Research article

Production possibility frontiers and socioecological tradeoffs for restoration of fire adapted forests

Alan A. Ager [a, *], Michelle A. Day [b], Kevin Vogler [c]

[a] USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 US Highway 10W, Missoula, MT 59808, USA
[b] Oregon State University, College of Forestry, Forest Ecosystems & Society, 321 Richardson Hall, Corvallis, OR 97331, USA
[c] Oregon State University, College of Forestry, Forest Engineering, Resources & Management, 043 Peavy Hall, Corvallis, OR 97331, USA

ABSTRACT

We used spatial optimization to analyze alternative restoration scenarios and quantify tradeoffs for a large, multifaceted restoration program to restore resiliency to forest landscapes in the western US. We specifically examined tradeoffs between provisional ecosystem services, fire protection, and the amelioration of key ecological stressors. The results revealed that attainment of multiple restoration objectives was constrained due to the joint spatial patterns of ecological conditions and socioeconomic values. We also found that current restoration projects are substantially suboptimal, perhaps the result of compromises in the collaborative planning process used by federal planners, or operational constraints on forest management activities. The juxtaposition of ecological settings with human values generated sharp tradeoffs, especially with respect to community wildfire protection versus generating revenue to support restoration and fire protection activities. The analysis and methods can be leveraged by ongoing restoration programs in many ways including: 1) integrated prioritization of restoration activities at multiple scales on public and adjoining private lands, 2) identification and mapping of conflicts between ecological restoration and socioeconomic objectives, 3) measuring the efficiency of ongoing restoration projects compared to the optimal production possibility frontier, 4) consideration of fire transmission among public and private land parcels as a prioritization metric, and 5) finding socially optimal regions along the production frontier as part of collaborative restoration planning.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Restoration programs in many socioecological systems face substantial challenges prioritizing activities and balancing competing objectives (Maron and Cockfield, 2008; Bullock et al., 2011; Allan et al., 2013). These challenges have inspired researchers to develop a wide range of decision support frameworks and tools to help disentangle the spatial and temporal dimensions of restoration goals, and prioritize landscapes for restoration projects (Moilanen et al., 2009; Noss et al., 2009; Watts et al., 2009). Analysis frameworks include the use of production possibility frontiers (PPF) to understand and communicate decision tradeoffs in the production of ecosystem services generated from restoration programs (Maron and Cockfield, 2008; Cavender-Bares et al.,

2015a). Tradeoff analyses reveal how the joint spatial organization of ecosystem stressors and services create conflicts and opportunities for restoration programs (Bennett et al., 2009; Allan et al., 2013; Schroter et al., 2014). For instance, spatially correlated restoration opportunities, i.e. co-located stressors and ecosystems services, create opportunities to achieve multiple restoration goals and sustain the production of various ecosystem services (Bennett et al., 2009). The use of PPFs and tradeoff analyses have been discussed as a useful framework for collaborative planning as a means to quantify decision tradeoffs to stakeholders and find socially acceptable and ecologically optimal outcomes (Schroter et al., 2014; Cavender-Bares et al., 2015b; King et al., 2015).

A potential application of PPFs and tradeoff analyses concerns the restoration of fire adapted forests in western North America. A century of selective logging, grazing, and fire suppression has led to widespread densification of forests and a reduction in fire resilient tree species (Noss et al., 2006; USDA Forest Service, 2012), most notably ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson). The result has been a substantial increase in forests that are now prone

to high intensity wildfires and bark beetle epidemics. Large scale restoration programs initiated on the US national forests have been addressing the problem using a number of management techniques including: 1) selective thinning to reduce stand density, reduce surface and ladder fuels, and remove fire and drought intolerant species; and 2) mechanical treatments and prescribed fire to reduce surface and activity fuels generated from thinning operations (Brown et al., 2004; Agee and Skinner, 2005) (Fig. 1). Forest restoration programs have been widely discussed in the literature including ecological aspects (Moore et al., 1999; Brown et al., 2004; Noss et al., 2006), planning frameworks (Franklin and Johnson, 2012), implementation plans (Rieman et al., 2010), scientific guidelines (Franklin and Johnson, 2012), social constraints (Franklin et al., 2014) and conflicts with biological conservation efforts (Myers, 1995; Prather et al., 2008).

Despite the scrutiny of the program, the issue of prioritizing restoration investments across vast tracts of federal forests in the western US and quantifying associated tradeoffs among expected ecosystem services has received little attention. Restoration planning is inherently complex owing to the broad mix of underlying socioecological goals (USDA Forest Service, 2006, 2013). For instance, restoring historical fire adapted structure in dry fire-prone forests (Noss et al., 2006) while meeting economic outputs expected from restoration programs (Rasmussen et al., 2012) may not result in acceptable levels of wildfire risk reduction for communities on adjacent private lands (Ager et al., 2015), and may adversely impact habitat conservation reserves (Gaines et al., 2010). Prioritization on US national forests in particular is further complicated by collaborative planning processes enacted in US federal statutes (Schultz et al., 2012; Butler et al., 2015) where diverse stakeholder groups actively participate in the planning process. Tradeoff analysis tools and frameworks (e.g., King et al., 2015) to support restoration planning, either in a collaborative venue or otherwise, do not exist at either policy or implementation scales, despite their potential to improve the chance of long-term success (Rappaport et al., 2015).

Fig. 1. Example restoration treatments within the Blue Mountains National Forests in eastern Oregon, USA. (a) Pre-treatment stand of ponderosa pine and western larch with advanced regeneration and densification from fire exclusion; (b) same stand as in (a) after receiving thinning treatment to reduce stocking density and select fire resilient species; (c) stand that has received mechanical thinning treatments five years prior is targeted for a maintenance underburning treatment to reduce surface fuels, mimicking natural fire; (d) same stand as in (c) after underburning treatment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In this paper we describe the application of new analytical methods to analyze restoration tradeoffs on 3 million ha of fire-prone forests in the interior Pacific Northwest, USA. The study area was identified as a national priority to restore ecological resiliency to the diverse forest ecosystems, protect communities from wildfire, and provide economic opportunity to local wood processing mills (Rasmussen et al., 2012). However, the compatibility of these various socioecological objectives under alternative prioritization schemes, has yet to be examined. We asked three primary questions: 1) are there significant tradeoffs among socioecological restoration outcomes expected from the program; 2) are there benefits to a prioritization framework, i.e. can restoration goals be achieved more rapidly by focusing restoration investments on key areas, or are restoration targets evenly distributed; and 3) how efficient are current restoration activities relative to optimal as defined by production possibility frontiers? The study provides both new methods and concepts for forest restoration planning and an example of socioecological tradeoff analysis using spatial optimization.

2. Methods

2.1. Study area

The four national forests (Malheur, Ochoco, Umatilla and Wallowa-Whitman) in the Blue Mountain ecoregion of eastern Oregon and southeastern Washington cover 2.5 million ha (Fig. 2). The area contains numerous small mountain ranges with steep canyons and large areas of plateau, and is dissected by several rivers as part of the Columbia River basin. Elevations are mainly between 900 and 1500 m, although the highest peaks reach close to 3000 m. Dry forests of largely ponderosa pine dominate the lower elevations, with dry mixed conifer (grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and moist conifer forests at the higher elevations. Cold dry forested areas are dominated by pure lodgepole pine (*Pinus contorta* Douglas ex Loudon) stands found throughout the area at mid to high elevations. The forests are a mosaic of stand age, density, and species composition as a result of harvest and natural disturbance. Wildfires and insect outbreaks in particular have impacted stand structure and composition over wide areas. About 22,000 ha (0.9%) are consumed annually by wildfires (1992–2013) (Short, 2015), most of which are lightning caused. Major forest insect epidemics are a regular occurrence (Ager et al., 2004) with current outbreaks observed for mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and western pine beetle (*D. brevicomis* LaConte). A number of studies in and around the Blue Mountains have documented departure in stand structure and species composition from historical conditions due to fire exclusion. Most recently Hagmann et al. (2013) reported that stand densities have more than tripled over the past 90 years (68 ± 28 trees ha^{-1} to 234 ± 122 trees ha^{-1}) while mean basal area increased by less than 20%. Most importantly, basal area of larger, fire resilient trees (>53 cm dbh) declined by >50%, and the abundance of large trees as a proportion of the total number of trees per hectare decreased by more than a factor of five.

The US Forest Service (USFS) plans forest restoration treatments on about 20,000 ha annually or about 1.3% of the total managed area (excluding wilderness and roadless areas). It is estimated that 34% (506,696 ha) of managed forests are in need of active restoration (USDA Forest Service, 2013). Restoration objectives include protecting and retaining ecosystem services including clean air, clean water, biodiversity, recreational opportunities, and other services that are threatened by large scale disturbance. Specific treatments mirror management activities on other national forests
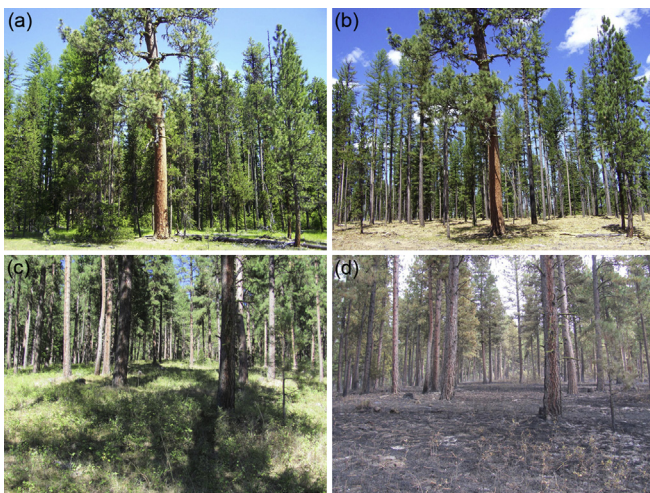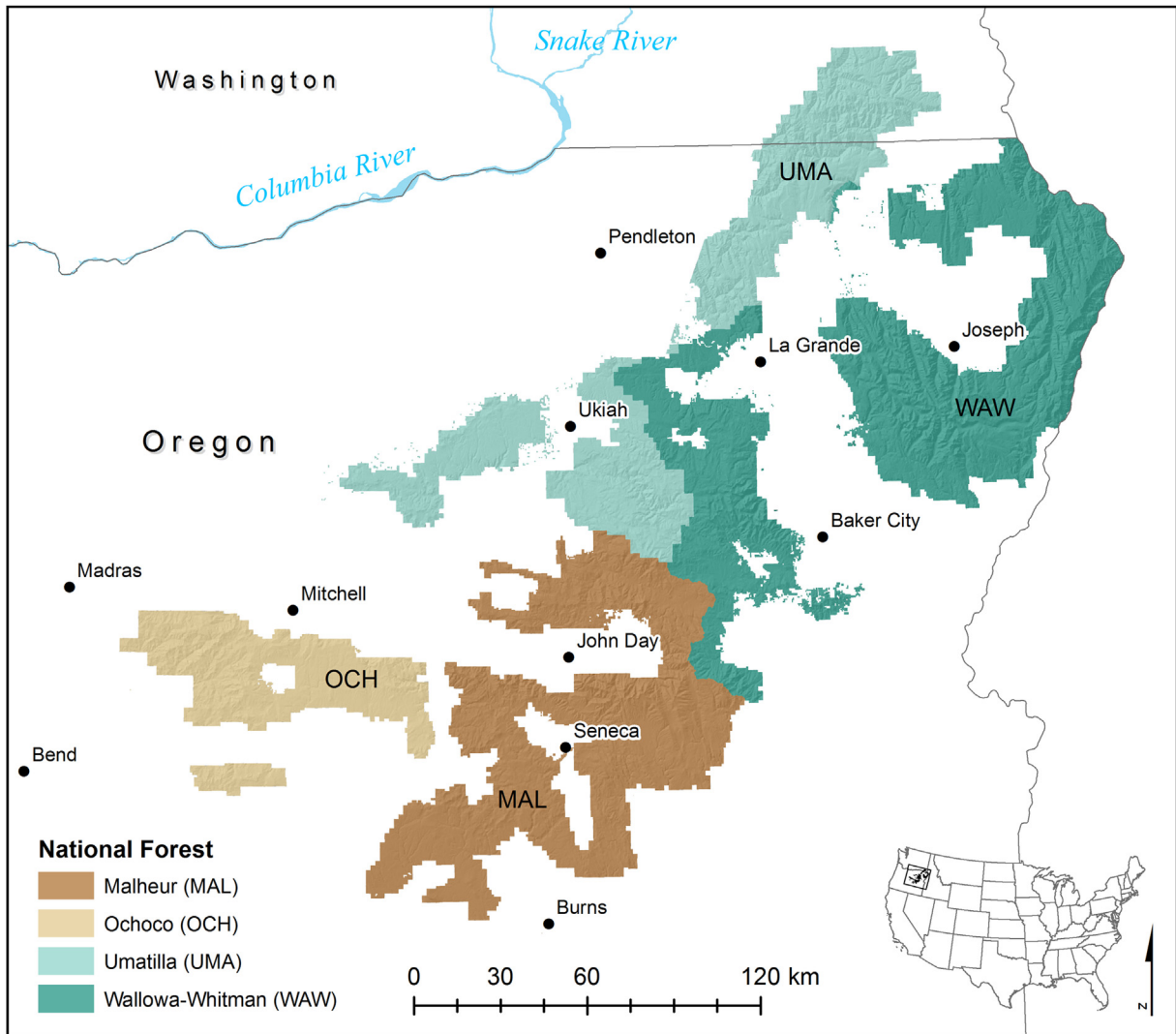
Fig. 2. Map of the Blue Mountains National Forests in eastern Oregon and southeastern Washington, USA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Agee and Skinner, 2005; Roccaforte et al., 2008), where over-stocked stands are thinned from below and surface fuels are treated to reduce potential wildfire behavior and improve forest health. Restoration projects specify on average treating about 5000 ha within a planning boundary of about 14,000 ha. Treatment thresholds (i.e., the selection of stands to treat) and the particular thinning intensities follow guidelines by Cochran et al. (1994; see Section 2.2.4).

2.2. Modeled restoration objectives

We obtained stand polygon layers for each of the four national forests from USFS GIS spatial data libraries and combined these into a single layer. The stand layer delineates forest vegetation based on tree species composition, tree density, tree size, and management history (Fig. S1) according to standard inventory protocols. The original stand polygon layer was created through photo interpretation of 1:12,000 color photos in the late 1980s. The stand delineation is continually updated for management activities and disturbances. The resulting combined layer contained 200,637 polygons averaging 12 ha in area. Many stand boundaries follow natural breaks in vegetation resulting from

topographic influences on growing conditions, particularly moisture (Fig. S1). The layer is used by the four national forests for a range of planning activities including design and implementation of restoration projects.

We then attributed each polygon with the following metrics describing restoration objectives (henceforth "objectives"): 1) potential fire hazard, 2) wildfire transmission to the wildland urban interface (WUI), 3) forest departure from historic conditions, 4) potential stemwood volume from mechanical thinning treatments, and 5) potential tree mortality from insects and disease (Fig. 3). Data sources for each objective are described below with additional details in Appendix S1. Each polygon was attributed with a land management designation based on respective forest plans, and only those areas whose primary management objectives included harvest activities to produce forest products were considered for treatment (Ager et al., 2015). This stratification removed wilderness and inventoried roadless areas, recreation sites, research natural areas, and a number of other protected or restricted areas. The remaining lands where treatments were allowed consisted of 145,395 polygons, ranging in size from <1 ha to 493 ha (mean = 10.6 ha), and covered 1,542,226 ha (64% of the study area).
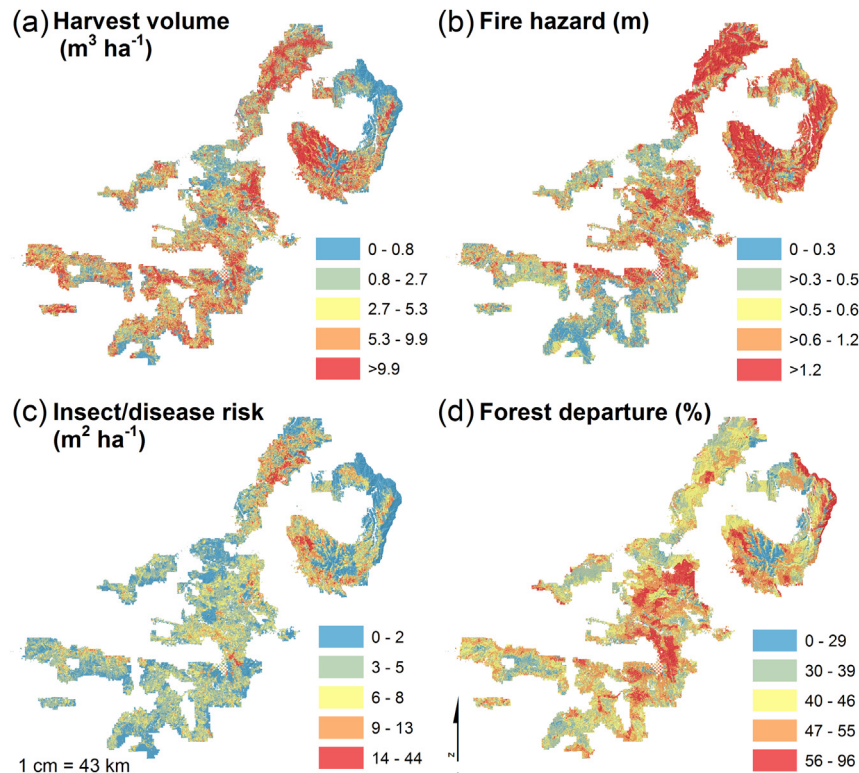
Fig. 3. Spatial distribution of restoration targets in the Blue Mountains National Forests of eastern Oregon and southeastern Washington. (a) Total live stemwood harvest volume generated from thinning treatments; (b) fire hazard as measured by average flame length from FlamMap (Finney, 2006) wildfire simulations; (c) insect and disease risk as measured by expected forest stand basal area mortality (FHTET, 2012); (d) forest departure based on vegetation departure from LANDFIRE (2013). See methods section for description and derivation of data sources and Appendix S1 for data source details.

2.2.1. Fire hazard

We used FlamMap (Finney, 2006) to simulate potential fire behavior for each stand assuming static weather conditions and fuel moisture (Appendix S1). FlamMap is a comprehensive fire simulation software package that is widely used in the US and elsewhere to model potential fire behavior. In the current application, surface and canopy fuels obtained from LANDFIRE (2013) data were used to estimate fire intensity as represented by flame length. Fire weather parameters were used from a previous study in the area and represented 97th percentile weather conditions for the central Blue Mountains (Appendix S1, Table 2). The analysis methods parallel those used on many national forests to identify high fire hazard areas for fuel reduction activities. The simulations were performed at 90 × 90 m resolution and the resulting grid of flame length was overlaid with the stand map to calculate average values for each stand (Fig. 3b).

2.2.2. Wildfire transmission to the wildland urban interface

We measured wildfire transmission to the wildland urban interface (WUI) adjacent to national forests using the methods of Ager et al. (2014). This approach used the SILVIS WUI data (Radeloff et al., 2005; SILVIS Lab, 2012) that provide spatially explicit housing and population densities for the coterminous US based on US census blocks (Appendix S1). The number of housing units within each census block was derived from the 2010 US Census data and included seasonal residences. We modified the SILVIS WUI data by removing polygons that were 1) classified as uninhabited, 2) classified as water, 3) <0.1 ha in size, or 4) >10 km from the national forest boundary. We maintained polygons with low housing unit densities to align with fire suppression efforts that target even individual structures in wildland areas. Each polygon retained SILVIS

housing unit (hereafter structure) values. There were a total of 52,202 WUI polygons covering an area of over 1.6 million ha.

We then used wildfire simulation outputs generated from the FSim model (Finney et al., 2011) to quantify area of WUI burned by ignitions located on adjacent national forests. Detailed simulation methods can be found in Finney et al. (2011) and Appendix S2. FSim produces both polygon-based fire perimeters and ignition points for each simulated fire. Ignitions were filtered to include locations within national forests and associated perimeters were intersected with WUI boundaries to determine WUI area burned annually by each ignition. Total WUI area burned per SILVIS polygon was calculated by summing the contributions from all ignitions reaching that polygon. We then estimated structures affected by each national forest-ignited fire as the product of housing units in the SILVIS polygon and the proportion of the polygon burned. These point data were smoothed using an inverse distance weighting model to generate a continuous 0.5 km raster grid using a 5 km fixed search radius for the entire study area. The resulting raster was resampled to 10 m and used to calculate the annual potential structures exposed to wildfire for each stand polygon (Fig. 4).

2.2.3. Forest departure from reference conditions

A national-scale map of vegetation departure was created by the LANDFIRE (2013) program, a US national scale forest and fuels conditions mapping project (Appendix S1). The departure layer (VDEP) describes departure between simulated current vegetation and historical vegetation conditions. Historical "reference" time period is defined as prior to European-American settlement and varies across the US but is prior to 1850 in the study area (Barrett et al., 2010). Historical conditions were derived from the LAND-SUM landscape succession and disturbance dynamics simulation
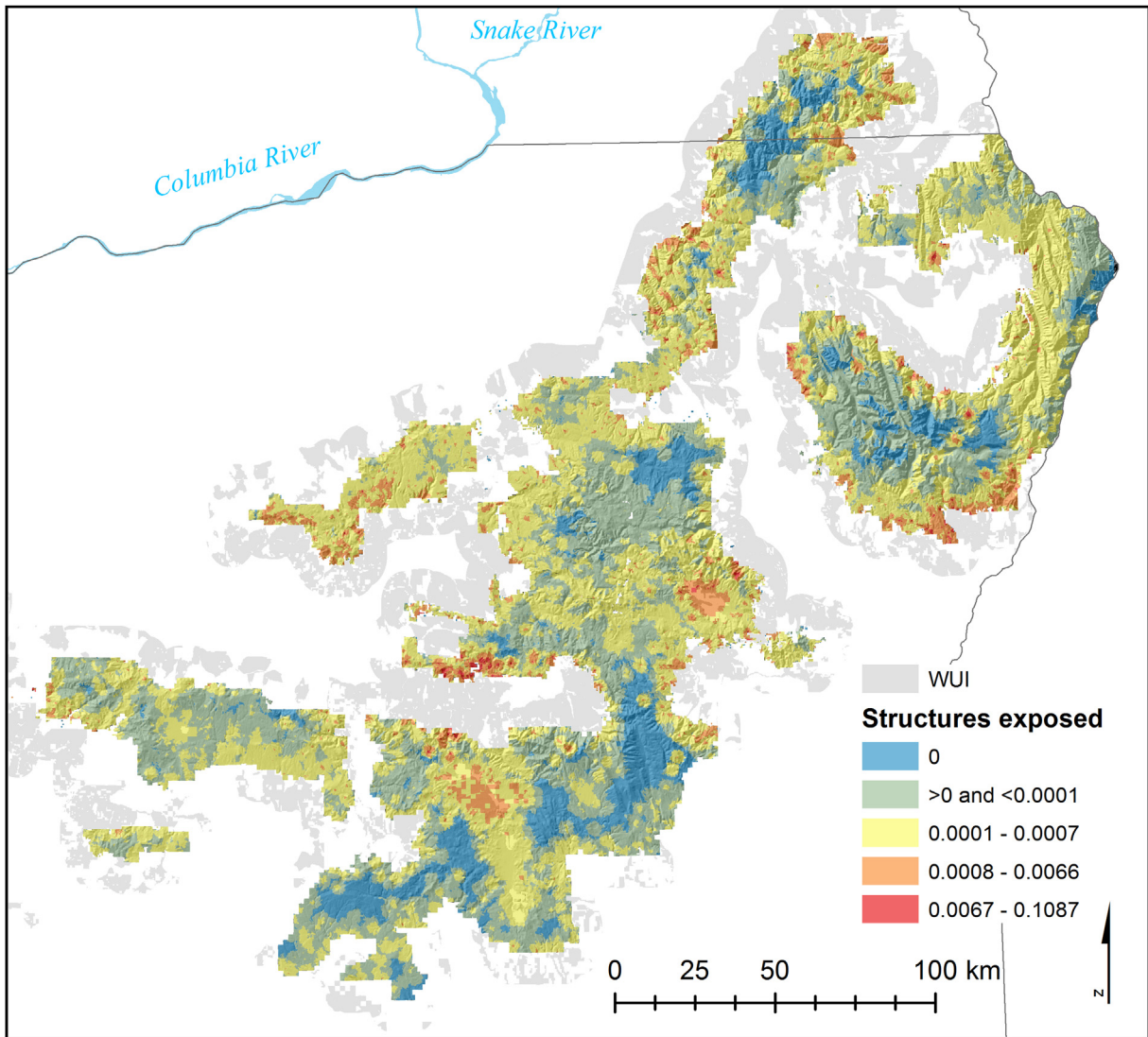
Fig. 4. Map of the Blue Mountains National Forests in eastern Oregon and southeastern Washington showing areas that have potential to transmit wildfire to the wildland urban interface (WUI) and impact structures based on FSim simulation outputs (Finney et al., 2011) and SILVIS WUI data (Radeloff et al., 2005). See Section 2.2.2 and Appendices S1 and S2 for additional details.

model (Keane et al., 2006). The vegetation departure (VDEP) scores range from 0 to 100, the latter value indicating the maximum departure from historic conditions. Vegetation departure (hereafter forest departure) can stem from both surplus and deficiencies of species composition and structure. High values for VDEP in the inland Pacific Northwest are generally indicative of stand densification and changes in species composition towards fire intolerant species. VDEP replaces the earlier fire regime-condition class score, and both systems are widely used to prioritize stands and landscapes for treatments as specified in the National Fire Plan (USDA-USDI, 2001). The 30 m resolution data were averaged for each polygon (Fig. 3d).

2.2.4. Harvest volume from restoration thinning treatments

Forest Inventory Data (FIA) and Current Vegetation Survey (CVS) data were derived from the LEMMA (Ohmann and Gregory, 2002) project and consisted of gradient nearest neighbor (GNN) imputed inventory plot data of stand structure and tree species lists (with tree height and dbh) for each 30 × 30 m pixel in the study area (Appendix S1). The GNN grid of inventory plots was intersected with the stand polygon layer and the population of 30 m pixels that represented each stand was identified. We then simulated a restoration thinning in each stand using the Blue Mountains variant of the Forest Vegetation Simulator (FVS, Dixon, 2002). Thinning prescriptions were adopted from operational practices by local Forest silviculturists developed in detail in previous studies (Ager et al., 2007). Stands where stand density index (SDI, Cochran et al., 1994) exceeded 65% of the maximum were thinned with tree removal ordered from smallest to largest, thus reducing ladder fuels that contribute to crown fire. Stands were thinned to 35% of the maximum SDI for the stand. Thinning prescriptions targeted removal of late-seral, fire-intolerant species (grand fir) in mixed-species stands, favoring early seral species such as ponderosa pine, western larch (*Larix occidentalis* Nutt.) and Douglas-fir. For each stand we averaged total thin volume reported by FVS (cubic feet per acre) and converted to m^3 ha^{-1} (Fig. 3a).

2.2.5. Insect and disease risk

We used spatial data from the National Insect and Disease Risk Map (FHTET, 2012) that incorporates 186 individual risk models to

estimate basal area loss due to major insects and diseases over a 15-year future period (Appendix S1). The process uses host tree species maps, and ancillary data such as climate, topography, soils, pest occurrence, etc., to model risk of mortality for individual pest agents. Native data are generated nationally at 240 m resolution. We averaged total basal area loss grid values for each polygon to derive average estimated basal area mortality from insects and disease (Fig. 3c).

2.3. Spatial optimization model

We used the Landscape Treatment Designer (LTD, Ager et al., 2012, 2013) to model hypothetical restoration scenarios and identify tradeoffs among different restoration objectives. LTD has some similarity to the widely used Marxan with Zones (Watts et al., 2009), although the program has specific and unique features to solve the problem of treating landscapes to design forest restoration projects (versus designing conservation reserves) and is substantially less complex in terms of creating input files and processing outputs, thus enabling field application by planning specialists. LTD uses a stand polygon coverage attributed with landscape conditions relative to restoration objectives. The user supplies a restoration scenario in terms of objectives, activity constraints, and stand treatment thresholds, and the program identifies one or more project areas within the landscape and treatment areas that maximize the objective:

$$Max \sum_{j=1}^{k} \left(Z_j * \sum (W_i N_{ij}) \right) \qquad (1)$$

Subject to

$$\sum_{j=1}^{k} (Z_j A_j) \leq C \qquad (2)$$

where C is a global constraint on investment level per project area (e.g., area treated), Z is a vector of binary variables indicating whether the jth stand is treated (e.g., $Z_j = 1$ for treated stands and 0 for untreated stands), N_{ij} is the contribution to objective i in stand j if treated, and A is the area of the jth treated stand. W_i is a weighting coefficient that can be used to emphasize one objective versus another. The LTD algorithm uses a relatively simple search heuristic (Fig. S2) that tests each polygon as a seed to build a restoration project in the surrounding landscape, absorbing adjacent stands based on their potential contribution to the objective value, and treating those that exceed the treatment threshold. Stands within the project area that do not exceed the treatment threshold are absorbed into the project without contributing to the objective or activity (treated area) constraint. Thus simulated project areas resemble the composition of actual ones in terms of the mosaic of treated and untreated stands. Eventually the treatment area constraint (Eq. (2)) is met and the objective value is recorded for the project area. The process is repeated until all polygons have been tested as a seed and the project area that maximized the objective is reported, along with objective values and details describing the stands that required treatment. The program also generates image files showing project areas and treatments, and shapefiles attributed with objective values.

We modeled a hypothetical five year restoration program based on historical management activities in the study area. The scenario called for 20 sequentially optimized projects, each treating 5000 ha to address one or more of the restoration objectives described above. Overstocked stands were assumed to generate wood volume from thinning treatments as described above, and surface fuels

reduction (mastication and underburning) were also assumed to be part of treatments where appropriate, although these activities were not explicitly modeled. We assumed that each of the restoration objectives (e.g., insects and disease, departure, wildfire) would be addressed by thinning and other treatments, consistent with operational planning of project areas and proposed treatments throughout the western US national forests.

We then examined tradeoffs between selected combinations of different objectives by changing the relative weights of each objective (Eq. (1)). These comparisons focused on change in harvest volume (i.e., provisional ecosystem service) resulting from refocusing treatments to areas that required treatment to meet other objectives related to stressor reduction and fire protection. Integer weights were varied in all combinations from 0 to 4 in increments of 1 in a pairwise fashion. Outputs were used to generate production possibility frontier relationships between harvest volume and each objective. For instance, weights of 1 and 0 for objective A and B respectively, represent maximum production for objective A, whereas weights of 2 and 2 for each objective represent a mixed production for both.

The algorithm to spatially aggregate polygons into project areas evaluated adjacent polygons for inclusion in the project area based on average per area (ha) condition of the polygon. We used average instead of total polygon value to remove potential bias from polygon size. However, overall optimality of the project was based on the total objective value calculated as the area weighted quantity (e.g., total harvest volume) to account for the differential contribution to the objective from polygons of different size. Thus, polygons were added to project area based on the mean value of the objective for that polygon, and when the area treatment constraint was met (5000 ha) the total objective value was summed for each polygon in the project. To standardize the reporting of the different objectives we calculated percentage contribution of each polygon to the study area and summed these values for each project, thus providing a metric that could be easily interpreted among the various objectives.

2.4. Comparison of modeled with actual restoration projects

We compared optimal project areas derived from modeling with 14 restoration projects (Table S1) either implemented or near implementation since 2012. We overlaid treatment polygons for each of these projects on our restoration objective layers and calculated the attainment towards the goals using the same methods as in the simulation projects. Since actual project areas varied in size (1317–8894 ha), it was necessary to re-scale the attainment values to match the 5000 ha treatment areas in the modeled projects. We then plotted the resulting values on the PPF to examine the optimality of actual restoration projects.

3. Results

Potential restoration progress for a sequence of 20 spatially optimized projects (five year restoration program) varied substantially among the five objectives analyzed (Fig. 5). Optimized projects were located on areas that had 3–31% of the total restoration need within the study area (mean = 11%). The different levels of attainment among the five restoration scenarios were the result of variable spatial grain in landscape conditions with respect to restoration objectives. In general, optimizing projects for a single restoration objective was associated with low attainment for the other objectives (reduction of 10–30%), with the exception of forest departure, where attainment of the non-optimized variables were often higher by 1–2% (Table 1, Fig. 5d). The decline in attainment over the prioritized sequence of 20 projects also varied among
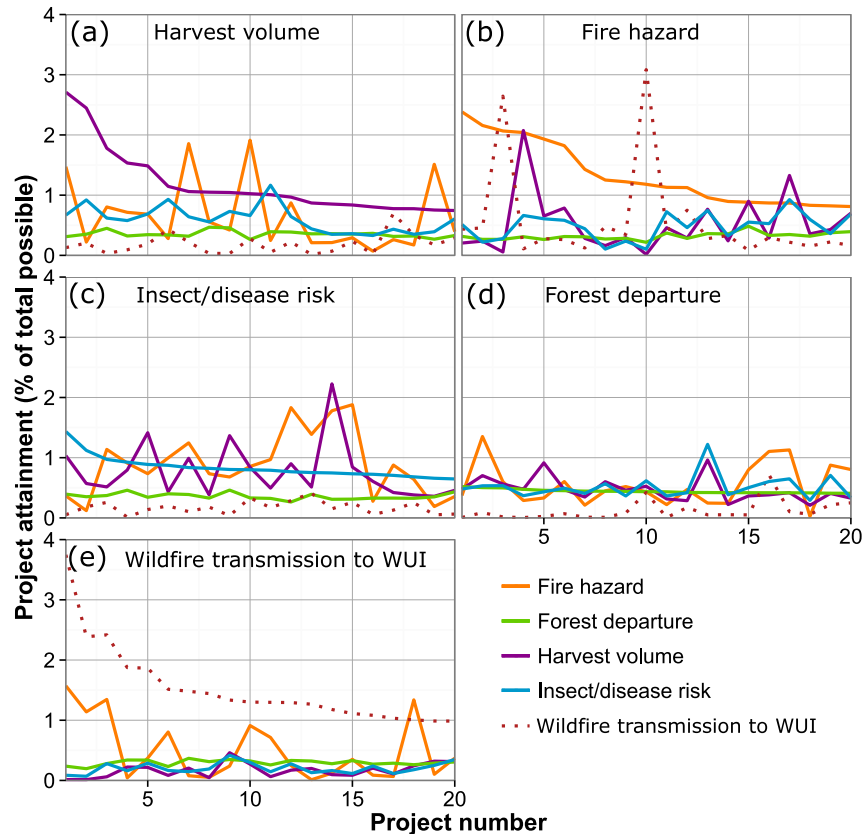
Fig. 5. Attainment of restoration objectives over a sequence of 20 projects on the Blue Mountains National Forests. Each panel shows outputs when one of the five restoration goals is optimized. (a) Total live stemwood harvest volume generated from thinning; (b) fire hazard as measured by average flame length from FlamMap (Finney, 2006); (c) insect and disease risk as measured by expected basal area mortality (FHTET, 2012); (d) forest departure based on LANDFIRE (2013); (e) wildfire transmission to the wildland urban interface (WUI) estimated from simulation (Finney et al., 2011).

restoration objectives, with WUI protection and harvest volume showing sharp declines between the most optimal (1st of 20) and lower priority projects (Fig. 5a,e). Forest departure and insect and disease risk exhibited relatively small differences among the sequence of optimized projects (Fig. 5c,d). Thus the value of spatial optimization and project prioritization for forest restoration programs varied among restoration objectives.

The spatial distribution of 20 optimal projects for each scenario (Fig. S3) was dispersed among all four national forests in the study area. Optimal projects for treating wildfire transmission to WUI were scattered widely, reflecting the distribution of communities and surrounding urban interface (Fig. 6a) while optimal projects for forest departure tended to be clustered in the central portion of the study area (Fig. 6b). Among all restoration objectives priority projects did not overlap spatially (Fig. S3). However there was an overlap of 2779 ha when the WUI protection scenario was not considered, or 0.2% of the treatable area. Insect risk, harvest volume

and fire hazard had the most project overlap with 10,808 ha (0.7% of the treatable area).

Total harvest volume across all 20 projects was over 2.4 million m^3 for the thinning scenario versus only 350,874 m^3 when wildfire transmission to WUI was prioritized. Potential economic viability of the projects was assessed in more detail by calculating percentage area within each project that exceeded a threshold of 35 m^3 ha^{-1} (500 ft^3 ac^{-1}). Harvest volumes at or above this level are generally considered to have positive economic benefits within the study area. In terms harvest volume over five restoration scenarios, area of stands within a single 5000 ha project that exceeded a thin threshold of 35 m^3 ha^{-1} (500 ft^3 ac^{-1}) was a high of 98% for the scenario where harvest volume was optimized, and a low of 0% for the WUI protection scenario. For the harvest volume scenario, the percentage of project area meeting a 35 m^3 ha^{-1} harvest volume threshold dramatically decreased from the 1st to 20th project (Fig. 7). In addition, the distribution of harvest volume within

Table 1
Restoration attainment values for five restoration objectives under a scenario where each variable is optimized within 20 projects with 5000 ha treated per project (100,000 ha total). Values represent percentage of total potential restoration attainment for the study area if all selected stands were treated.

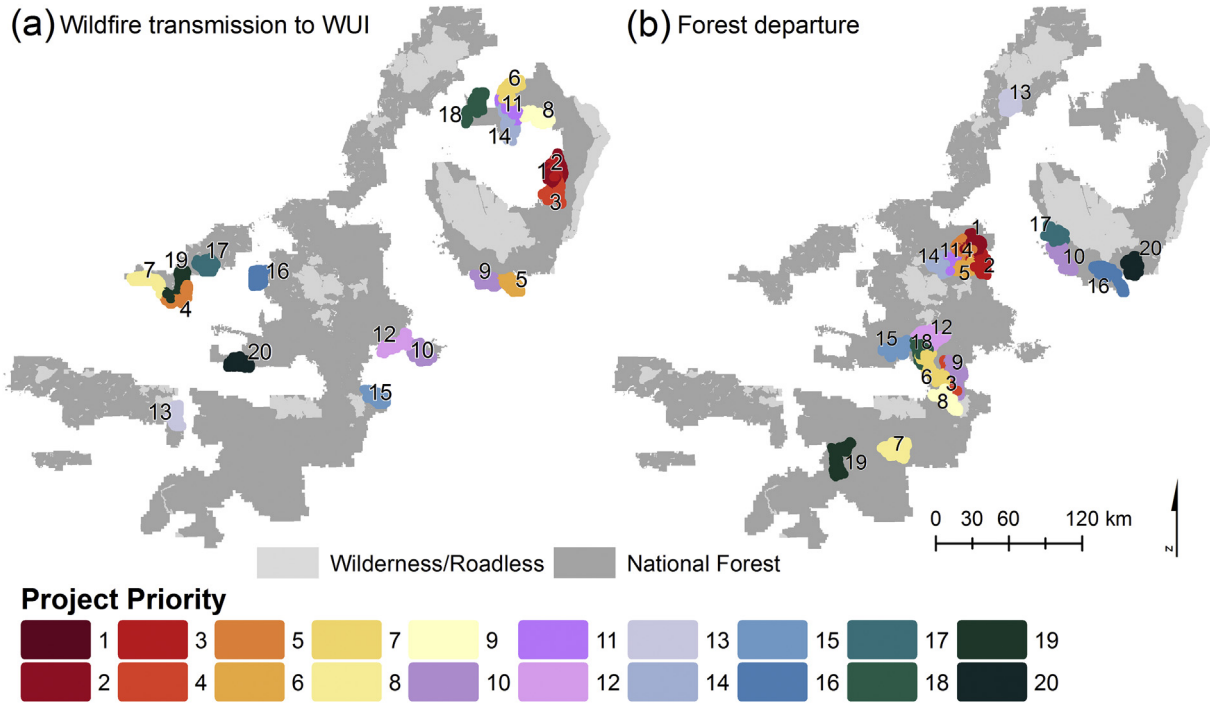| Restoration priority	Restoration outputs (% of total landscape)				
	Harvest volume	Forest departure	Fire hazard	Insect/disease risk	Wildfire transmission to WUI
Harvest volume	23.7	7.1	13.2	12.1	3.7
Forest departure	9.4	8.9	11.1	10.3	2.4
Fire hazard	10.5	6.4	26.7	9.7	11.1
Insect/disease risk	15.6	7.2	18.0	16.7	3.3
Wildfire transmission to WUI	3.4	5.9	10.0	4.1	30.6

Fig. 6. Optimal restoration project locations for a 5-year restoration scenario on the Blue Mountains National Forests prioritizing (a) wildfire transmission to the wildland urban interface (WUI) based on FSim simulation outputs (Finney et al., 2011) and (b) forest departure based on vegetation departure from LANDFIRE (2013). See Section 2.3 for details regarding calculations. Each project area treated 5000 ha. Project area boundaries were enlarged in mapping to make them more visible at this scale.

projects changed dramatically between the first and 20th project (Fig. 8).

Production possibility frontiers (PPF) between harvest volume (Fig. 9) and the other four restoration metrics were convex for the first priority project and the mean for all projects, and roughly concave for the 20th priority project. While restoration goals were coincident with harvest volume for response metrics such as forest departure and fire hazard, sharp tradeoffs were observed for the WUI protection scenario (Fig. 9d). Moreover tradeoffs became sharper as more projects were implemented. For instance the opportunity cost of increasing harvest volume in the highest priority project was generally lower than for the 20th project for all restoration objectives. Although the tradeoffs appear relatively
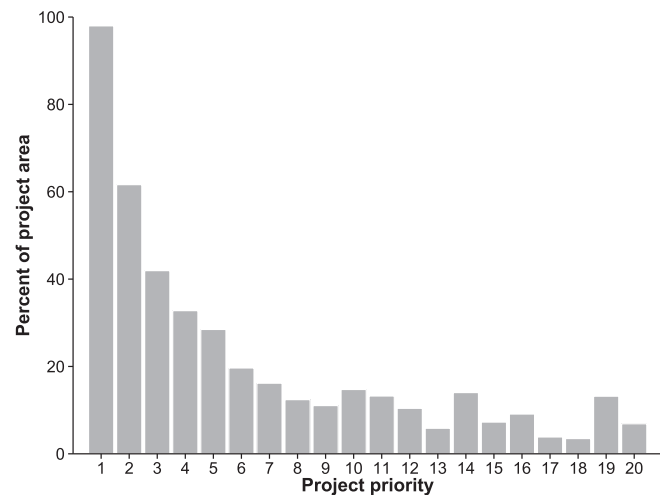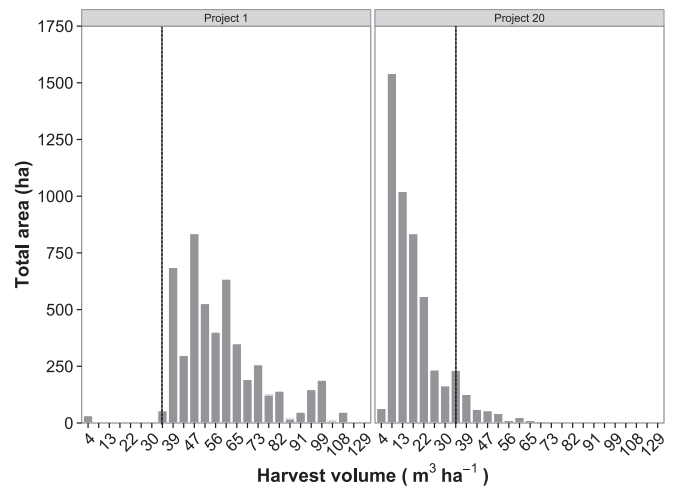

Fig. 8. Total treatable area in the Blue Mountains National Forests by harvest volume classes for the first (Project 1) and last (Project 20) priority project for optimizing harvest volume. Dotted vertical line indicates a reference harvest volume of 35 m^3 ha^{-1} (500 ft^3 ac^{-1}).

small on a percentage basis, the quatities in terms of restoration attainment are substantial, given that each scenario (20 projects) treats over 5% of the study area that is available for forest restoration treatments.

Project areas on the PPF were located in geographically distinct regions within the study area. For example, optimizing fire hazard versus harvest volume (Fig. 10) resulted in projects located in several locations including the southeastern portion of the Wallowa-Whitman (optimal fire hazard, Fig. 10, dark red project areas), and northeastern corner of the Umatilla (optimal harvest volume, Fig. 10, dark blue project areas; and a mix of both
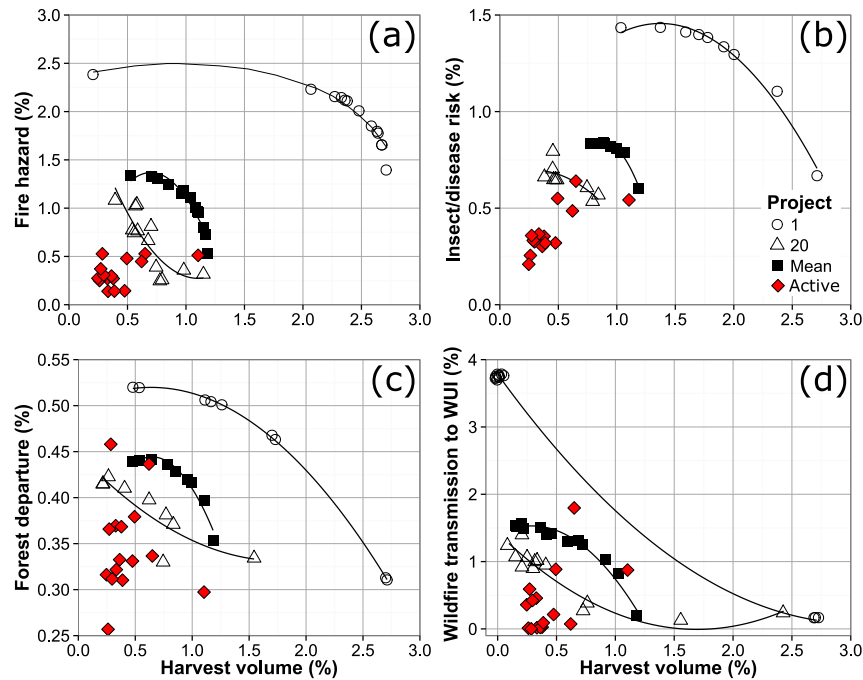

Fig. 7. Percent of total project area (5000 ha) with a harvest volume yield of ≥35 m^3 ha^{-1} (500 ft^3 ac^{-1}) over a sequence of 20 projects modeled to optimize harvest volume on the Blue Mountains National Forests.

Fig. 9. Production possibility frontiers between selected restoration objectives for a sequence of 20 restoration projects. The first (highest priority), 20th (lowest priority), and mean attainment for all projects are shown. Axes show attainment as a percentage of the total possible in the study area. Attainment of actual active projects planned by the Forest Service within the study area, as described in Table S1, are shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

objectives, orange project areas).

Comparison of optimized projects with a sample of 14 active projects from the four national forests showed that in general planned projects were located well inside of the PPF for the first and 20th projects, but in three cases were above the mean value (Fig. 9c and d). Moreover we did not observe projects at either

Fig. 10. Production possibility frontier for fire hazard and harvest volume, and associated project area location for the northeastern Wallowa-Whitman and Umatilla National Forests. See Fig. 2.

extreme of the different PPFs, with most projects being relatively balanced with respect to the attainment of one objective versus the other. The attainment of restoration goals was lowest for wildfire transmission to WUI among the metrics analyzed.

4. Discussion

To our knowledge this work is the first to apply spatial optimization to quantify socioecological tradeoffs and production frontiers for a large-scale terrestrial restoration program. The model is relatively simple to use compared to other exact (e.g., integer programming) optimization systems (Appendix S3) and is now being applied as part of the restoration efforts in several regions in the western US to prioritize planning areas and analyze tradeoffs. In other recent work, we examined priorities and tradeoffs for a portion of the study area (Wallowa-Whitman NF) using similar restoration metrics and a scenario where planning areas were defined by watershed boundaries on the national forest (Vogler et al., 2015). Rather than using spatial optimization, restoration goals were maximized within each planning area by simply sorting the stands based on their contribution to the objective. However, this latter approach has several limitations, the foremost being that relatively few national forests expend the effort to build comprehensive planning area maps, and the use of pre-defined planning boundaries precludes the identification of spatially optimized planning areas.

The value of prioritizing restoration projects was clearly shown for the study area for specific restoration metrics (Fig. 5). Our study area was representative of many other national forests in the western US, and thus this overall finding can likely be extrapolated beyond the study area. We believe that the model and methods can be utilized by federal forest restoration programs in many ways including: 1) prioritization of restoration projects at multiple scales on public and adjoining private lands, 2) identification and
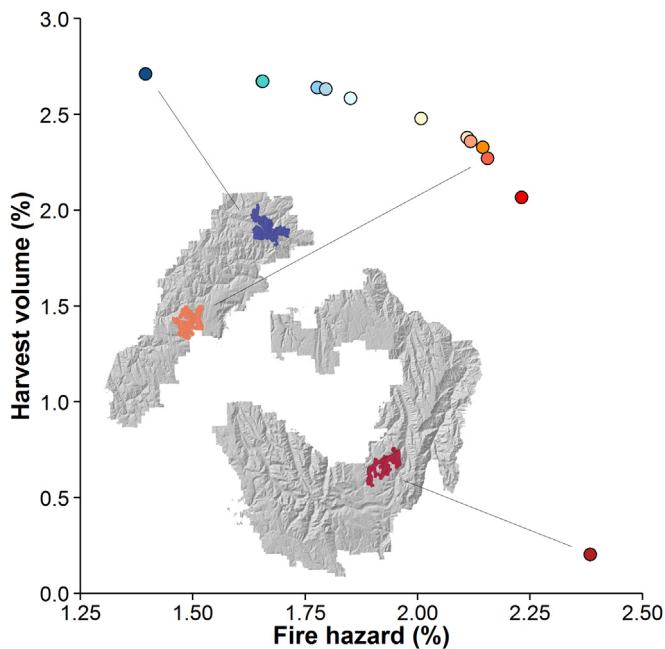
mapping of conflicts between ecological restoration and socioeconomic objectives, 3) measuring efficiency of ongoing restoration projects compared to optimal production frontiers, 4) assessment of fire transmission among public and private land parcels as a prioritization metric, and 5) finding socially acceptable regions along the PPF (King et al., 2015) as part of collaborative restoration planning (Schultz et al., 2012; Butler et al., 2015). Clear tradeoffs were observed among the various restoration goals resulting from the lack of spatial covariance among different stressors and ecosystems services (Anderson et al., 2009; Allan et al., 2013). Federal forest restoration policy in the US has long assumed a strong spatial correlation among the various goals (USDA Forest Service, 2006). However, linkages between forest departure, provisional ecosystem services, and community wildfire protection issues are weakened by past wildfires, harvesting activities, variation in ecological conditions, and spatial patterns of socioeconomic values, especially at the scale at which restoration projects are planned and executed on US national forests (e.g., 5000—25,000 ha). Specific ecological tradeoffs noted in the results stem from the diversity of existing forest structure and species composition within the study area. For instance, high insect-caused mortality is both observed and predicted in dense, mature lodgepole pine forests that grow in mid-to high-elevation cold forests. Conversely, many WUIs are located in lower elevation forest—grassland transition zones that have high forest departure from fire exclusion, and low potential thin volume due to historical harvesting activities. By contrast, mixed conifer forests in moist settings have high productivity and departure from fire exclusion and relatively high potential thin volumes.

Our comparison of actual forest restoration projects with production frontiers provided an opportunity to analyze local efficiency of widespread restoration and fuel management activities on federal lands in the US (Fig. 9). Evaluating restoration progress is generally recognized as a difficult problem and needs to consider both ecological and socioeconomic outcomes (Wortley et al., 2013). We demonstrated how production frontiers combined with empirical data on ongoing projects can be used to establish targets and monitoring benchmarks that are needed for restoration programs (Wortley et al., 2013). Our analyses suggested that recently implemented restoration projects were generally suboptimal with respect to key restoration metrics (Fig. 9), which is not surprising since tools have heretofore not been available to identify landscape production frontiers for restoration projects.

Unlike many other terrestrial restoration programs, forest restoration has the potential to generate provisional ecosystem services (revenue from harvested wood) that can partially fund the program (Deal et al., 2012; USDA Forest Service, 2012). However, both restoration and fire protection projects do not typically generate high-value materials (Rainville et al., 2008). The juxtaposition of ecological settings with human values generates sharp tradeoffs between community wildfire protection and these provisional ecosystem services. These tradeoffs complicate prioritization of restoration programs for economic objectives, which aim to generate revenue to both support expanded restoration activities in areas that will not generate positive revenues, and improve community resilience in rural areas (USDA-USDI, 2014). Our study specifically showed a sharp decline in the production of wood material with decreasing project priority, and the 4th project out of the top 20 had little commercial wood material (Fig. S4).

The application of spatial optimization for prioritizing restoration of fire-prone forests offers several important advances over existing methods used in US federal land management agencies. Current policy dictates a prioritization process based on a stand-scale fire regime-condition class rating that measures fire exclusion on a stand by stand basis (USDA-USDI, 2001). The evaluation process ignores fuel contagion that can catalyze large fires on national forests and transmit fire to the WUI. Moreover, consideration of economic and social viability of projects is left to an ad hoc process of pondering large numbers of maps in collaborative settings without knowledge concerning tradeoffs and optimal project design. Understanding tradeoffs with spatial optimization and production possibility frontiers is arguably a key precursor to the development and prioritization of restoration and conservation plans (Allan et al., 2013).

Studies on tradeoffs and spatial prioritization in conservation biology and natural resource literature cover a diverse range of ecosystems and associated services (Maron and Cockfield, 2008; Chhatre and Agrawal, 2009; Hauer et al., 2010; White et al., 2012; Schroter et al., 2014; Cattarino et al., 2015). For instance Allan et al. (2013) examined joint analysis of stressors and ecosystem services on restoration effectiveness and provisioning services in the Great Lakes region of the US, focusing on a wide range of stressors and their spatial distributions. Schroter et al. (2014) examined the problem of tradeoffs between creating forest protected areas and timber production, and calculated the opportunity cost to inform conservation policy development. In the current study the focus was on restoring ecological processes on a landscape rather than conservation of specific biodiversity values as in many previous studies discussed above.

It is well recognized that social barriers pose a substantial challenge to restoration programs on federal forests (Franklin et al., 2014). The enactment of the Collaborative Forest Landscape Restoration Program (USDA Forest Service, 2016) provides for public participation in restoration planning to facilitate trust and conflict resolution among diverse stakeholders that derive ecosystem services from federal forests (Butler et al., 2015). However, without science-based decision support tools to prioritize and quantify tradeoffs, collaborative planning groups are missing strategic information about the opportunity cost associated with their particular values and interests in terms of long range progress towards socioecological restoration goals.

Modeling forest restoration programs poses many challenges and a number of assumptions concerning the impact of treatment on stressors were implicit in the study. For instance, we assumed that stands selected for active restoration would receive the appropriate suite of treatments including mechanical thinning, fuels mastication, and underburning, thereby addressing the particular issue at hand. We also assumed that treatments substantially reduced forest departure, insect and disease issues, and wildfire transmission to the WUI. These assumptions are not inconsistent with current operational planning on the national forests and literature (Brown et al., 2004). Our modeled projects assumed restoration treatments in every stand within the project area, thus affecting significant landscape-scale change in forest conditions to improve resiliency to natural disturbance.

Landscape decision support tools to prioritize restoration management in the western US will play an increasingly important role in the development of restoration programs and contribute to the process of creating resilient forests while meeting concomitant demands for biodiversity, amenity values, and socioeconomic outputs (Noss et al., 2009). Optimization models can facilitate attainment of these goals by prioritizing management activities, and identifying opportunities, conflicts, and investment tradeoffs (Christensen and Walters, 2004). Future work on production possibilities for restoration should also account for long-term landscape policy and disturbance feedbacks (fire, insects and disease) and their effects on tradeoffs over time (Spies et al., 2014; Rappaport et al., 2015). Understanding social constraints as part of restoration programs (Franklin et al., 2014) will also be an important step to improve collaborative restoration planning, and

potentially can be accomplished by combining social preferences with PPFs as advocated in other studies (see Fig. 1 in King et al., 2015). Future work can help link prioritization across the multiple scales of restoration planning, from national forests to landscapes, stands, and tree neighborhoods (Larson and Churchill, 2012). As in other restoration systems (Wilson et al., 2011; Rappaport et al., 2015), quantitative prioritization and tradeoff analyses are an important step in US forest restoration programs to achieve long-term goals of creating fire resilient landscapes and fire adapted communities, as well as sustaining the myriad of ecosystem services generated from public lands.

Acknowledgments

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.01.033.

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. 211, 83—96.

Ager, A.A., Day, M.A., McHugh, C.W., Short, K., Gilbertson-Day, J., Finney, M.A., Calkin, D.E., 2014. Wildfire exposure and fuel management on western US national forests. J. Environ. Manag. 145, 54—70.

Ager, A.A., Day, M.A., Short, K.C., Evers, C.R., 2015. Assessing the impacts of federal forest planning on wildfire risk mitigation in the Pacific Northwest, USA. Landsc. Urban Plann. 147, 1—17.

Ager, A.A., Hayes, J.L., Schmitt, C.L., 2004. Simulating mortality from forest insects and diseases. In: Hayes, J.L., Barbour, R.J. (Eds.), Methods for Integrated Modeling of Landscape Change: Interior Northwest Landscape Analysis System. Gen. Tech. Rep. PNW-GTR-610. USDA Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 104—116.

Ager, A.A., McMahan, A.J., Barrett, J.J., McHugh, C.W., 2007. A simulation study of thinning and fuel treatments on a wildland-urban interface in eastern Oregon, USA. Landsc. Urban Plann. 80, 292—300.

Ager, A.A., Vaillant, N., Owens, D.E., Brittain, S., Hamann, J., 2012. Overview and Example Application of the Landscape Treatment Designer. Gen. Tech. Rep. PNW-GTR-859. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Ager, A.A., Vaillant, N.M., McMahan, A., 2013. Restoration of fire in managed forests: a model to prioritize landscapes and analyze tradeoffs. Ecosphere 4, 29.

Allan, J.D., McIntyre, P.B., Smith, S.D.P., Halpern, B.S., Boyer, G.L., Buchsbaum, A., Burton Jr., G.A., Campbell, L.M., Chadderton, W.L., Ciborowski, J.J.H., Doran, P.J., Eder, T., Infante, D.M., Johnson, L.B., Joseph, C.A., Marino, A.L., Prusevich, A., Read, J.G., Rose, J.B., Rutherford, E.S., Sowa, S.P., Steinman, A.D., 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. Proc. Natl. Acad. Sci. 110, 372—377.

Anderson, B.J., Armsworth, P.R., Eigenbrod, F., Thomas, C.D., Gillings, S., Heinemeyer, A., Roy, D.B., Gaston, K.J., 2009. Spatial covariance between biodiversity and other ecosystem service priorities. J. Appl. Ecol. 46, 888—896.

Barrett, S., Havlina, D., Jones, J., Hann, W., Frame, C., Hamilton, D., Schon, K., Demeo, T.E., Hutter, L., Menakis, J., 2010. Interagency Fire Regime Condition Class Guidebook. Version 3.0. USDA Forest Service, US Department of Interior, and The Nature Conservancy, Homepage of the Interagency Fire Regime Condition Class website. https://www.frames.gov/files/7313/8388/1679/FRCC_Guidebook_2010_final.pdf.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394—1404.

Brown, R.T., Agee, J.K., Franklin, J.F., 2004. Forest restoration and fire: principles in the context of place. Conserv. Biol. 18, 903—912.

Bullock, J.M., Aronson, J., Newton, A.C., Pywell, R.F., Rey-Benayas, J.M., 2011. Restoration of ecosystem services and biodiversity: conflicts and opportunities. Trends Ecol. Evol. 26, 541—549.

Butler, W.H., Monroe, A., McCaffrey, S., 2015. Collaborative implementation for ecological restoration on US public lands: implications for legal context, accountability, and adaptive management. Environ. Manag. 55, 564—577.

Cattarino, L., Hermoso, V., Carwardine, J., Kennard, M.J., Linke, S., 2015. Multi-action planning for threat management: a novel approach for the spatial prioritization

of conservation actions. Plos One 10 (5), e0128027.

Cavender-Bares, J., Balvanera, P., King, E., Polasky, S., 2015a. Ecosystem service trade-offs across global contexts and scales. Ecol. Soc. 20, 22.

Cavender-Bares, J., Polasky, S., King, E., Balvanera, P., 2015b. A sustainability framework for assessing trade-offs in ecosystem services. Ecol. Soc. 20, 17.

Chhatre, A., Agrawal, A., 2009. Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. Proc. Natl. Acad. Sci. 106, 17667—17670.

Christensen, V., Walters, C.J., 2004. Trade-offs in ecosystem-scale optimization of fisheries management policies. Bull. Mar. Sci. 74, 549—562.

Cochran, P.H., Geist, J.M., Clemens, D.L., Clausnitzer, R.R., Powell, D.C., 1994. Suggested Stocking Levels for Forest Stands in Northeastern Oregon and Southeastern Washington. Res. Note PNW-RN-513. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Deal, R.L., Cochran, B., LaRocco, G., 2012. Bundling of ecosystem services to increase forestland value and enhance sustainable forest management. For. Policy Econ. 17, 69—76.

Dixon, G.E., 2002. Essential FVS: a User's Guide to the Forest Vegetation Simulator. Internal Report. USDA Forest Service, Forest Management Service Center, Fort Collins, CO.

FHTET, 2012. 2012 National insect & disease risk map. In: USDA Forest Service, Forest Health Technology Enterprise Team.

Finney, M.A., 2006. An overview of FlamMap fire modeling capabilities. In: Fuels Management-How to Measure Success. Proceedings RMRS-P-41. USDA Forest Service, Rocky Mountain Research Station, Portland, OR, pp. 213—220.

Finney, M.A., McHugh, C.W., Grenfell, I.C., Riley, K.L., Short, K.C., 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stoch. Environ. Res. Risk Assess. 25, 973—1000.

Franklin, J.F., Hagmann, R.K., Urgenson, L.S., 2014. Interactions between societal goals and restoration of dry forest landscapes in western North America. Landsc. Ecol. 29, 1645—1655.

Franklin, J.F., Johnson, K.N., 2012. A restoration framework for federal forests in the Pacific Northwest. J. For. 110, 429—439.

Gaines, W.L., Harrod, R.J., Dickinson, J., Lyons, A.L., Halupka, K., 2010. Integration of Northern spotted owl habitat and fuels treatments in the eastern Cascades, Washington, USA. For. Ecol. Manag. 260, 2045—2052.

Hagmann, R.K., Franklin, J.F., Johnson, K.N., 2013. Historical structure and composition of ponderosa pine and mixed-conifer forests in south-central Oregon. For. Ecol. Manag. 304, 492—504.

Hauer, G., Cumming, S., Schmiegelow, F., Adamowicz, W., Weber, M., Jagodzinski, R., 2010. Tradeoffs between forestry resource and conservation values under alternate policy regimes: a spatial analysis of the western Canadian boreal plains. Ecol. Model. 221, 2590—2603.

Keane, R.E., Holsinger, L.M., Pratt, S.D., 2006. Simulating Historical Landscape Dynamics Using the Landscape Fire Succession Model LANDSUM Version 4.0. Gen. Tech. Rep. RMRS-GTR-171CD. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

King, E., Cavender-Bares, J., Balvanera, P., Mwampamba, T.H., Polasky, S., 2015. Trade-offs in ecosystem services and varying stakeholder preferences: evaluating conflicts, obstacles, and opportunities. Ecol. Soc. 20, 25.

LANDFIRE, 2013. Homepage of the LANDFIRE Project. USDA Forest Service and USDI.

Larson, A.J., Churchill, D., 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. For. Ecol. Manag. 267, 74—92.

Maron, M., Cockfield, G., 2008. Managing trade-offs in landscape restoration and revegetation projects. Ecol. Appl. 18, 2041—2049.

Moilanen, A., Wilson, K.A., Possingham, H.P., 2009. Spatial Conservation Prioritization: Quantitative Methods and Computational Tools. Oxford University Press, Oxford.

Moore, M.M., Covington, W.W., Fule, P.Z., 1999. Historical variability concepts in ecosystem management-reference conditions and ecological restoration: a Southwestern ponderosa pine perspective. Ecol. Appl. 9, 1266—1277.

Myers, R.L., 1995. Designing fire regimes for biodiversity conservation. In: First Conference on Fire Effects on Rare and Endangered Species and Habitats. International Association of Wildland Fire, Coeur D'Alene, Idaho, p. 1.

Noss, R., Nielsen, S., Vance-Boland, K., 2009. Prioritizing ecosystems, species and sites for restoration (Chapter 12). In: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), Spatial Conservation Prioritization: Quantitative Methods and Computational Tools. Oxford University Press, Oxford, pp. 158—170.

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T., Moyle, P.B., 2006. Managing fire-prone forests in the western United States. Front. Ecol. Environ. 4, 481—487.

Ohmann, J.L., Gregory, M.J., 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, USA. Can. J. For. Res. 32, 725—741.

Prather, J.W., Noss, R.F., Sisk, T.D., 2008. Real versus perceived conflicts between restoration of ponderosa pine forests and conservation of the Mexican spotted owl. For. Policy Econ. 10, 140—150.

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., McKeefry, J.F., 2005. The wildland-urban interface in the United States. Ecol. Appl. 15, 799—805.

Rainville, R., White, R., Barbour, J., 2008. Assessment of Timber Availability from Forest Restoration within the Blue Mountains of Oregon. Gen. Tech. Rep. PNW-GTR-752. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Rappaport, D.I., Tambosi, L.R., Metzger, J.P., 2015. A landscape triage approach: combining spatial and temporal dynamics to prioritize restoration and conservation. J. Appl. Ecol. 52, 590–601.

Rasmussen, M., Lord, R., Vickery, B., McKetta, C., Green, D., Green, M., Hemstrom, M., Potiowsky, T., Renfro, J., 2012. National Forest Health Restoration: an Economic Assessment of Forest Restoration on Oregon's Eastside National Forests (Prepared for: Governor John Kitzhaber and Oregon's Legistlative Leaders).

Rieman, B.E., Hessburg, P.F., Luce, C., Dare, M.R., 2010. Wildfire and management of forests and native fishes: conflict or opportunity for convergent solutions? Bioscience 60, 460–468.

Roccaforte, J.P., Fulé, P.Z., Covington, W.W., 2008. Landscape-scale changes in canopy fuels and potential fire behaviour following ponderosa pine restoration treatments. Int. J. Wildland Fire 17, 293–303.

Schroter, M., Rusch, G.M., Barton, D.N., Blumentrath, S., Norden, B., 2014. Ecosystem services and opportunity costs shift spatial priorities for conserving forest biodiversity. Plos One 9, e112557.

Schultz, C.A., Jedd, T., Beam, R.D., 2012. The Collaborative Forest Landscape Restoration Program: a history and overview of the first projects. J. For. 110, 381–391.

Short, K.C., 2015. Spatial Wildfire Occurrence Data for the United States, 1992-2013 [FPA_FOD_20150323], third ed. USDA Forest Service, Rocky Mountain Research Station.

SILVIS Lab, 2012. 2010 Wildland Urban Interface (WUI) Maps. University of Wisconsin, Madison, WI.

Spies, T.A., White, E.M., Kline, J.D., Fischer, A.P., Ager, A.A., Bailey, J., Bolte, J., Koch, J., Platt, E., Olsen, C.S., Jacobs, D., Shindler, B., Steen-Adams, M.M., Hammer, R., 2014. Examining fire-prone forest landscapes as coupled human and natural systems. Ecol. Soc. 9.

USDA-USDI, 2001. National Fire Plan. A Collaborative Approach for Reducing Wildland Fire Risks to Communities and the Environment. United States Department of Agriculture-United States Department of Interior, Washington, DC.

USDA-USDI, 2014. The National Strategy: the Final Phase in the Development of the National Cohesive Wildland Fire Management Strategy.

USDA Forest Service, 2006. Ecosystem Restoration: a Framework for Restoring and Maintaining the National Forests and Grasslands. USDA Forest Service, Washington, DC.

USDA Forest Service, 2012. Increasing the Pace of Restoration and Job Creation on Our National Forests. USFS Report. United States Department of Agriculture, Forest Service, Washington, D.C.

USDA Forest Service, 2013. Restoration of Fire-dependent Forests: a Sense of Urgency. USDA Forest Service, Pacific Northwest Region, Portland, OR.

USDA Forest Service, 2016. Collaborative Forest Landscape Restoration Program. USDA Forest Service.,.

Vogler, K.C., Ager, A.A., Day, M.A., Jennings, M., Bailey, J.D., 2015. Prioritization of forest restoration projects: tradeoffs between wildfire protection, ecological restoration and economic objectives. Forests 4403–4420.

Watts, M.E., Ball, I.R., Stewart, R.S., Klein, C.J., Wilson, K., Steinback, C., Lourival, R., Kircher, L., Possingham, H.P., 2009. Marxan with zones: software for optimal conservation based land- and sea-use zoning. Environ. Model. Softw. 24, 1513–1521.

White, C., Halpern, B.S., Kappel, C.V., 2012. Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. Proc. Natl. Acad. Sci. 109, 4696–4701.

Wilson, K.A., Lulow, M., Burger, J., Fang, Y., Andersen, C., Olson, D., O'Connell, M., McBride, M.F., 2011. Optimal restoration: accounting for space, time and uncertainty. J. Appl. Ecol. 48, 715–725.

Wortley, L., Hero, J.M., Howes, M., 2013. Evaluating ecological restoration success: a review of the literature. Restor. Ecol. 21, 537–543.