale-related effects on production frontiers (Cavender-Bares et al., 2015; King et al., 2015) that are important to consider in decentralized land management agencies that prioritize management activities at multiple scales in the implementation of forest management policies.

2. Methods

2.1. Study area

The study area included the 79 national forests, grasslands, and scenic areas in the six western Forest Service regions (Fig. 1). The Forests cover over 59 million ha and contain a diverse array of forest and rangeland ecosystems. The Forest network is divided by numerous mountain ranges including the Rockies, Sierra Nevada, and Cascades, creating pronounced gradients in vegetation, climate, and fire regimes. A previous wildfire assessment on these national forests contains additional description of the national forests included in the study (Ager et al., 2014). The forests produce around 8.4 m^3 of merchantable wood volume per year (average 2013).

We identified areas that could be managed by removing protected areas and highly restricted areas for mechanical management (e.g., wilderness, recreation and roadless areas), as identified in the USGS Protected Areas Database and Forest Service databases (USGS, 2016; USDA Forest Service, 2017d, 2017e). The remaining area was further modified to remove non-vegetated lands using LANDFIRE data (Rollins, 2009), and areas that either burned in wildfire or received mechanical, timber harvest or prescribed fire treatments since 2009 (MTBS Data Access, 2017; USDA Forest Service, 2017f, 2017c). The latter date corresponds to the year of the imagery used to generate inventory data as described below. The resulting land base considered available for management consisted of 29 million ha (30 million ha removed, 51 percent). For analysis, the national forests were partitioned into 1,443,208 individual forest stands by overlaying a 50 ha hexnet layer (Fig. 1C). Due to intersections with administrative boundaries, the individual hexagons ranged in size from 5 ha to 78 ha (mean = 41 ha). A small number of hexagons larger than 50 ha were created after slivers along ownership boundaries were dissolved. The hexagons were then aggregated into 2350 planning areas (average manageable area = 12,874 ha) based on 12-digit hydrologic unit codes (Fig. 1B). The resulting spatial structure of the data resembled typical planning areas on national forests in terms of the size and management units within them (USDA Forest Service, 2018). Planning areas typically follow the same watershed boundaries to integrate hydrologic, transportation, and other considerations into project planning.

2.2. Wildfire exposure to the WUI

The SILVIS polygon-based spatial data (Radeloff et al., 2005) were used to create a WUI layer to examine wildfire exposure to private property adjacent to national forests. We removed polygons that had low structure density (< 2 housing units km^{-2}) with a lower concern of transmission. We used probabilistic wildfire risk components generated from FSim (Finney et al., 2011; Short et al., 2016) to quantify the area of WUI burned and structures affected by ignitions located on adjacent national forests using methods found in Ager et al. (2014) and Ager et al. (2018). In short, FSim generates daily wildfire scenarios for a large number of wildfire seasons using relationships between historical Energy Release Component (ERC, Bradshaw et al., 1983) and historical fire occurrence. Wildfires are simulated with the minimum travel time (MTT, Finney, 2002) algorithm under weather conditions derived from time series analysis of historical weather. Weather data are derived from the network of remote automated weather stations located throughout the US (Zachariassen et al., 2003). FSim outputs include the ignition location of each fire, fire perimeters, and additional outputs not used in the present study.

Fire perimeters and ignition points generated from FSim were filtered to include only ignitions within national forest USFS administered lands. Each perimeter was intersected with the WUI polygon layer to determine the percentage of each WUI polygon burned. The total number of housing units within each WUI polygon was retrieved from the 2010 US census data (US Census Bureau, 2016), and used to estimate the structures affected by multiplying the percentage burned by the total structures in the polygon. The sum total of all structures affected in different WUI polygons was then summed and the resulting value assigned to the source (ignition) hexcell. The resulting values were annualized by dividing by the number of simulated fire seasons in the FSim outputs. The annualized estimates of structures affected was summed for all ignitions within each hexcell. About 18% of all stands had ignitions that resulted in fires that reached WUI polygons.

Finally, we used wildfire transmission results to identify areas where large fires are likely to ignite and spread into the WUI. These "firesheds" define areas where ignitions have a high probability for causing structure exposure (Fig. 2). We used ordinary kriging in ArcGIS on the ignition layer using a binary field that set annual structure exposure to 1 and non-exposure to 0. To convert the continuous surface to a discrete boundary (i.e., the fireshed) we used a threshold of 0.1 meant to capture ignition locations where there was at least a nominal (10%) annual chance of exposure.

2.3. Historical and estimated harvest volume

We obtained data for 2013–2017 on harvest target attainment from the western US national forests from Forest Service cut and sold reports (USDA Forest Service, 2017b) (Table 1). We used the 5-year historical average as the basis for allocating the total harvest target. Harvest

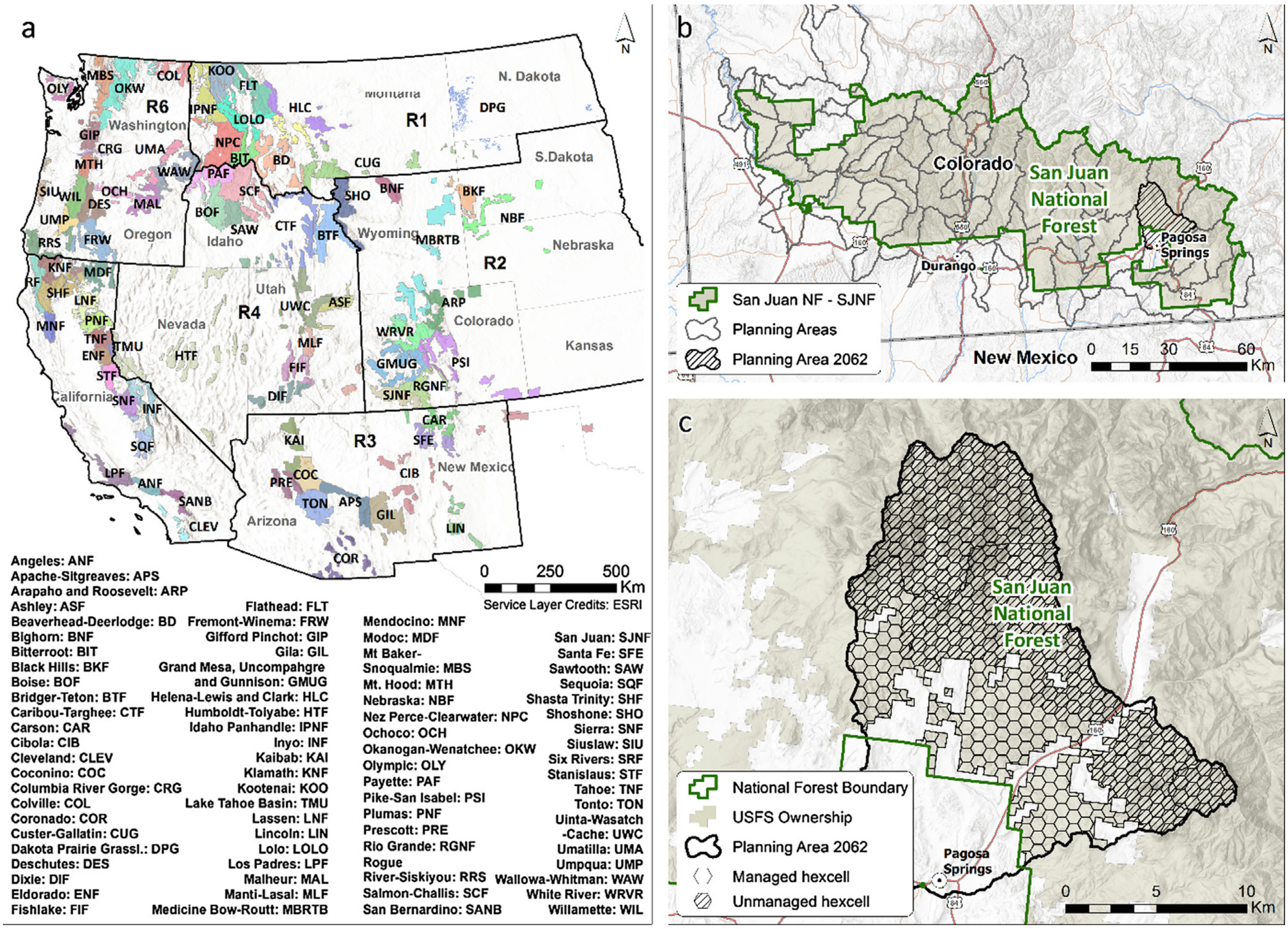

Fig. 1. (A) The 79 national forests in the western US study area and associated Forest Service regions (R1-R6), (B) a single example planning area on the San Juan National Forest, and (C) the 50 ha hexnet stand layer within an example planning area.

volume was estimated for each forested stand by processing inventory tree lists with the Forest Vegetation Simulator (FVS, Dixon, 2002). The respective FVS variant was used for each national forest (Fig. A1). Tree lists for the study area were obtained from Riley et al. (2016), where forest inventory data (FIA, Roesch and Reams, 1999) were extrapolated to 30 m pixels. We simulated stand improvement harvests in each stand using a thin-from-below to a target basal area (Table A2). Harvest prescriptions were generalized from operational practices by forest silviculturists and removed smaller, fire intolerant species to reduce ladder fuels and create fire resilient conditions (Jain et al., 2012). A diameter at breast height (dbh) cap of 53.3 cm was used for all forests except in the southwest region where a lower limit (40.6 cm) is the established practice (USDA and USDI, 1994). Timber harvest volume was summed from 30 m pixels in the Riley (2016) data to the scale of each hexcell (Fig. 1C) to generate an estimate of potential merchantable harvest volume for each hexcell (Fig. 3).

2.4. Priority simulation model

We used the Landscape Treatment Designer (LTD, Ager et al., 2013) to simulate three management scenarios: (1) prioritize harvest volume (MaxWood), (2) prioritize reduction of structure exposure in the WUI (MaxWUI), and (3) a balanced scenario prioritizing a mix of objectives (MaxWoodWUI). For the MaxWood scenario, the algorithm iterated through each planning area (36 planning areas were not included that had insufficient treatable area) and chose stands that could maximize harvest volume if treated, until an area constraint of 10% per planning area was met. The 10% area treated was chosen after examination of a number of typical Forest Service restoration projects around the western US that showed that 10% was a reasonable assumption for the area treated for commercial harvest (USDA Forest Service, 2018). Typical projects on western US national forests treat an additional 10–20% with non-commercial treatments including thinning, mastication, broadcast burning, pile burning, and other fuel reduction activities. These latter activities were not modeled in this study. The resulting list of volume by planning area was filtered to identify the fewest planning areas (highest volume per ha) to meet the historical annual target for the western national forest system (Table 1), thereby maximizing volume per treated area. The MaxWUI scenario used the same process applied to the WUI exposure data to identify a set of planning areas that when treating 10% of the area could address areas with the highest potential exposure to the WUI. To simulate the tradeoff between the two scenarios we weighted the two objectives from 0 to 10 in increments of 1 in all combinations and excluded redundant weight combinations (e.g., weights of 1, 1 equal 2, 2, etc.). This resulted in 65 unique solutions for each planning area and provided a range of alternative treatment priorities within each planning area. These objective values were plotted to examine production frontiers for each planning area. To build a balanced MaxWoodWUI scenario, where each planning area was selected based on the joint production of the two objectives, we filtered the 65 solutions per planning area to a solution that equally weighted the two objectives. In all simulations, the raw values for each stand were re-scaled to the percentage of the maximum value for the respective data sets to eliminate measurement scale effects. A total of 152,750 optimizations were performed (2350 planning areas and 65 weighted combinations per planning area).

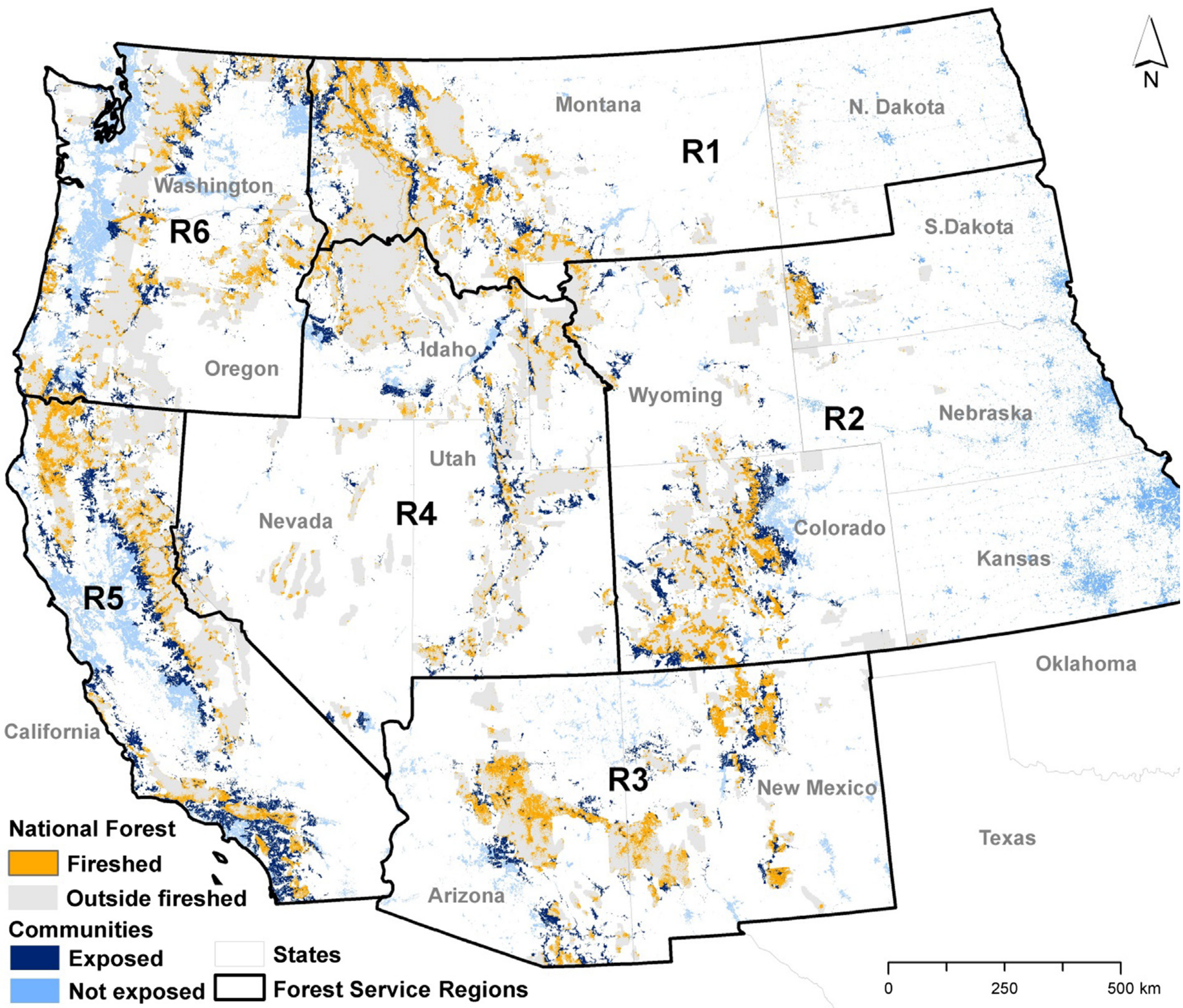

Fig. 2. Map of community firesheds and associated communities exposed to wildfires ignited on adjacent national forests for the 79 national forests in the western US. Firesheds delineate areas inside national forests where ignitions cause structure exposure to nearby communities.

Table 1
Total convertible cut volume and value for the 79 western national forests for 2013 to 2017. Data obtained from USDA Forest Service cut and sold reports (USDA Forest Service, 2017b). BBF is billions of board feet, and CCF is thousands of cubic feet.

Year	Convertible cut volume			Convertible cut value
	BBF	CCF	m3	USD
2013	1.50	2,934,309	8,309,024	$68,222,424
2014	1.59	3,061,906	8,670,337	$82,045,211
2015	1.55	2,974,728	8,423,477	$82,191,964
2016	1.55	2,981,899	8,443,783	$79,360,309
2017	1.46	2,822,059	7,991,169	$83,356,119
Average	1.53	2,954,980	8,367,558	$79,035,206

It is important to note that we assumed commercial treatments eliminated potential wildfire transmission to the WUI in the stands that were treated, meaning that an ignition in the treated stand would be successfully suppressed within the treated planning area. While this assumption oversimplifies the effect of fuel management on wildfire risk, it is consistent with the attainment accounting for Forest Service management activities and targets (USDA Forest Service, 2017a), and provides a method to understand the magnitude and pattern of spatial variation and covariation in the two objectives. Estimating risk reduction using burn probability modeling (Ager et al., 2007) for the 152,750 simulations is not computationally practical. We also note that in a typical planning area on western US national forests, additional area (10–20%) is also treated with prescribed fire and surface fuels mastication (Agee and Skinner, 2005) as part of the typical treatment package (USDA Forest Service, 2018). We did not simulate these latter activities nor assume benefits since the focus was specifically on harvest volume tradeoffs. Implementation of these companion treatments would contribute to additional reduction in wildfire risk over that assumed in this study.

3. Results

Production frontiers (PFs) for the planning areas showed wide variation in the production of volume versus treating areas that transmit fire to the WUI (Fig. 4). The PFs were mostly asymmetrical and concave to the origin (convex to the outer surface) and indicated sharp tradeoffs between MaxWood and MaxWUI scenarios at the outer margins. For most planning areas there are portions on the PFs where the marginal benefit from improving the attainment of one restoration objective exceeded twice the loss in the other objective (Fig. 4). The PF for the entire study area between MaxWood and MaxWUI (outer border of points Fig. 4A) traced the outer hull of the population of PFs. Maximum levels of joint production were evident for all planning areas where the marginal benefits of changing production in one or the other

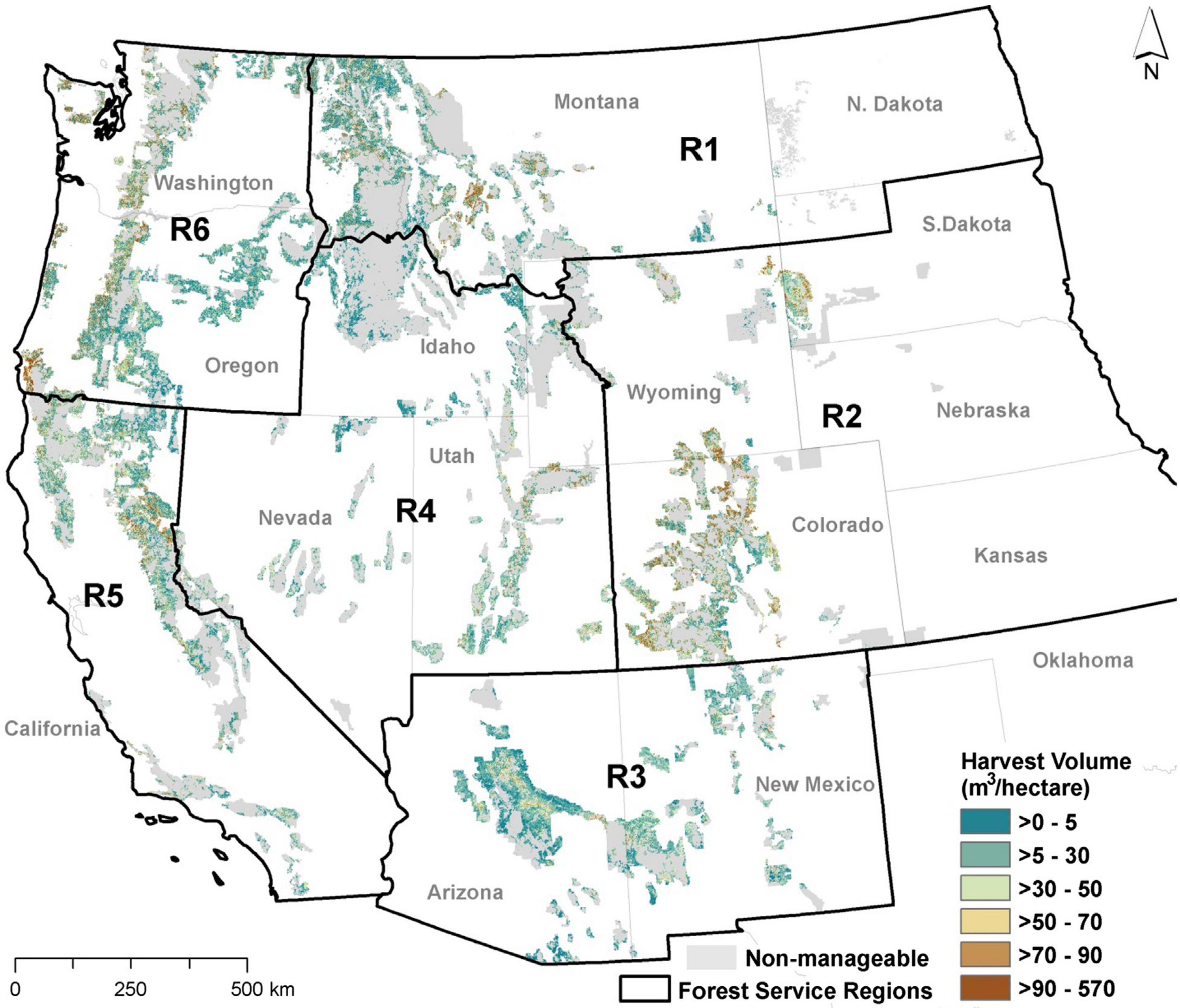

Fig. 3. Potential harvest volume on the 79 national forests in the western US. Stands are excluded from management using designations in the Protected Areas Database (USGS, 2016), other restricted areas (e.g., roadless area, USDA Forest Service, 2017d), and disturbances since 2009 (USDA Forest Service, 2017f, c).

outputs were equal. Relatively few planning areas lacked some tradeoff between harvest volume and WUI protection, those being areas where one or the other objective was not available in the entire planning area. Joint production for the optimal 30 planning areas (Fig. 4B) was highest for the Okanogan-Wenatchee in the Pacific Northwest (region 6), and steeper tradeoffs were evident in the southwest (region 3) and California (region 5).

When harvest volume was prioritized (MaxWood scenario) the historical harvest (2013–2017) on western US national forests (8,367,558 m^3) was achieved by treating 59,260 ha, or 0.22% of the treatable area (Fig. 5B, Table A1). Doubling the harvest required 140,500 ha or 0.54% of the treatable area (Fig. 5B). For the MaxWUI scenario, the current harvest level in the study area was achieved in 158,500 ha or 0.6% of the treatable area, 2.7 times the area under the MaxWood scenario (Fig. 5B, Table A1). Thus, prioritizing treatment to address wildfire transmission to the WUI required an increase in area treated of 270% to reach current levels of wood volume. Among the planning areas required to achieve current levels of harvest, the average yield was about 52 $m^3\,ha^{-1}$ for the MaxWUI scenario versus 154 $m^3\,ha^{-1}$ for the MaxWood scenario (Fig. 5C). The average volume per ha harvested dropped dramatically with increasing area treated for the MaxWUI scenario. A total of 40 planning areas had to be treated to achieve historical harvest volumes under the MaxWood scenario versus 158 for the MaxWUI scenario (Fig. 5C, 5D). The number of planning areas required to achieve 2X historical harvest (16,735,116 m^3) equaled 97 for the MaxWood scenario versus 307 for the MaxWUI scenario.

Cumulative attainment with area treated varied dramatically among the scenarios (Fig. 5A), with 12% of the total estimated structure exposure in treated areas at historical harvest levels under the MaxWUI scenario, corresponding to 158 planning areas (Fig. 5A and B, Table A1). Note that 100% attainment cannot be reached for any objective when treating only 10% of each planning area (data not shown).

The location of the highest priority planning areas for the MaxWUI and MaxWood scenarios (Fig. 6) were markedly different and illustrate spatial variation in the respective management goals. The highest priority planning areas for MaxWood were located primarily in the Pacific Northwest region (Fig. 6A) and Colorado (region 2), whereas the MaxWUI planning areas were located primarily in the Pacific Southwest and Southwest regions (Fig. 6B). There was minimal overlap, i.e. planning areas that were priorities for both scenarios, illustrating the spatial divergence between the alternative scenarios. However, the balanced MaxWoodWUI scenario showed strong overlap with priority areas in the MaxWUI scenario (Fig. 7).

4. Discussion

We quantified tradeoffs between treating areas to protect the WUI from wildfire originating on national forest lands and the production of

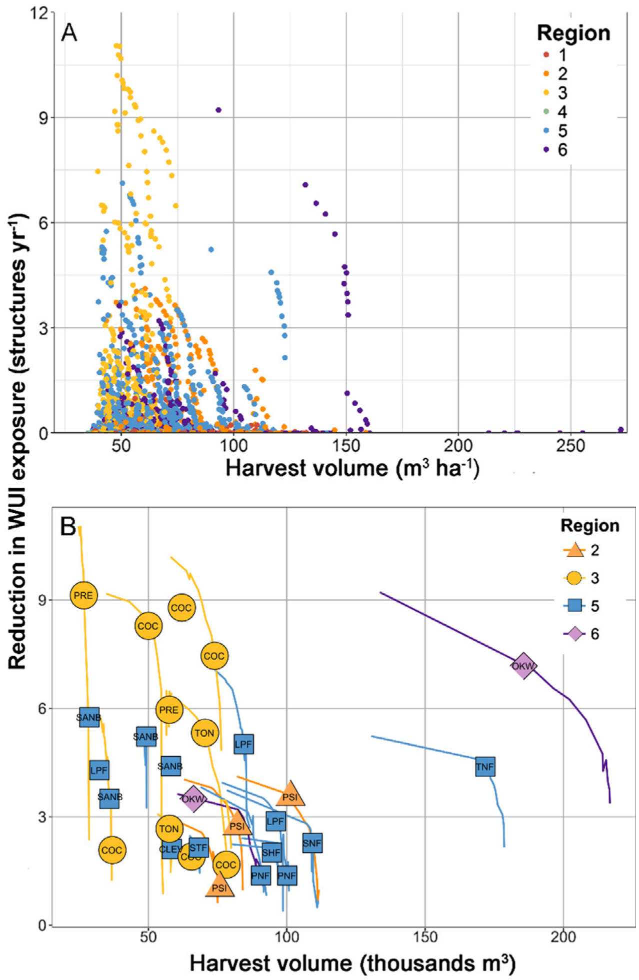

Fig. 4. Production frontiers for planning areas between harvest volume and wildland urban interface (WUI) structure exposure from wildfires ignited on national forest land (Balanced or MaxWoodWUI scenario). (A) All 2350 planning areas where points represent individual solutions, and (B) the 30 planning areas with the highest joint production labeled by national forest. CLE = Cleveland; COC = Coconino; LPF = Los Padres; OKW = Okanogan-Wenatchee; PNF = Plumas; PRE = Prescott; PSI = Pike-San Isabel; SANB = San Bernardino; SHF = Shasta Trinity; STF = Stanislaus; TNF = Tahoe; TON = Tonto.

wood volume to meet agency mandated targets. This is the first large-scale tradeoff analysis on federal forests we are aware of and the results can be used in many ways to bring transparency about tradeoffs into future decisions about timber targets versus reducing wildfire risk to the WUI emanating from national forest lands. The results provide a cross-scale linkage between strategic forest management goals for the national forests and the implementation of actual planning areas. Although we discuss limitations to the analyses below, scrutiny of our results will lead to improvements in information systems and modeling, thereby providing ways to understand management priorities and tradeoffs at a range of scales.

Harvest volume is a byproduct of the myriad of socioecological forest management goals but is an important benchmark for agency activities as part of the longstanding Forest Service mission to sustain rural economies (USDA Forest Service, 2017a). Timber and biomass programs are important to rural communities and economies (USDA Forest Service, 2017a) with 2.94 billion board feet of timber volume sold in 2017 (USDA Forest Service, 2017b) and a target of 3.2 billion board feet for 2018 (USDA Forest Service, 2017a). At the same time, in 2017 hazardous fuels reduction projects were implemented on 849 thousand ha (2.1 million acres) in the WUI (USDA Forest Service, 2017a) and WUI protection remains a major focus of US federal fire policy (Steelman, 2016). Clearly, decisions are being made at local levels to prioritize forest management activities that protect structures in rural communities from wildfires ignited on national forests that may be incompatible with providing socio-economic benefits to the same communities. Providing employment in the wood products industry and related supply chain has and always will be a key mission of the Forest Service and the total average value of wood products harvested on national forests exceeds 79 million USD annually (Table 1, USDA Forest Service, 2017b). However, reducing wildfire risk and producing wood products conflict in multiple ways, both spatially, as we show in our results, and functionally in terms of the types of activities that are needed to reduce the fire deficit in the western US (Butler et al., 2015; Kalies and Yocom Kent, 2016).

It is important to note that the tradeoffs we examined pertain to how treatments are applied within individual planning areas to meet specific objectives. The sum total of these planning area tradeoffs manifests as a system-wide tradeoff under a global harvest target. The system-wide solution identifies the highest priority areas within the western US national forests for WUI protection versus timber production. However, allocating current budgets according to these priority schemes is not feasible under the current distribution of workforce that plans and executes timber sales. Comparison of our outputs with current forest harvest targets provides a measure of efficiency towards meeting individual goals.

The often-heard argument that logging necessarily reduces wildfire risk has merit only if one considers that removing value from land (i.e., logs) reduces expected loss more than it affects fire spread and severity. Instances where fuel treatments have exacerbated fire behavior are common in the literature (Kalies and Yocom Kent, 2016). Although collaborative forest restoration programs (USDA Forest Service, 2016) emphasize economic benefits from restoration activities, much of the work needed to reduce the wildfire deficit does not result in wood products, including prescribed fire, fuels mastication, pre-commercial thinning, and pruning. Thus harvest targets established as part of budget appropriations (USDA Forest Service, 2017a) and subsequently allocated to the 79 national forests are not always central to the restoration mission, and our analysis specifically shows that addressing other issues reduces the efficiency of meeting these targets in terms of area treated and projects implemented. Increasingly the agency is being scrutinized regarding protecting communities from wildfires transmitted off the national forests (GAO, 2002, 2007). In the US and many other fire-prone regions globally (e.g., Oliveira et al., 2017), exurban development combined with land use practices and climate anomalies contribute to the growing wildfire-WUI problem, which has been the subject of a large number of papers in the last few years.

Our analysis identified specific planning areas and national forests where joint production of two restoration objectives can be efficiently attained (Fig. 4). Elsewhere there are localized tradeoffs that can be recognized in terms of the efficiency of applying forest management to reduce wildfire risk and generate wood products. Expectations to generate revenue from projects that are focused on the reduction of WUI exposure should be commensurate with the production frontier (PF), which varies spatially and by scale. We showed the inefficiency associated with meeting harvest targets while prioritizing hazard reduction management activities that target lands contributing fire to the urban interface adjacent to national forests.

The variation we observed in production functions stems from the juxtaposition of national forest lands and developed areas along the montane gradients in the western US (Fig. 8). For instance areas with national forest at higher elevation relative to the urban interface, and consisting of relatively low productivity dry forest with a history of past management, generate steep tradeoffs compared to communities located at higher elevation surrounded by higher productivity forests. The production functions can also be interpreted relative to fire intensity since the higher elevation forests are more likely to have a high

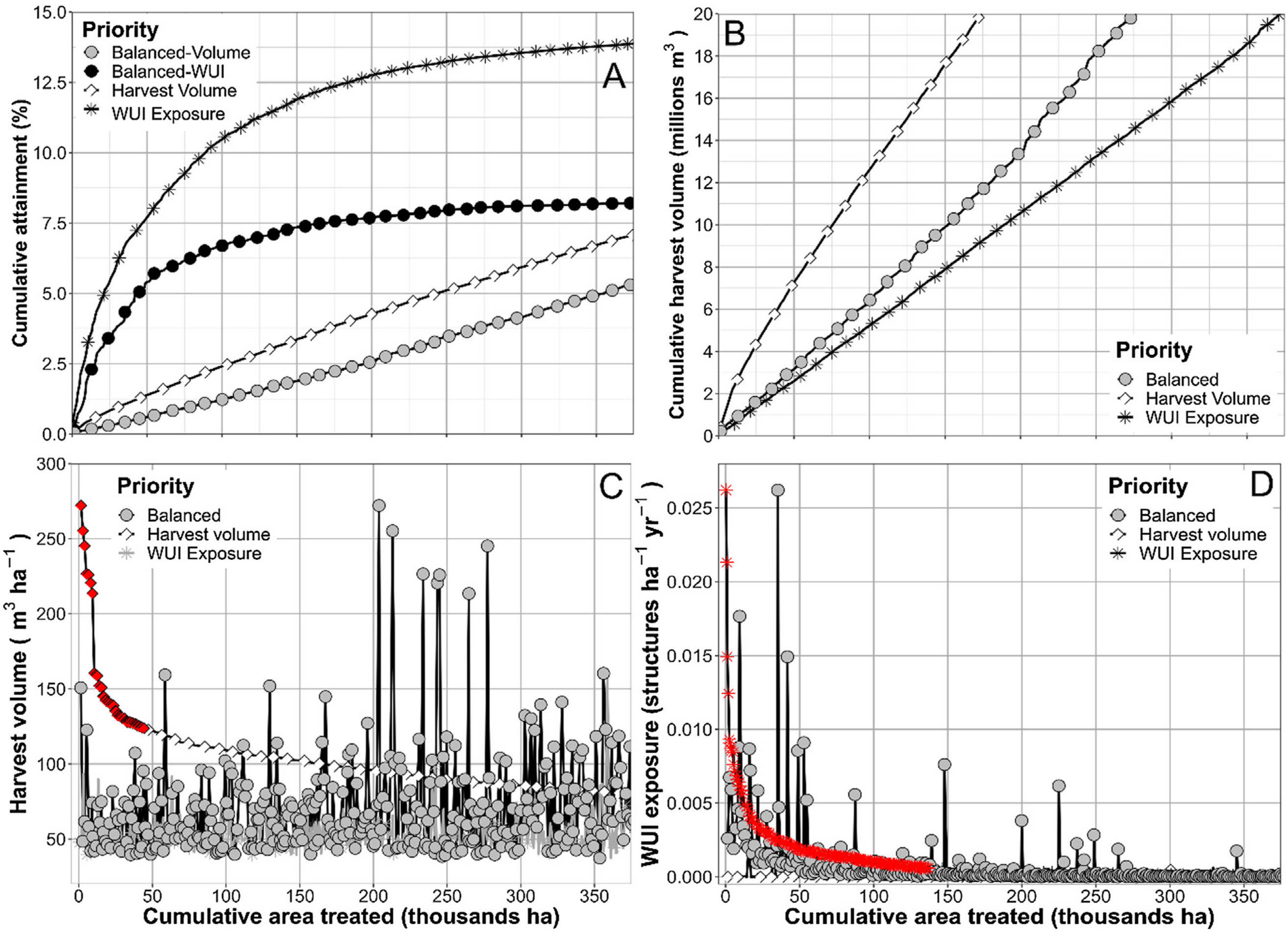

Fig. 5. (A) Cumulative area needed to treat to achieve mean historical (2013–2017) harvest volume (8,367,558 m^3) in the western US when harvest volume (MaxWood) or reduction in wildland urban interface (WUI) structure exposure from wildfires (MaxWUI) are each prioritized individually, and when a balanced scenario (MaxWoodWUI) is prioritized. Note that 100% attainment cannot be reached for any objective when treating only 10% of each planning area; (B) Cumulative attainment in harvest volume under the three different scenarios; (C) Treatment efficiency in harvest volume under the three different scenarios; (D) Treatment efficiency in WUI exposure reduction under the three different scenarios. Red symbols indicate the number of planning areas to reach historical harvest levels in panels C (40) and D (158). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

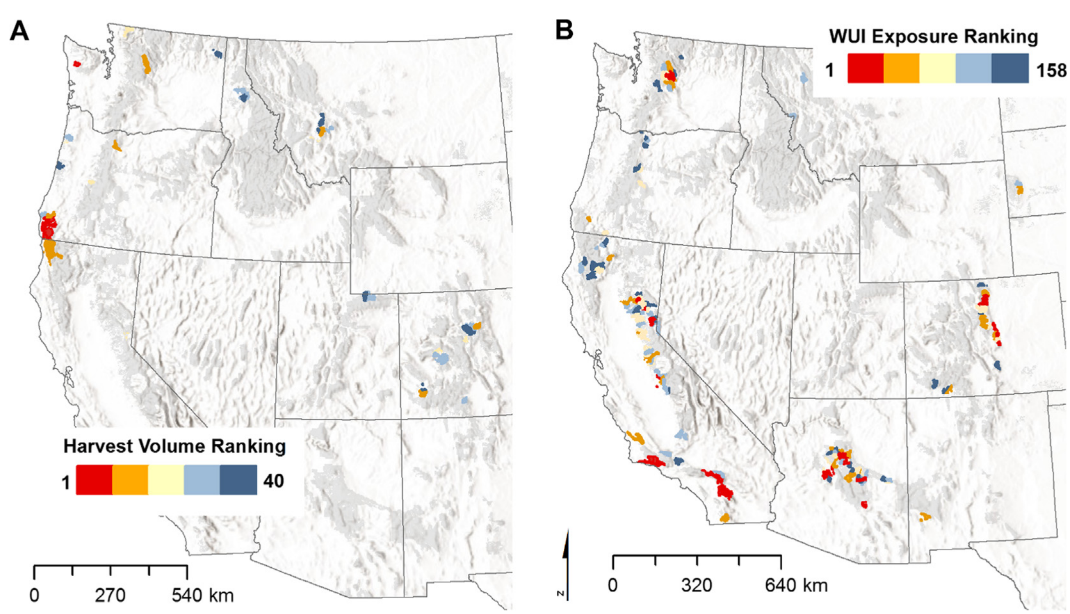

Fig. 6. Location of top priority planning areas in the western US to reach historical (2013–2017) harvest volume (8,367,558 m^3) when prioritizing (A) harvest volume (MaxWood) or (B) wildland urban interface (WUI) structure exposure to wildfires ignited on national forest land (MaxWUI). The number of planning areas changes as priorities change as indicated by the ranking legend.

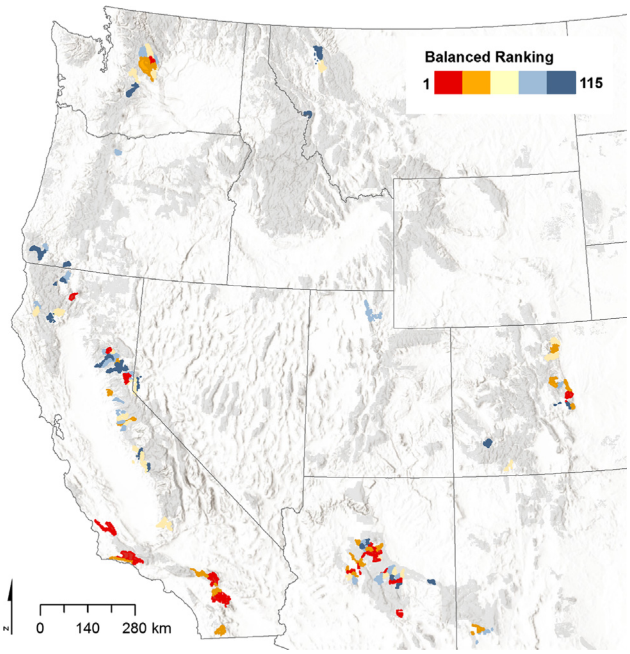

Fig. 7. Location of top priority planning areas in the western US to reach historical (2013–2017) harvest volume (8,367,558 m^3) when prioritizing joint production of both harvest volume and wildland urban interface structure exposure to wildfires in a balanced scenario (MaxWoodWUI). The number of planning areas changes in comparison to Fig. 6 as priorities change as indicated by the ranking legend.

propensity of crown fire activity (Agee, 1998).

The broad mix of socio-economic and ecological goals of federal forest management programs, including the two we examined here, creates a complex prioritization problem for land managers. Restoration (Stephens et al., 2016) and fuel management (Reinhardt et al., 2008) programs have finite resources that need to be allocated to most efficiently meet long-term goals. The prioritization problem on national forests has led to the completion of numerous assessments (Calkin et al., 2010; Lee et al., 2011; USDA Forest Service, 2011; Ryan and Opperman, 2013; USDA-USDI, 2013; FHTET, 2014; Dillon, 2015; Cleland et al., 2017) but the implications of following them in terms of tradeoffs have not been explored at national scales. The use of PFs can help land managers and stakeholders in collaborative planning processes identify the tradeoffs and understand the opportunity cost associated with particular ecological versus socio-economic priorities. Production frontiers can also be used to analyze the efficiency of current restoration efforts. As we have pointed out previously (Ager et al., 2016), neither collaborative restoration planning nor national assessments explicitly consider tradeoffs in prioritization schemes.

The problem of wildfire transmission from public lands, including national forests in the western US, has not been systematically assessed and mapped, although there are a number of smaller-scale studies that document local scale effects. The relative contribution of public lands to community wildfire risk varies by community (Ager et al., 2017a), and damages from wildfires are as likely to be caused by fuels and conditions within the community as from the surrounding landscape. The community archetypes (Paveglio et al., 2015) method is one approach being used to sort out the type of risk and mitigating efforts specific to each community. However, existing community guidance for WUI protection planning does not provide the means to identify the scale and spatial extent of risk, which is needed before integrated mitigation programs (e.g., cohesive strategy, USDA Forest Service, 2015b) can be designed. The challenge for public land managers is to organize landscape fuel treatments that couple the biophysical aspects of fire occurrence and spread with the social component of landowner propensity to treat fuels. In this way conflicts and opportunities to achieve federal wildland fire policy goals, including fire-adapted communities, fire-resilient landscapes, and wildfire response (USDA-USDI, 2013) can be identified and mapped to facilitate implementation of policies that will inform risk governance at the proper scale. In the specific case of fuel management on western US national forests, current programs are

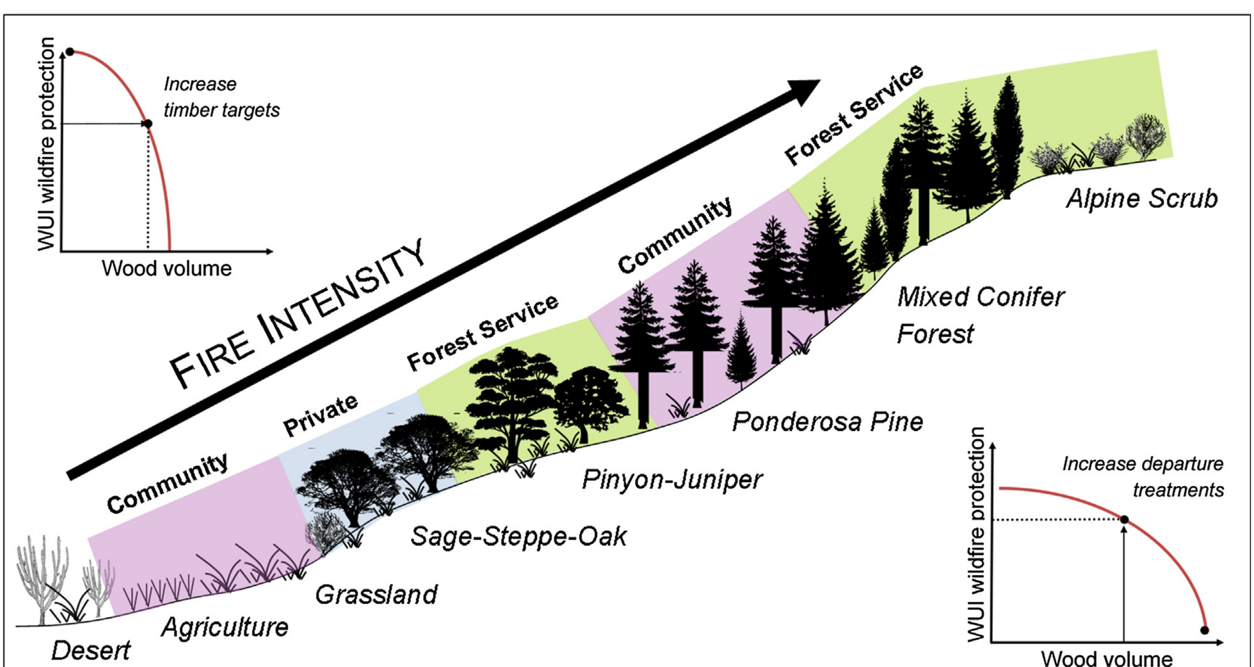

Fig. 8. Typical gradient of vegetation and public – private ownership patterns in the western US and production frontier for treating wildfire risk to the wildland urban interface (WUI) versus generating harvest volume on national forest lands. The bulk of the WUI is located adjacent to dry forests at lower elevations while productive forests with higher harvest volumes are generally located distant to the urban interface. The net effect is a change in the production frontiers as shown in the inset figures.

highly motivated by transboundary issues, especially wildfire transmission to the WUI (USDA Forest Service, 2017a). However, evaluation of fuel treatment strategies for transboundary risk has been largely ignored in several recent reviews (Kalies and Yocom Kent, 2016; Vaillant and Reinhardt, 2017). This gap is significant since transboundary risk constrains fire protection and restoration goals in areas fragmented by jurisdictions, ownerships, and fire regimes.

Our methods can be used to explore a wide range of investment alternatives for the western US national forests and model outcomes at the scale of planning areas. For instance, the modeling system can be used to explore the efficiency of current harvest target allocations to each national forest relative to an optimal scenario where the target is allocated based on available harvest volume. In a broader sense, the modeling approach can help identify synergies between organizational scales and biophysical conditions on national forest lands thereby contributing to long-term agency goals to improve forest conditions by refining investment strategies at multiple organizational scales. The system we created can be used to integrate a number of agency assessments that describe fine-scale conditions, constraints, and management opportunities. Our system fills a void in decision support and research tools in understanding and implementing strategic and tactical operational planning on national forests. The LTD model is being increasingly used by researchers and practitioners for landscape modeling experiments (Ager et al., 2013; Vogler et al., 2015; Salis et al., 2016; Chiono et al., 2017; Alcasena et al., 2018). Although the program does not have the functionality of a landscape disturbance succession model (Scheller and Mladenoff, 2004), it has many features for short-term (1–5 year) planning efforts within public land management agencies where static landscape conditions are assumed for the purpose of prioritizing near-term investments in forest management. As we have demonstrated here and in previous studies, the program can be used at a range of scales from ranger districts to national forests to regions. Existing forest landscape simulation models (Scheller and Mladenoff, 2004; Keane et al., 2011; Ager et al., 2017b; Spies et al., 2017) do not have the capacity to model strategic issues at regional ($> 10^7$ ha) scales due to computational limitations. In contrast to the information provided by numerous prioritization assessments completed by the Forest Service (Calkin et al., 2010; Lee et al., 2011; USDA Forest Service, 2011; Ryan and Opperman, 2013; USDA-USDI, 2013; FHTET, 2014; Dillon, 2015; USDA Forest Service, 2015a; Cleland et al., 2017) our analysis framework provides a simple way to understand how spatial variation and covariation in multiple management objectives affect alternative prioritization at multiple scales (watersheds, forests, regions). The system can be used to build optimal stand treatment designs that meet larger scale objectives (e.g., Ager et al., 2013) and constraints under the various priorities identified in assessments, while providing a cross-scale linkage between national policy and on-the-ground implementation.

We acknowledge a number of flaws in our study and consider it the first step in understanding subcontinental scale tradeoffs among management goals on public lands. In particular, the harvest volume estimates can only be considered coarse given that we assumed two constant upper diameter limits which may vary more dramatically by region according to local guidelines. The same is true for post-harvest basal area thresholds which were varied among biophysical types (Table A2) but lacked local specificity. A higher level of specificity in the harvest prescriptions would probably not change the outcome of the study, but the PFs for some forests might change based on lower or higher levels of potential harvest in specific planning areas. We deliberately did not present national forest scale results because of these limitations, although the modeling exists to generate them. The other limitation is that we assumed treating 10% of the planning area would be accompanied by another 20% treatment with mechanical and prescribed fire, treating a total of 30% of the landscape and thereby substantially reducing wildfire spread rates and intensity. The result of the project implementation would improve suppression effectiveness and reduce the potential for large fires to burn and spread to the adjacent WUI. Reviews of fuel treatment projects and encounters with wildfire have documented the potential to achieve the effects we assumed, although variability among fire events and fuel treatment methods adds to the uncertainty (Kalies and Yocom Kent, 2016).

Our future work will include refining prescriptions and the treatable land base and an integrated analysis of several existing Forest Service assessments to contrast and identify tradeoffs associated with social and economic priorities as identified in Forest Service assessments (see references above). Specific investment strategies will be explored under a range of forest management constraints using site-specific data from existing assessments and historical activities. This analysis will potentially catalyze cross-discipline dialogue about achieving agency targets while simultaneously addressing socio-economic and ecological outcomes.

We are also exploring how the different spatial arrangement of management activities under different optimization scenarios affects landscape structure and function, which in turn affects the intensity and propagation of disturbances and other processes. In fuel planning it is well documented with both empirical data and simulation modeling that the spatial arrangement of fuel treatments can have a dramatic effect on the rate of wildfire spread across a landscape (Loehle, 1999; Finney, 2007; Lehmkuhl et al., 2007; Parisien et al., 2007; Konoshima et al., 2008; Wei et al., 2008; Kim et al., 2009). Capturing the differential fire behavior with simulation models is computationally difficult for the thousands of landscape scenarios used to quantify production frontiers.

Finally, our end objective is to create a socio-economic and ecological typology of tradeoffs and opportunities on national forests (Paveglio et al., 2015; Evers et al., 2019) that can contribute to a system-wide understanding of how opportunities and conflicts are organized at various spatial scales within the agency. In this way , the organization can achieve a system-wide understanding of the management opportunities within and among the 154 national forests and grasslands.

Acknowledgements

We thank Stu Brittain of Alturas Solutions for programming work on LTD. We also acknowledge Kevin Vogler and Andrew McMahan for their work on harvest modeling.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2018.12.003.

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