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The economic reality of the forest and fuel management deficit on a fire prone western US national forest

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ABSTRACT

Recent extreme wildfire seasons in the United States (US) have rekindled policy debates about the underlying drivers and potential role forest management can play in reducing fuels and future wildfire. Most US western national forests face a substantial backlog of treatments and manifold management issues related to wildfire, forest health, and wildfire protection and constitute the major part of the wildfire problem. However, the precise schedule and detailed assessments that map the type and amount of treatments needed, as well as the associated cost are rarely assessed. We simulated restoration trajectories on the US fire prone Umatilla National Forest that faces complex management challenges related to wildfire and forest resiliency. The treatments were targeted to specific ecological conditions based on a decision tree developed in consultation with specialists. Planning areas were then prioritized based on fire protection of the wildland-urban interface (WUI), forest products, and stand resiliency. The results revealed a backlog of 211,893 ha, that when treated would generate $320 million in revenue from forest products, and cover 80% of the forest. The treatment area estimate was more than double prior estimates based on ecological departure from historic condition. Financial sensitivity analysis showed that high priority fuel treatments were revenue positive on 22% of the planning areas. The study established a restoration blueprint in terms of amount, location, and treatment type to support funding requests to the agency and schedule internal and external capacity to complete the work. The work also contributes to ongoing collaborative restoration planning to help stakeholders understand the opportunity cost of specific restoration objectives. The case study and framework can be widely extrapolated to the national forests in the western US to improve financial evaluation of forest and fuel management and estimate future management inputs. This work represents a rare instance of a bottom-up spatially explicit assessment of a restoration backlog, and prioritization of planning areas to reduce that backlog on a US national forest.

1. Introduction

The 2020 wildfire season in the western US exposed society to extreme wildfire events that, despite extensive literature on future wildfire risk, were not predicted. These and other recent extreme wildfire seasons in the US have rekindled policy debates about the potential role forest management can play in reducing fuels and future wildfires and the cost to change the current wildfire trajectory. Forest and fuel management programs in the US and globally are guided by broad principles of forest landscape restoration to "regain ecological integrity and enhance human well-being in deforested or degraded landscapes" (Mansourian and Vallauri, 2005; Hessburg et al., 2015). However, on public lands, programs to reduce fuels and restore wildfire resiliency face substantial challenges to accelerate treatments at the scale that might affect fires burning at the "gigafire" scale (>1 million acres (Gabbert, 2020)).

Forest landscapes in the western US are historically dependent on fairly frequent, low- to moderate-severity fire regimes (Collins et al., 2010). However, widespread habitat degradation and uncharacteristic fire, insect, and disease outbreaks have led to the current departure from historical forest structure and natural range of variation, in need of restoration (Haugo et al., 2015). In the western US, restoration

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treatments are designed to at least temporarily restore the structure of forests that are typically overstocked with shade tolerant late seral forest tree species (Ager et al., 2007). Restoration treatments include thinning followed by surface fuels treatments such as mastication and broadcast burning (Jain et al., 2012) that take into consideration the fire dependency of the system and historical forest community structure. Those treatments restore forest resiliency in the sense of promoting forest health and reducing impacts of wildfire (USDA Forest Service, 2016a; Stephens et al., 2021).

On US federal forests lands, restoration programs are implemented in projects ranging from 5000 to 50,000 ha, and include a commercial timber and biomass revenue component to ensure that projects are implemented by private contractors that perform the mechanical activities and contribute to rural economies (USDA Forest Service, 2016b). The Collaborative Forest Landscape Restoration Program (CFLRP) and similar legislated programs have substantially expanded the scale of projects and accelerated implementation via collaborative networks (Butler et al., 2015). In the long run, the hope is that restoration treatments will be followed up by management including broadcast burning that will sustain wildfire resilience into the future (Babbitt and Glickman, 2000). However, even for initial restoration treatments, costs for planning, infrastructure, and some of the treatments, including broadcast and pile burning, are borne by the federal government, and current funding and agency capacity is insufficient to ensure wider implementation of forest restoration programs. Detailed assessments of precisely what types of treatments are needed, where, and how much they will cost to meet fire management objectives, including improving landscape resiliency to wildfire, and decreasing wildfire risk to developed areas, are rare. Currently, in the US Forest Service the only systematic assessment of the "restoration backlog" estimates that 80 million acres are in need of some kind of treatment (Statements, 2018).

Despite extensive multicriteria decision support tools and spatial models that have been developed for forest management (Pukkala and Kangas, 1993; Kangas et al., 2000; Reynolds et al., 2009; Borges et al., 2017) and other restoration environments (Maron and Cockfield, 2008; Vogler et al., 2015; Pohjanmies et al., 2019), few of these closely examine financial aspects and define what it would take in terms of investments and treated area to achieve the restored condition. Most literature in forested and other systems has been concerned with balancing the many and diverse goals that are inherent with forest management on public lands including wildfire risk reduction, wildlife habitat improvement, resiliency, biodiversity, water resources, and other tangible and intangible benefits (Collins et al., 2010, Gaines et al., 2010, USDA Forest Service, 2011, Schroder et al., 2016, Cleland et al., 2017). The multi-objective nature of land management goals has motivated many studies to understand spatial and temporal trade-offs, especially between ecological and fire protection objectives (Hartsough et al., 2008; Bullock et al., 2011; Schroder et al., 2016; Syphard et al., 2016; Triviño et al., 2017). However, none of this work has specifically identified a blueprint and financial plan for addressing treatment needs on a large fire prone landscape (>500,000 ha), including a mix of restoration treatments and the associated costs for each one. Detailed assessments of treatment requirements to restore fire resiliency and associated costs as decribed in this paper can be expanded over larger scales to better quantify the financial resources required to reduce the backlog of areas needing treatment.

In this paper we address the gap in the aforementioned assessments by first conducting a detailed assessment of the restoration "backlog" on a 267,599 ha fire prone national forest in the interior Pacific Northwest USA. This assessment identified the suite of treatments in each of the 40 planning areas on the forest to meet restoration goals, along with the costs and revenues if the treatments were implemented, providing a blueprint or action plan for the forest for the next 5–10 years. We then examined the extent to which revenue generated from forest management offset surface fuel treatments and non-commercial thinning activities, thereby expanding the treatment area. In this way the financial dynamics of projects in relation to increasing restoration area could be examined for break-even points. Although this practice is not new, the extent to which the project shape, size and treatment portfolio can be optimized to maximize area treated and thus minimize reliance on external financial subsidies has not been modeled at the landscape scale (Barbour et al., 2008; Ager et al., 2017). The analyses identified the sensitivity of treatment type and arrangement on the financial viability of the projects that has heretofore not been reported. We discuss the manifold benefits to public land management agencies for this type of assessment and the requirements to complete similar assessments over wider areas. This work represents the first spatially explicit, economic assessment of the restoration portfolio backlog, and prioritization of planning areas and treatments to effectively reduce it under multiple objective priority schemes.

2. Materials and methods

2.1. Study area

Our study area is the Umatilla National Forest (Umatilla NF) in the Blue Mountains ecoregion (USDA Forest Service, 1994) of northeast Oregon and southeast Washington in the US (Fig. 1). The Umatilla NF is about 520,000 ha in size, mostly located in elevations ranging from 500 m to 1500 m with highest peaks close to 2300 m. The region has a Mediterranean climate with a mean annual temperature of 7.5 °C and average annual precipitation of 518 mm, with most precipitation falling in the winter, including rain and snow. The vegetation is characterized by mixed dry forests with different dominant species, mainly ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) in lower elevations, and dry mixed conifer (grand fir (*Abies grandis (*Douglas ex D. Don) Lindl) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)) at higher elevations. Cold-dry forests found at mid to high elevation areas are dominated by lodgepole pine (*Pinus contorta* Douglas ex Loudon).

Our analysis was conducted on 267,599 ha designated for active forest management excluding special management designation areas (i.e., wilderness, research natural areas, inventoried roadless areas, experimental forest and riparian habitats), non-forested areas (i.e. grasslands, shrubland, etc.) and non-vegetation areas (i.e., rock, water, etc.) (USDA Forest Service, 2016b). The study area was broken into 40 landscape management planning areas (PAs) based on 12th field hydrological unit (HUCs) watersheds which were combined to meet the minimum area requirements for planning. Each PA ranges from 6303 to 31,128 ha in size with an average of about 6700 ha (Fig. 1).

The study area was heavily managed for timber production until the mid-1990s. In the last two decades, maximal even flow harvesting polices were implemented producing 0.56 million cubic meters of timber per year on average (USDA Forest Service, 2016b). Intensive timber management, over a century-of fire suppression practices and frequent natural disturbances, such as insect outbreaks and wildfires, collectively altered forest structure and species composition leaving the landscape currently vulnerable to large-scale disturbances. Stand density has tripled in the region over the past 90 years and the proportion of large, fire resistant trees (>53 cm diameter at breast height (d.b.h.)) decreased by more than five times (Hagmann et al., 2013).

2.2. Stand data

Individual forest stands were defined using corporate USDA Forest Service spatial databases. The stand layer was obtained from the Umatilla NF and used for project planning with stand boundaries following natural breaks in vegetation type and changes in stand structure from past management activities. Each stand was attributed with data on potential vegetation and stand inventories. A total of 34,144 stands were included in our study area that are available for restoration treatment. Forest stands range in size from 1 ha to 261 ha with an average of 7.6 ha. The available stands were grouped into the 40 PAs. Each PA contains

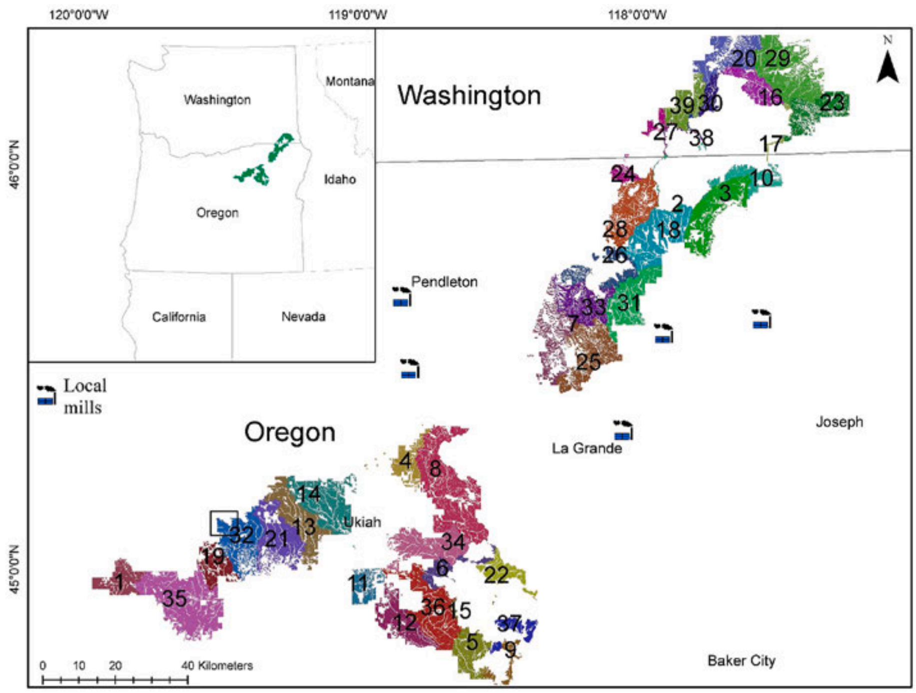

Fig. 1. A study area map showing 40 planning areas across the Umatilla National Forest and local mill locations. Local mills were considered in this study for timber production revenue and haul cost estimation.

880 stands on average (Fig. 1).

2.3. Decision key for assigning treatments to stands

Extensive consultation with Forest Service Staff on the Umatilla NF led to the development of a decision key to assign treatment packages to

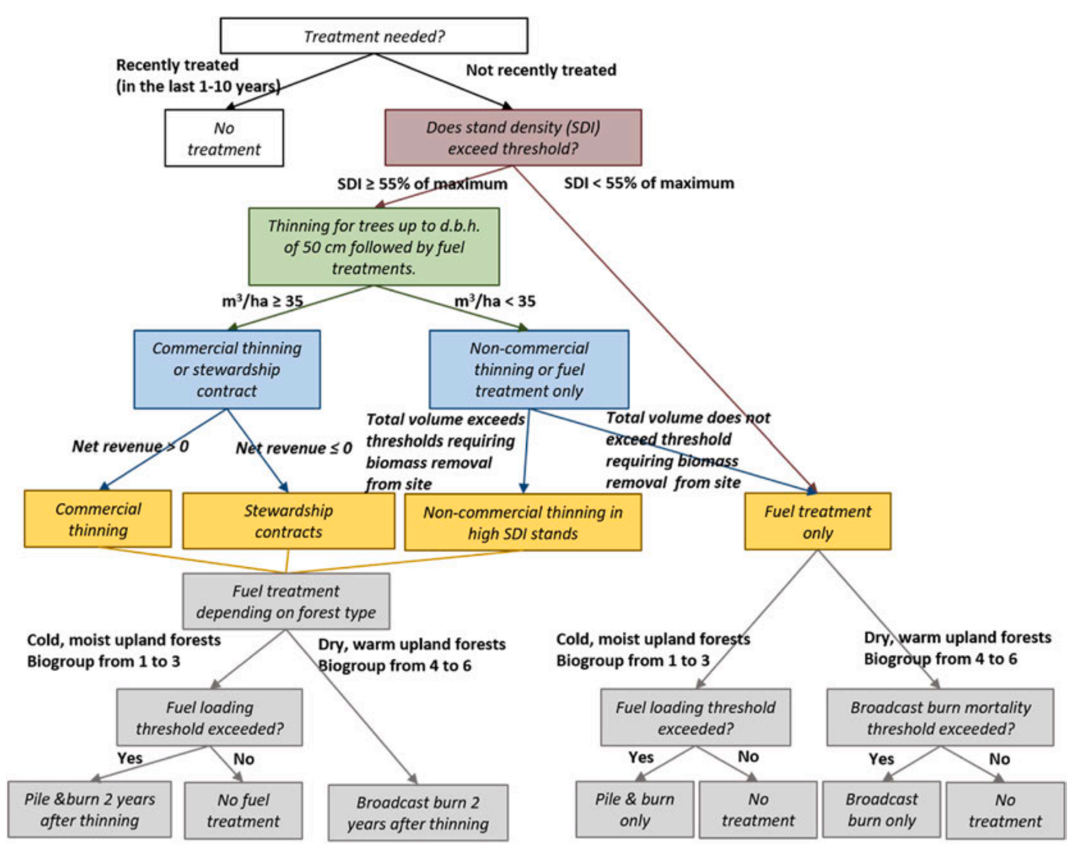

Fig. 2. A decision-tree developed to assign a prescription to each stand based on stand characteristics and treatment thresholds.

all stands in the study area. The decision key was developed using stand attribute thresholds, as well as local knowledge about current silvicultural practices (Fig. 2). The decision key had multiple branches, each representing a treatment option determined by stand attribute thresholds (Table 1). Prescriptions were formulated for sequences of restoration treatments including mechanical thinning and surface fuels treatments that replicate practices on the Umatilla NF and elsewhere in the ecoregion (Table A1). Depending on the path taken by each stand, the assigned prescription was stand density treatment only, surface fuel treatment only, the combination of the two, or no action at all. Individual treatments are described in the following sections.

2.4. Stand thinning treatments

To model the thinning treatments, the Umatilla NF established six biological groupings (Biogroups) which were based upon upland forest Plant Association Groups (Table A2). Differences among Biogroups are related to moisture and temperature gradients within the study area. Plant Association Groups of cool to cold were assigned to Biogroups 1 to 3. Plant Association Groups from hot to warm or warm moist were assigned to Biogroups 4 to 6.

Stands eligible for a thinning treatment were filtered based on thresholds for stand density index (SDI, Cochran et al., 1994). Maximum SDI for each Plant Association Group was assigned according to Cochran et al. (1994). If SDI exceeded 55% of the maximum SDI for stands in Plant Association Groups, we simulated a thinning from below to achieve a post-thin stocking of 30% of the maximum SDI. Thinning from below prioritized removal of smaller trees to reduce ladder fuels, in order to prevent torching and crowing fire behavior. Additionally, thinning treatments targeted removal of off-site, fire-intolerant species (e.g., grand fir) and retention of fire tolerant historic species (e.g., ponderosa pine). Maximum tree size for harvest was set at 53.3 cm in order to meet late-old structure objectives as specified in local harvest guidelines (USDA and USDA and USDI, 1994).

For thinning volume estimation, forest stands eligible for thinning were modeled with the Forest Vegetation Simulator (FVS) Blue Mountains variant to estimate removal volume (Keyser and Dixon, 2015). FVS can process forest inventory data and simulate silvicultural treatments

Table 1
Stand thresholds used to determine treatment types.

Treatment availability	Threshold	Justification
No treatment	Thresholds for treatments do not apply (e.g., stand received treatment in last 15 years)	Stand does not need treatment
Available for treatment	Stand density index (SDI) > 55% of maximal SDI	Stand is overstocked
Commercial thinning or stewardship contract	Merchantable volume >35 m^3 ha^{-1}	Stand is productive
Commercial thinning or stewardship contract	Net revenue >$0	Stand is profitable
Non-commercial thinning	Thinning volume >0 m^3 ha^{-1} and <35 m^3 ha^{-1}	Biomass removal
Broadcast burn, post-thinning	Treatment = thinning and forest type = dry, warm upland forest	Post thin surface fuel reduction
Pile & burn, post-thinning	Treatment = thinning, forest type = cold, moist forest and fuel loading >3.6 ton/ha in the 0–7.6 cm diameter size class	Post thin surface fuel reduction
Pile & burn only	Forest type = cold, moist forest and fuel loading >3.6 ton/ha in the 0–7.6 cm diameter size class	Surface fuel reduction only
Broadcast burn only	Forest type = dry, warm upland forest, post-fire tree mortality <50% for trees larger than d.b.h. of 22.8 cm and >50% for trees smaller than d.b.h. of 7.6 cm	Surface fuel reduction only

in forest stands. Tree lists for the study area were obtained from the Umatilla NF Field Sampled Vegetation (FSVeg) inventory system and consisted of estimated trees per acre by size class and species. All plots were grown to 2020 conditions using FVS for simulating the thinning treatments in the same year. A specific FVS prescription file was formulated for each of the combined Biogroups, and ArcFuels (Vaillant et al., 2013) was used to automate this FVS modeling process. See Ager et al. (2017) for more details about FVS modeling.

2.5. Surface fuel treatments

Broadcast burn and pile & burn are two typical fuel treatments on the Umatilla NF. Broadcast burn refers to a prescribed fire used for habitat restoration and fuels reduction purposes. Pile & burn is to burn piles of cut vegetation from fuels management activities (Jain et al., 2012). Only thinned stands in Biogroups 1 through 3 received pile & burn in the second year after thinning if resulting surface fuel loading exceeded desired levels (e.g., 3.6 ton/ha in the 0–7.6 cm diameter size class). All thinned stands in Biogroups 4 through 6 received broadcast burn the second year after thinning. Unthinned stands from Biogroups 4 through 6 received broadcast burn if the simulated mortality was less than 50% for trees larger than d.b.h. of 22.8 cm, and mortality greater than 50% for trees smaller than d.b.h. of 7.6 cm. A specific FVS prescription file was formulated for each of the combined Biogroups to simulate surface fuel treatments.

2.6. Financial valuation

We estimated potential revenue from restoration treatments using the residual value appraisal guidelines from Rummer (2008). Residual value was estimated based on log values after subtracting costs associated with harvesting, hauling, and ancillary expenses. Parameters for the costs are tabulated in Appendix B and were derived from local transaction data on the Umatilla NF. We did not consider extraneous project implementation costs such as road re-construction or decommissioning, planning costs, or other costs borne by the Forest Service.

Delivered log values of harvested timber were calculated using the economics extension of FVS by converting modeled harvest volume outputs into logs of specific size and species (Martin, 2013). Average pond values by species and size class for all dimensional sawmills within the study area (Table A1) were collected from timber sale specialists on the Umatilla NF and used to calculate the total value of delivered logs from each stand. Log pond values were only calculated for stands that generated greater than 35 m^3 ha^{-1} of merchantable timber, assuming stands producing less were not commercially viable.

Harvesting costs were calculated based on slope and tree size class consistent with methods used in previous studies (Rainville et al., 2008; Rummer, 2008). A ground-based harvesting system was assigned for stands having a slope less than or equal to 35%, and a cable harvesting system was assigned for all stands that exceeded the 35% threshold (Table A2). Average slope per stand was calculated from digital elevation data with a resolution of 30 m.

Timber hauling costs from individual stands to the nearest wood processing facility were estimated using the road network data for the study area. The road network consisted of approximately 750,000 road sections which were classified by driving speed. Round-trip travel time between each stand and the nearest processing facility (Table A3) was computed for the shortest path using travel distance and speed (Dijkstra, 1959). One additional hour of delay time was added for loading, unloading and wait times. Round trip costs per one cubic meter of timber were then estimated using travel time, truck hourly cost of $100, and truck load capacity of 12 m^3.

If stand thinning generates revenue less than its costs (i.e., negative net revenue), it was assumed that the thinning was performed under a stewardship contract. If thinning was not commercially viable (i.e., volume removal <35 m^3 ha^{-1}), it was assumed to be a non-commercial thinning incurring costs of $1600/ha. The costs of pile & burn and broadcast burn were assumed to be $1110/ha and $110/ha, respectively.

2.7. Restoration objectives

Three restoration objectives were considered for the study based on discussion with Umatilla NF staff. Each objective was implemented by targeting treatments to specific stands that most effectively addressed the objective through treatments. The objectives were considered interdependent, and no one objective was envisioned as the sole driver of forest and fuel management activities on the Forest.

2.7.1. Improve forest structure and resiliency through thinning and surface fuels reduction

For the forest structure restoration objective, we used overstocking conditions of individual stands as a metric to guide the selection of restoration stands and treatments. The overstocking condition was computed as a ratio of current to maximum SDI values for each stand (Figure A1a). To account for stand size, we multiplied the ratio by the number of acres in the stand. We then normalized the values to between 0 and 1, for easy comparison, by dividing by the maximum ratio found across the study area. This normalized metric of stand overstocking condition was used to rank and select stands for thinning treatments restoring forest structure.

2.7.2. Minimize wildfire risk to the urban interface

Wildfire risk reduction was measured for WUI areas adjacent to the study area using methods found in Ager et al. (2014). We used SILVIS WUI data (Radeloff et al., 2005) for the study area, but removed SILVIS 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 therefore included polygons with very low structure densities to correspond to current fire suppression efforts that aim to protect individual structures in the WUI. There were 52,202 WUI polygons containing structure density data covering an area of over 1.6 million ha.

We used wildfire simulation outputs generated from FSim (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). FSim produces both polygon-based fire perimeters and ignition points for each simulated fire. Ignitions were filtered for those occurring within national forest boundaries and associated perimeters were intersected with WUI boundaries to determine WUI area burned annually by each ignition. Total WUI area burned per stand was calculated by summing contributions from all ignitions reaching that stand.

We estimated annual structures affected by each national forest-ignited fire as the product of the housing units within each stand polygon and the proportion of the polygon burned. The resulting 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 mean structure exposure was attributed to each stand, which was used as a metric to rank and select stands for treatments. We accounted for stand size and normalized the metric as previously described. Stands with high values of the metric (i.e., high potential of wildfire risk reduction) were prioritized for vegetation and fuels treatments.

2.7.3. Maximize merchantable timber production to meet the desired volume target

Stands were selected to maximize merchantable timber volume from restoration treatments across a given planning area. The FVS estimated thinning volume per stand was used as the metric, and stands with a relatively large volume of merchantable timber were prioritized for treatments.

2.7.4. Combination of restoration objectives

We combined the aforementioned three objective metrics using an equally weighted scheme to investigate the effect of multiple restoration objectives on stand selection for treatments. A linear combination of the normalized metrics obtained through an equally weighted sum was used, and stands with high values (i.e., potential to contribute to the general problem) were prioritized for treatments. Different weights were also applied to analyze trade-offs among restoration objectives. These analyses were not designed to be directly implemented in the forest action plan, but to provide insights on how different restoration objectives affect the selection of stands and treatments across a planning area.

2.8. Modelling scenarios

We used ForSys-R, a modified version of the Landscape Treatment Designer (Ager et al., 2016) to model scenarios that prioritized stands in each planning area based on the three restoration objectives described above. ForSys-R has specific design features for sequencing or optimizing spatial fuel treatment patterns as part of restoration planning. ForSys-R uses a shapefile of forest stand polygons attributed with restoration objectives. The user enters a restoration scenario by specifying one or more objectives (e.g., revenue), activity constraints (e.g., budget, area treated), and stand treatment thresholds (e.g., fire behavior). The program then selects stands for treatment to maximize the objective function calculated as:

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

Subject to

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

where C is a global constraint on activity per planning area, Z is a vector of binary variables indicating whether the jth stand is treated ($Zj = 1$) or untreated ($Zj = 0$), Nij is the contribution to objective i in stand j if treated, and Aj is the area of the jth stand. The normalized metric defined in each restoration objective was used for Nij as explained further below. Wi is a weighting coefficient that can be used to emphasize one objective versus another. The ForSys-R program can be used to solve optimization problems with or without spatial adjacency constraints. In the current application, we used existing planning areas obtained from the Umatilla NF and used the program to identify stands to treat that maximize the objective value, while meeting constraints. Given multiple planning areas, the program iterates through each planning area, then reports the maximum objective value and the selected treatment stands. The process of modeling scenarios involved a nested prioritization of stands for treatments (Figure A2). In this way the financial dynamics of treatments in relation to the restoration footprint can be examined for break-even points.

The decision key described in the above section resulted in 12 possible prescriptions including a no treatment option (Table 2). Prescriptions including commercial thinning were prioritized first as they could possibly generate positive net revenue (Prescriptions a through c in Table 2). Our intention was to use the revenue from profitable treatments to offset treatment costs of other areas for a larger final restoration footprint. The second sequenced prescriptions were those with stewardship contracts which could generate revenue, albeit negative (Prescriptions d through f in Table 2). Prescriptions including non-commercial thinning or with fuels treatments only (Prescriptions g through k in Table 2) are pure cost activities without any revenue generation, and therefore received lower priority for the planning purpose.

Each prescription contributes differently to each restoration objective. Prescriptions a through f in Table 2 may contribute to all

Table 2
Areas identified in need of restoration treatments, and their estimated costs and revenues.

Prescriptions	Area (ha)	(%)	Cost (MM $)[a]	Revenue (MM$)
a. Commercial thin only	37	0	0.2	0.3
b. Commercial thin and broadcast burn	9165	3	53.9	88.0
c. Commercial thin and pile & burn	13,113	5	105.1	151.2
d. Stewardship contract only	171	0	1.2	0.8
e. Stewardship contract and broadcast burn	3004	1	28.1	18.6
f. Stewardship contract and pile & burn	10,340	4	107.0	61.3
g. Non-commercial thin only	3633	1	5.8	–
h. Non-commercial thin and broadcast burn	52,718	20	90.6	–
i. Non-commercial thin and pile & burn	39,592	15	107.7	–
j. Broadcast burn only	36,159	14	4.0	–
k. Pile & burn only	43,961	16	48.9	–
l. No treatment	55,706	21	–	–
Total	267,599	100	552.5	320.2

[a] MM = millions

restoration objectives, whereas prescriptions with non-commercial thinning (g through i) may affect forest structure restoration and wildfire risk reduction objectives, but not the harvest volume objective. Stands with fuels treatments can only contribute to the wildfire risk reduction objective, but not the other two objectives.

2.9. Trade-off analysis

To analyze trade-offs between any two restoration objectives for a given planning area, we computed a weighted sum of normalized objective values for each stand. We used relative weights ranging from 0 to 10 for each restoration objective in increments of 1, generating 121 cases of combined objective values. For each case, we ranked stands based on the combined objective value, and chose stands from the highest rank until the total area reached about 1000 ha. The cumulative amount of objective attainment from these stands was then plotted against the two objectives represented by the horizontal and vertical axes. As the result, the full set of all 121 cases generates a trade-off curve for the planning area illustrating possible trade-off relationships between the given two restoration objectives.

2.10. Project scheduling

We scheduled restoration treatment activities across the entire Umatilla NF over the next 10 years in order to understand the internal and external capacity requirements and constraints in implementing restoration projects. All 40 planning areas were ranked in terms of their area-based contribution to restoration objectives, and 4 planning areas were scheduled to be completed per year from the highest rank. The objectives forest structure restoration and wildfire risk reduction were considered in scheduling project areas, and the results were compared for the effects of the objective on yearly quantity of different treatment activities.

3. Results

3.1. Areas in need of restoration treatments

Our decision key approach for treatment assignment shows that a total of 211,893 ha (80% of the study area) are currently in need of restoration treatment on the Umatilla NF (Table 2). Among them, over 131,773 ha (49%) were selected for thinning treatment due to their overstocked conditions (Prescriptions a through i), and 208,052 ha (78%) were selected for prescribed fire based upon their estimated tree mortality and fuel loading conditions (Prescriptions b, c, e, f, h, i, j, and k).

Treating all areas that are in need of restoration would require total operating costs of nearly $553 million (Table 2). The stands assigned with revenue generating treatments (i.e., commercial thinning and stewardship contracts) incurred high operating costs due to high costs of timber harvesting and hauling. The estimated operating costs for those thinning stands were $295 million including post thinning prescribed fires (53% of total costs), covering only 35,830 ha in area (13% of the total study area). The total amount of timber revenue generated from these stands was estimated at $320 million with commercial thinning being the only revenue source.

Fig. 3 shows the spatial distribution of stands with thinning and prescribed fire treatments across the Umatilla NF. Stands in need of thinning for reducing overstocking were widely distributed across the study area, but commercial thinning treatments were more concentrated in the northern part due to their high timber volume. Many no thinning stands with a low SDI ratio were also located in the northern part of the study area. Most of the high performing were assigned broadcast burn or pile & burn treatments as they met the mortality and fuel loading thresholds. The total areas of broadcast burn and pile & burn treatments are similar, but they are spatially clustered because of the moisture and temperature gradient in the forest.

The distribution of treatment types varied widely within planning areas because of their Plant Association Group and current stand conditions including surface fuel loading (Fig. 4a). This variation resulted in large differences in operational costs and revenues among planning areas (Fig. 4b and c). Some planning areas included many recently treated areas, and thus showed a large portion of no treatment areas in these results (e.g., PAs 15 and 21 in Fig. 4a). Only a few planning areas were able to generate more revenue than treatment costs (e.g., PAs 20, 28 and 32), thus most planning areas require additional resources to complete necessary restoration treatments.

3.2. Financial sensitivity analysis

Fig. 5 shows the results of the treatment assignment process for each restoration objective. For simplicity in presentation, the top 10 planning areas among 40 were chosen under each objective and presented. They were selected based on high objective attainment at break-even points. Stands in each planning area were plotted for their contribution to net revenue (y-axis) and objective attainment (x-axis) following the order of prescription and stand prioritization, i.e. a group of stands receiving revenue-generating prescriptions were plotted first, and within each group, stands with higher objective attainment were plotted first. Each stand's contribution to the objective attainment is expressed as a percentage which is a portion of the total possible attainment from the entire study area. Cumulative net revenue in Fig. 5 increases as stands positive net revenue stands are added to the solution. Stands plotted after the highest peak of the graph are the ones where treatment costs exceed revenue or treatments generate no revenue. The baseline of the x-axis represents cumulative net revenue of $0, indicating all the stands plotted above the 0 basline can be treated without financial subsidies in the planning area.

Most of high performing planning areas were able to achieve more objective by utilizing revenue generated by commercial thinning (Fig. 5a and b). Some planning areas were able to treat all treatment-eligible stands and still have a revenue surplus (e.g., PA 5 in Fig. 5a), while others required financial subsidies to be able to treat all eligible stands as shown by their graphs falling below the x-axis. For the merchantable timber volume objective, stands with potential timber production were prioritized (Fig. 5c). Cumulative net revenue increased as more commercial thinning stands were included, but started

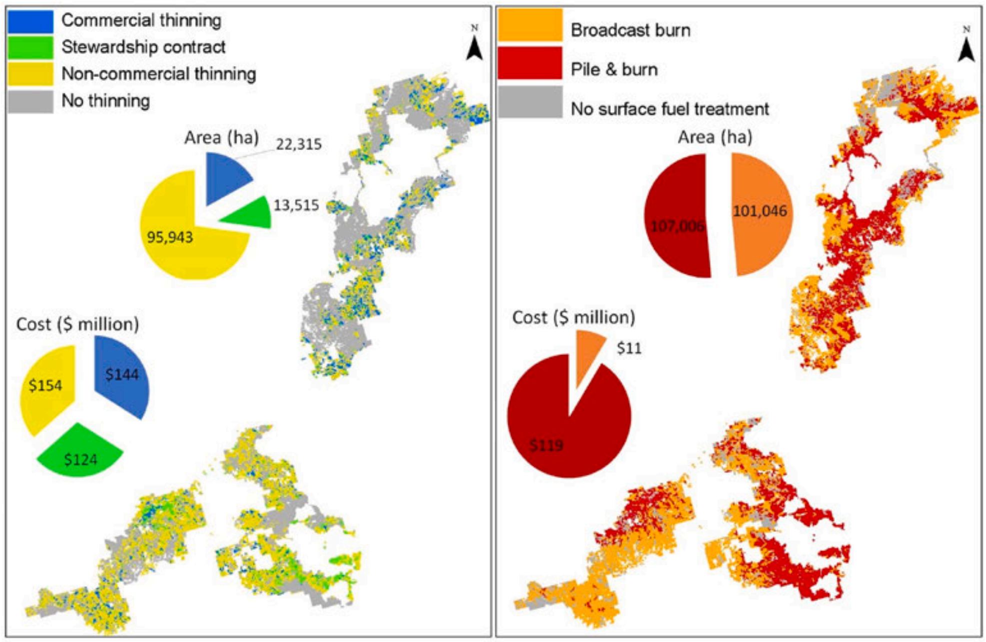

Fig. 3. Spatial distribution of assigned treatments in the study area.

decreasing when stewardship contracts were added. Under this merchantable volume objective, net revenue of the top 10 planning areas ranged between -$1.2 million and $10.1 million with total harvesting volume ranging from 33,000 m^3 to 130,000 m^3 per planning area (Fig. 5c). Fig. 5d presents the top 10 planning areas for the combined objective. While some of the planning areas were consistently included in the top 10 across all objectives (e.g., PAs 5, 12 and 19), other planning areas were not ranked high for all three objectives. This result implies that the restoration objectives may conflict or complement each other depending on the characteristics of planning areas.

3.3. Tradeoff analyses

Figure A3 presents the results of trade-off analyses for the three restoration objectives. In some planning areas, there was a positive trade-off relationship between forest structure restoration and merchantable volume objectives in most planning areas (Figure A3a), indicating that more merchantable timber production helps achieve more forest structure restoration objective (e.g., PA 5 in Figure A3a). However, some planning areas showed minor trade-offs (e.g., PA 9), indicating that some planning areas have a large number of overstocked stands, but those stands have highly variable merchantable timber volume.

By contrast, there were negative tradeoffs between wildfire risk reduction and the other two objectives (Figures A3b and A3c) indicating a potential conflict between the objectives. It appears that some planning areas have low trade-offs (i.e., flat trade-off curve), especially those showing high attainment of the wildfire risk reduction objective (e.g., PAs 14, 28 and 32). These planning areas include many stands located close to the WUI, and therefore the wildfire risk reduction objective becomes easily attainable regardless of forest structure restoration level or merchantable timber volume. On the other hand, most of other planning areas that have a limited number of stands near the WUI, show larger trade-offs between the objectives (e.g., PAs 5, 12, and 20), indicating more stands near the WUI were selected when larger weight was given to the wildfire risk reduction objective.

3.4. Project scheduling

The results of treatment scheduling show that the total area of thinning activities ranged between 2300 and 29,000 ha per year, widely fluctuating over time because of the differences in area coverage of each planning area (Fig. 6). Some of the areas to be thinned will receive fuels treatments in the following year, and thus the total area of fuels treatments in each year includesd both the areas with fuels treatment only and the area scheduled for thinning in the previous year. Under the forest structure restoration objective, a general trend shows more thinning activities scheduled earlier years than later years. Consequently, the rate of objective attainment was higher in earlier years as shown in a steeper slope of the attainment curve between Years 1 and 4 (Fig. 6a2). There was a large amount of surface fuels treatment activities scheduled under both objectives across the planning horizon, but 60% of activities were post-thinning treatments under the forest structure restoration objective, whereas under the wildfire risk reduction objective 60% of activities were surface fuels treatments only. For objective attainment, the wildfire risk reduction objective saw slightly faster cumulative objective attainment compared to forest structure restoration. Under the wildfire risk reduction objective, 67% of the objective was attained in 4 years by treating only 36% of the total treatment areas, compared to 64% objective attainment in 41% of area treated under the forest structure restoration objective.

4. Discussion

This study offers a spatially-explicit, multi-scale assessment approach that can help land managers 1) evaluate the current restoration backlog and its financial implications, 2) locate and prioritize treatment opportunities, and 3) understand internal and external capacity and resources required for project implementation. It builds on previous work of Ager et al. (2017) and Vogler et al. (2015), which delineated other decision support frameworks for landscape restoration with economic opportunities. Although top-down estimates for restoration needs on US national forests have been estimated at a range of scales in prior studies, there have been few attempts to combine site specific conditions, local knowledge and current management practices into large landscape scale modeling for assessment and prioritization of

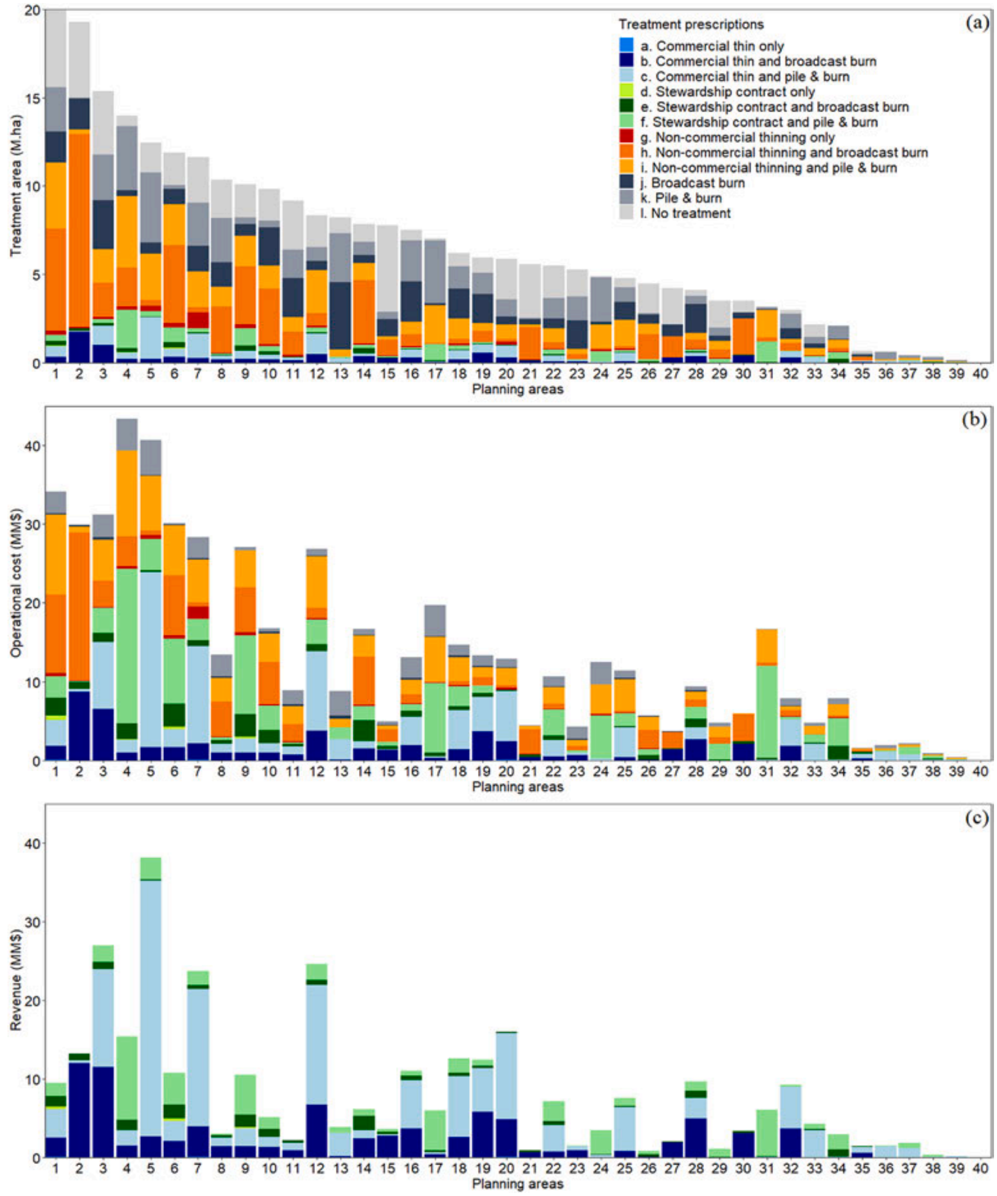

Fig. 4. Distribution of treatment prescriptions within each of the 40 planning areas in terms of area (a), estimated costs (b), and revenue (C).

forest restoration. Some studies identified restoration needs and locations based on ecological departure (Haugo et al., 2015), but they describe a wide range of species and structures that are outside of the natural range of variability without connecting them to specific silvicultural and surface fuels treatments, or to financial assessments to rectify the problem. Detailed decision trees have also been developed in the past for restoration treatments (Jain et al., 2012), but examples where they have been prioritized and scheduled within an economic framework are rare. A bottom-up approach like the one presented here has long been needed to connect decision trees with spatial information on conditions, financial information and local knowledge and practices. Weaving this information together creates the input needed for spatial planning to address the restoration backlog and develop practically implementable restoration plans.

The approach presented in this study can provide detailed forecasts on the rate of treatment to achieve specific restoration goals and information on resources required to attain them. For instance, the current estimates of restoration need on the Blue Mountains National Forests vary, with initial estimates suggesting that 34% (506,696 ha) of the forested area is in need of active restoration (USDA Forest Service, 2016a). These estimates were developed from the conceptual framework of the LANDFIRE and FRCC programs that assessed forest departure from historical conditions of vegetation and fuels (LANDFIRE, 2013). Using a more recent analysis of forest departure for the Pacific Northwest, Haugo et al. (2015) and DeMeo et al. (2018) estimated roughly 33% (81,169 ha) of the manageable forests within the Umatilla NF were in a state of structural and species departure from historical conditions, due primarily to development of dense, multistory forest stands. However, all of these past estimates including the nationwide assessment of restoration need by US federal agencies (Barrett et al., 2010) were mainly based on ecological departure or the fire regime condition class framework (Hardy et al., 2001) that do not account for the need to mitigate fire hazard at the forest and private interface and protect communities at risk. In contrast, our bottom-up approach takes into account not only ecological parameters at a stand level, but at a broader scale, the community needs fpr fire risk mitigation and other ecosystem services while following the operational practice guidelines of national forests (Barbour et al., 2005; Ager et al., 2007). Our study shows that incorporation of local knowledge and needs resulted in substantially larger contiguous areas needing one or more restoration

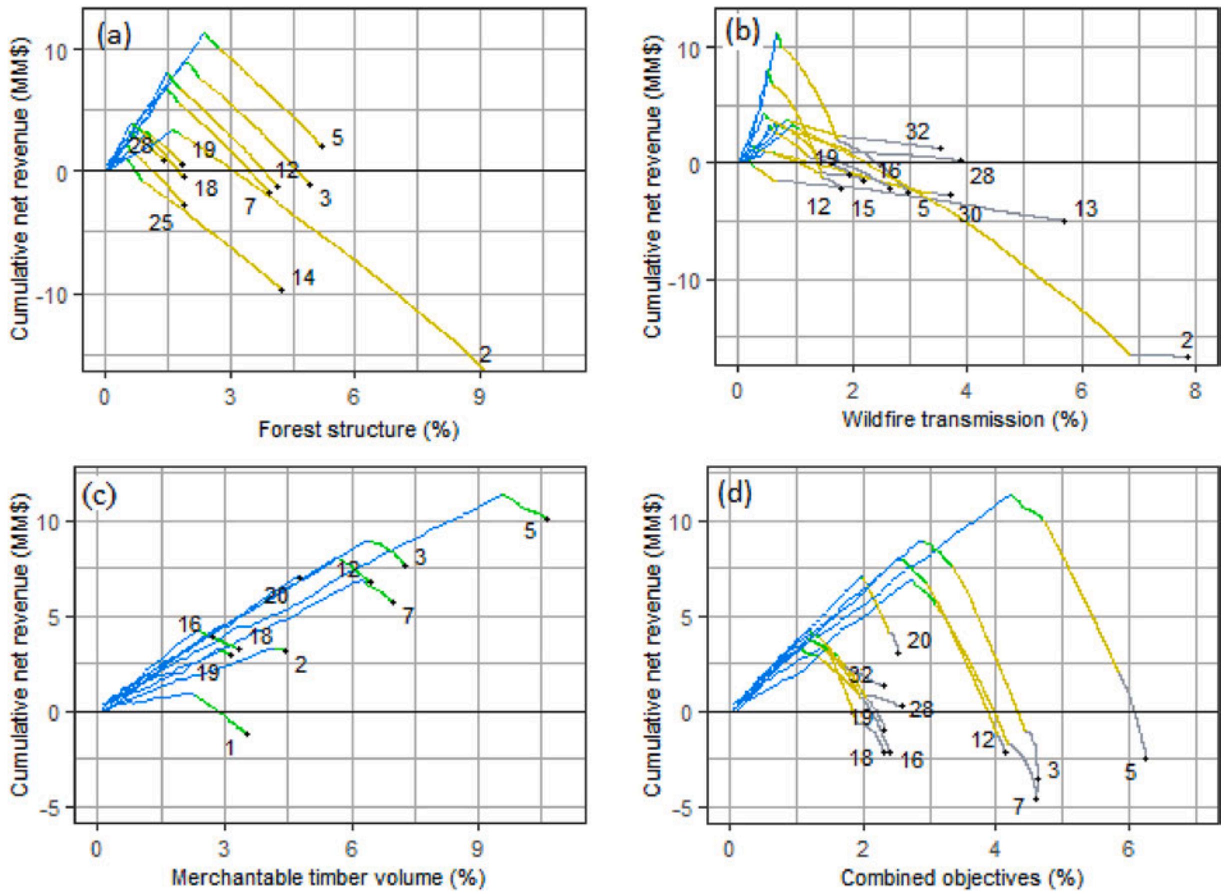

Fig. 5. Financial analyses for 10 top-performing planning areas under the three restoration objectives and the combined objective, shown by the cumulative net revenue and the percent objective attainment. Blue, green, yellow and gray lines represent prescriptions a through c, d through f, g through i, and j and k shown in Table 2, respectively. Horizontal axes show objective attainment as a percentage of the total from the entire study area. Numbers at end of lines indicate planning areas. MM = millions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

treatments (211,893 ha, 80%), compared to those approaches considering only ecological departures.

Despite these differeneces, all of the aforementioned approaches indicate that there is a large portion of the Umatilla NF currently needing restoration treatment. However, only about 2800 ha or 1% of the manageable lands receive restoration treatment annually (USDA Forest Service, 2016c), and thus the current pace of forest restoration lags behind ingrowth and densification of the forest. More overstocked stands need to be thinned and surface fuels treated to reduce the potential of severe and extensive wildfires and insect and disease disturbance (Quigley et al., 2001; Hayes et al., 2004). Our project scheduling example shows that approximately 13,000 ha should be thinned, and 21, 000 ha receive fuel treatments annually if all backlog treatments were to be completed over the next 10 years. Although this example might not represent real project scheduling and implementation, it provides insights into the agency's internal capacity needed for undertaking restoration projects at a desirable rate, as well as the external capacity requirements, such as road infrastructure and local forest industries.

Our study found the financial viability of restoration projects is highly dependent on the capacity of providing specific economic outputs, i.e. volume from commercial thinning, which is a limited resource depending on the region of the forest. For this reason, in many places the economics of restoration projects can be tenuous under current practices, as noted in earlier studies (Barbour et al., 2008, USDA Forest Service, 2017). Our financial sensitivity analysis illustrated the use of revenue from commercial thinning as a resource to scale up treatments and extend performance of objective attainment without financial subsidies until the break-even point. Under the wildfire risk reduction objective, on average about 27% of each planning area can be treated with positive net revenue, achieving 31% of the possible maximum objective attainment in our study area. Conversely under the forest structure restoration objective the area treated decreases to 23% of the planning area and the objective attainment increases to 41% while maintaining positive net revenue.

On public lands, there is a substantial challenge to balance ecological and socio-economic objectives, and designing and implementing landscape-scale projects that meet both objectives is a difficult task (Stanturf et al., 2019; Chazdon et al., 2020). The situation in the western US is paralleled elsewhere in many other restoration programs globally (Aronson and Alexander, 2013), although forest restoration programs in the western US are one of the few that can generate revenue. Scenarios to reduce the backlog, including ones that used revenue from profitable treatments to offset costs of other treatments with negative net revenue, are valuable to assess restoration opportunities for larger areas. Moreover, the financial assessment and sensitivity can be used to estimate the amount of external funding needed and the marginal efficiency of such investment in restoration goal attainment. For example, the amount of required external funding can be estimated using the cumulative negative net revenue of each planning area, and the impact of the investment can be assessed as the attainment of restoration objectives that are made possible by the external funding. Fig. 7 exemplifies the use of our results in assessing the marginal efficiency of investment, where planning area 13 shows the highest return on investment, i.e. large objective attainment with a relatively small amount of external funding.

Our tradeoff analysis can help land managers understand the relationship between restoration objectives, as well as inform decision

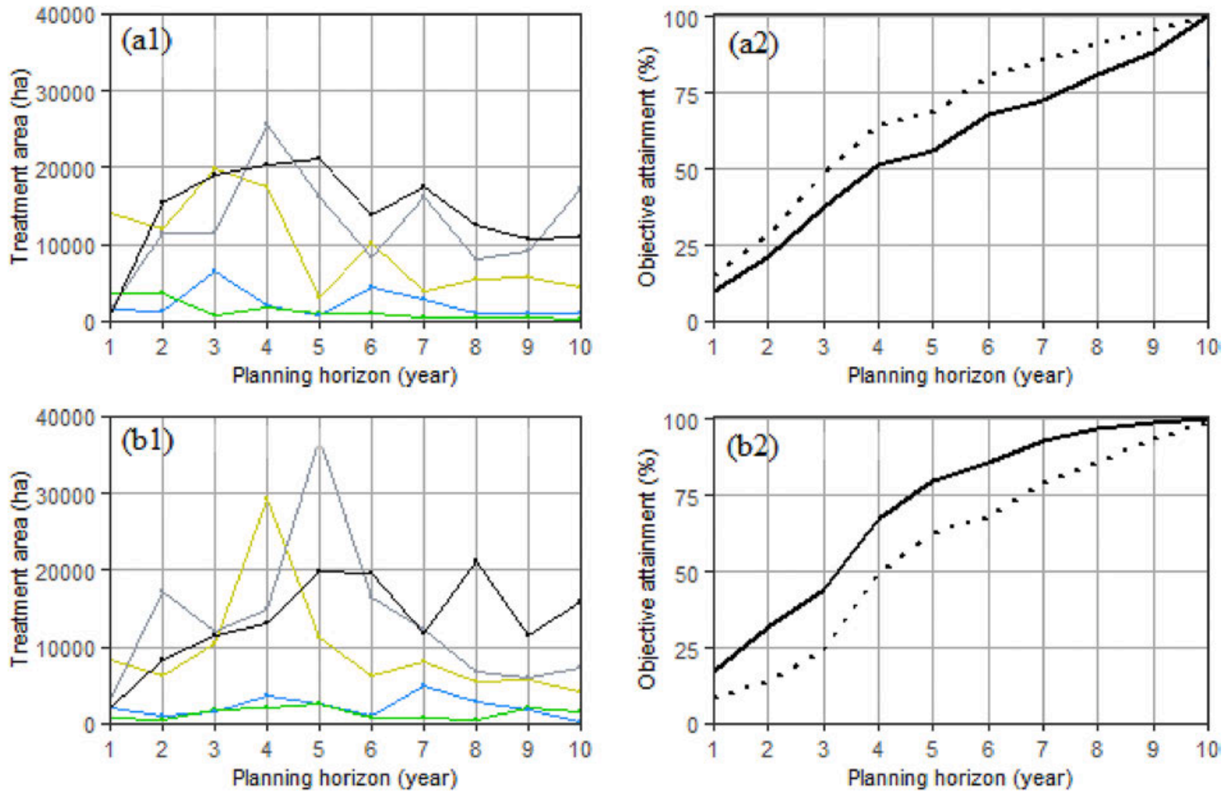

Fig. 6. The distribution of treatment activities (a1 and b1) and cumulative objective attainment (a2 and b2) across a 10-year planning horizon when four planning areas are selected per year under two restoration priorities. Blue, green, yellow, gray and black lines in a1 and b1 represent commercial thinning, stewardship contract, non-commercial thinning, broadcast burn and pile & burn treatments, respectively. Dotted and solid lines in b1 and b2 represent the amount of objective attainment under the forest structure restoration and fire transmission, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

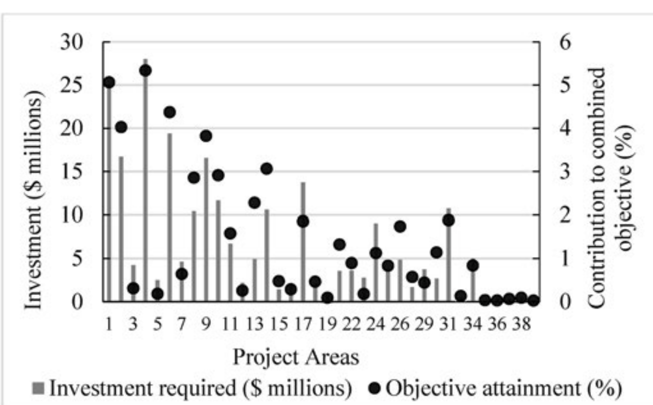

Fig. 7. The amount of external investment required to complete all treatments in each planning area (grey bars) and the objective attainment that can be achieved by the investment (black dots).

making and strategy formulation. The production possibility frontiers resulted from this study show tradeoffs between objectives vary widely among planning areas depending on their locations. The results are similar to those of earlier studies conducted across a number of national forests in the western US (Ager et al. 2016, 2017, 2019) and in other regions (Triviño et al., 2017; Pohjanmies et al., 2019). These results also suggest the tradeoffs may vary with spatial scale. For instance, decisions made at a planning area may not lead to optimal outcomes at a forest or regional scale. Multi-scale assessments are needed to maximize the benefits of restoration activities across multiple scales. Gonzalez-Olabarria et al. (2019) used expert knowledge definition rules to identify objective landscape units for wildfire suppression activities at a larger scale, and then priority treatments within those landscape units at a smaller scale. Likewise, our study demonstrates a unique approach that allows integration of outcomes and spatial considerations at various scales from the entire national forest level for restoration objective evaluation to the individual stand level for treatment effects and financial sensitivity, providing an intuitive analysis platform for multi-scale assessments.

Future work can use our approach to examine the effects of spatial patterns of treatments on a landscape that is highly fragmented in terms of fire regimes, financial conditions, and restoration needs. For instance, one planning problem that has yet to be resolved is how to finance restoration treatments in economically marginal dry forest ecosystems that require large-scale broadcast burning. Here, the goal is to apply fuel treatments as large and contiguous as possible while minimizing cost (Ager et al., 2010). Although the use of optimization techniques increases the complexity of design and implementation, it can be integrated into the current platform to consider spatial constraints or requirements (Chung et al., 2013; Ager et al., 2016). This study would complement recent efforts exploring the design of restoration projects to obtain economic and socio-ecological opportunities (Addington et al., 2020; Florec et al., 2020). The absence of long-term stand prescriptions in our analysis including repeated burn treatments limits the ability to incorporate the long-term ecological effects of treatments on desired species and structural diversity. Future studies should explore ways to extend the planning time horizon and integrate long-term treatments and their effects into project area prioritization and scheduling.

5. Conclusions

Estimates of forest management needs are a key input into federal forest policy to restore fire resilient forests in the western US, but previous estimates of the restoration backlog have been primarily based on fire regimes and ecological departure related to forest species and structure without reflecting on the ground activities to minimize wildfire risk. Using a detailed treatment decision tree built from local silviculture and fuel specialists, this study offers a bottom-up, spatially explicit assessment of a restoration backlog and prioritization of planning areas to provide more realistic estimates of restoration needs and their financial implications. Our methods can be readily implemented elsewhere on public lands throughout the western US using existing forest vegetation data (Riley et al., 2018) coupled with local knowledge on national forests, and used to establish a restoration plan in terms of amount, location, and treatment type. Expanding the approach more widely can lead to improved estimates of forest management and investment needs to undertake broader scale restoration and address the growing wildfire issues. The methods can also facilitate collaborative restoration planning to help stakeholders understand the opportunity cost of specific restoration objectives (Butler and Esch, 2019). Integrating the financial assessment of harvested materials can help guide private investments in local industrial infrastructure and in general improve financial evaluation of forest and fuel management. Our approach does not rely on complex optimization modeling that requires extensive user support, therefore offers a higher degree of transparency and accessibility for forest planning to address both ecological and socio-economic objectives.

Credit author statement

Pedro Belavenutti: Investigation, Software, writing original draft, Woodam Chung: Methodology, Resources, reviewing and editing, Alan Ager: Conceptualization, Supervision, Resources, writing and editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112825.

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