

Balancing Ecological and Economic Objectives in Restoration of Fire-Adapted Forests: Case Study From the Four Forest Restoration Initiative

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CORRIGENDUM

An additional author, Kevin C. Vogler, was added to the list of authors on the front cover, citation, and Authors list. The Tresearch entry was also changed. These changes were made in August 2021.

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Abstract

We examined tradeoffs between managing for fire resilience versus economic objectives for a large scale (240,000 ha) federal collaborative forest restoration project in the southwestern United States—the Four Forest Restoration Initiative—created to improve fire resilience in fire-adapted ponderosa pine forests that have experienced a century of fire exclusion. However, scaling up forest restoration to substantially change fuels and future fire behavior over large areas is constrained by marginal economic returns from harvested materials. We simulated a range of forest management scenarios and varied the objectives to select areas within those scenarios based on the potential to generate revenue (sale of harvested logs) or improve fire resiliency (reduce crown fire). We found that maximizing fire resiliency cost \$44 per ha for the first 9,000 ha treated. By contrast, maximizing revenue generated an average of \$552 per hectare treated for the same treated area. We identified a scenario that blended financial and resiliency objectives such that revenue could be generated while improving fire resiliency nearly as well as the optimal scenario. These results revealed tradeoffs among and within project areas for the two objectives and demonstrated that a relatively simple optimization algorithm could be incorporated into the collaborative restoration planning process to understand and communicate tradeoffs between financial and fire resiliency objectives.

Keywords: collaborative forest planning, forest economics, forest restoration, scenario planning, spatial optimization, production frontiers

Cover photo

A view of ongoing forest restoration activities in the Parks West project on the Kaibab National Forest, Arizona. Courtesy photo provided to Mark Nigrelli.

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Introduction

The dry pine ecosystem in the western United States covers over 12.6 million acres (Baker 2015) and is a critically important source of wood products, water, biodiversity, and recreation (Noss et al. 2006). Numerous studies have documented the structural transition of these forests in the last century and the effects on fire regimes and ecological resiliency (Merschel et al. 2018; Moore et al. 2004) and biodiversity (Laughlin et al. 2006; Metlen and Fiedler 2006). Landscapes that historically burned with frequent low-intensity fire are now experiencing high-severity wildfires more frequently, catalyzed by climate change (Abatzoglou and Williams 2016; Rocca et al. 2014; Schoennagel et al. 2017; Westerling 2016; Westerling et al. 2006), spatial homogenization of fuels from past fires (Hessburg et al. 2019), and historic management practices (Covington and Moore 1994; Spies et al. 2014). These patterns suggest that the current fire trajectory under changing climate will lead to large type conversions and extirpation of the dry forest ecosystem (Kerns et al. 2020). U.S. federal land management agencies have responded with large scale collaborative restoration initiatives to improve ecological resiliency and support economic interests of forest-dependent communities (GAO 2015; USDA FS 2012, 2015b, 2020). The U.S. Forest Service, together with the National Park Service and the Bureau of Indian Affairs, manage 70 percent of all western forests (Westerling 2016) and are funded to treat about 800,000 ha with a combination of mechanical thinning, mastication, pile burning, and prescribed fire. These activities are effective at reducing high-severity fire, potentially improving long-term carbon storage (Dore et al. 2010; Finkral and Evans 2008), sustaining resilient biodiversity (Laughlin et al. 2006; Metlen and Fiedler 2006; Mitchell et al. 2006), and protecting communities from adverse fire impacts (Kalies and Yocom Kent 2016).

Dry forest restoration programs in the United States face substantial tradeoffs among multiple economic and ecological goals on landscapes valued for a wide range of ecosystem services. In particular, achieving fire resiliency objectives requires costly removal of small diameter trees and woody debris that contribute to severe fire behavior but reduces the economic viability and scale of the programs (Ager et al. 2017; Chung et al. 2012). Economic objectives are best optimized by harvesting of larger diameter trees and allocating treatments to stands with higher commercial volume, which ensures that projects are economically viable to contractors. Finding the balance that maximizes the economic opportunity for contractors while creating large fire resilient landscapes is a key to creating and sustaining fire resilient forests and the federal restoration programs that bring about the required management activities.

Tradeoffs among economics, fire resiliency, biodiversity, and ecosystem services are widespread in forest management systems (Kline and Mazzotta 2012; Triviño et al. 2017) and have been extensively studied with multi-objective planning and optimization models (Christensen et al. 2009; Foresta et al. 2016; Hof and Joyce 1992; Mazziotta et al. 2017; Peterson et al. 2003; Schroder et al. 2016; Schröter et al. 2014). In general, tradeoffs from forest management occur over both space and time, are nonlinear and scale dependent, and involve both negative and positive aspects of forest management. While tradeoffs in fire adapted systems mostly concern how management can reduce losses from wildfire disturbances (Schroder et al. 2016), in boreal systems the concern is the negative impacts of logging on biodiversity and other ecosystem services (Triviño et al. 2017). Tradeoffs among multiple conflicting objectives are common in forest management systems and can be compensated by diversifying management to include a wider array of harvesting practices (Pohjanmies et al. 2019; Triviño et al. 2017). Nonlinearity means that the steepness of the tradeoff among variables can be affected by the level of the production of each of the other objectives and is central to the idea of production frontiers.

Despite the many studies on tradeoffs and examples of multi-objective planning and optimization in forestry, application to the problem of dry forest restoration is limited to a few studies (Ager et al. 2017; Kennedy et al. 2008; Lehmkuhl et al. 2007; Schroder et al. 2016), and field application in the U.S. Collaborative Forest Landscape Restoration Program (CFLRP) programs is nonexistent. To advance knowledge about tradeoffs in ecological restoration and the application of multi-objective decision support tools, we examined economic and fire resiliency tradeoffs on the largest ongoing CFLRP located in the southwestern United States, the Four Forest Restoration Initiative (4FRI). We applied a heuristic spatial optimization model (Ager et al. 2019) to build a restoration plan that balanced economics with fire resiliency objectives, and mapped priority planning areas and treatment units within them. The modeling framework and implementation is substantially less complex than other mathematical optimization approaches in the forestry literature, and its wider application to restoration planning has the potential to help advance the goals of forest restoration on fire prone public lands in the western United States and elsewhere.

Methods

Study Area

The 4FRI project is a 970,000 ha landscape level restoration project funded in 2010 under the CFLRP (fig. 1). 4FRI is one of 23 CFLRP projects intended to “encourage the collaborative, science-based ecosystem

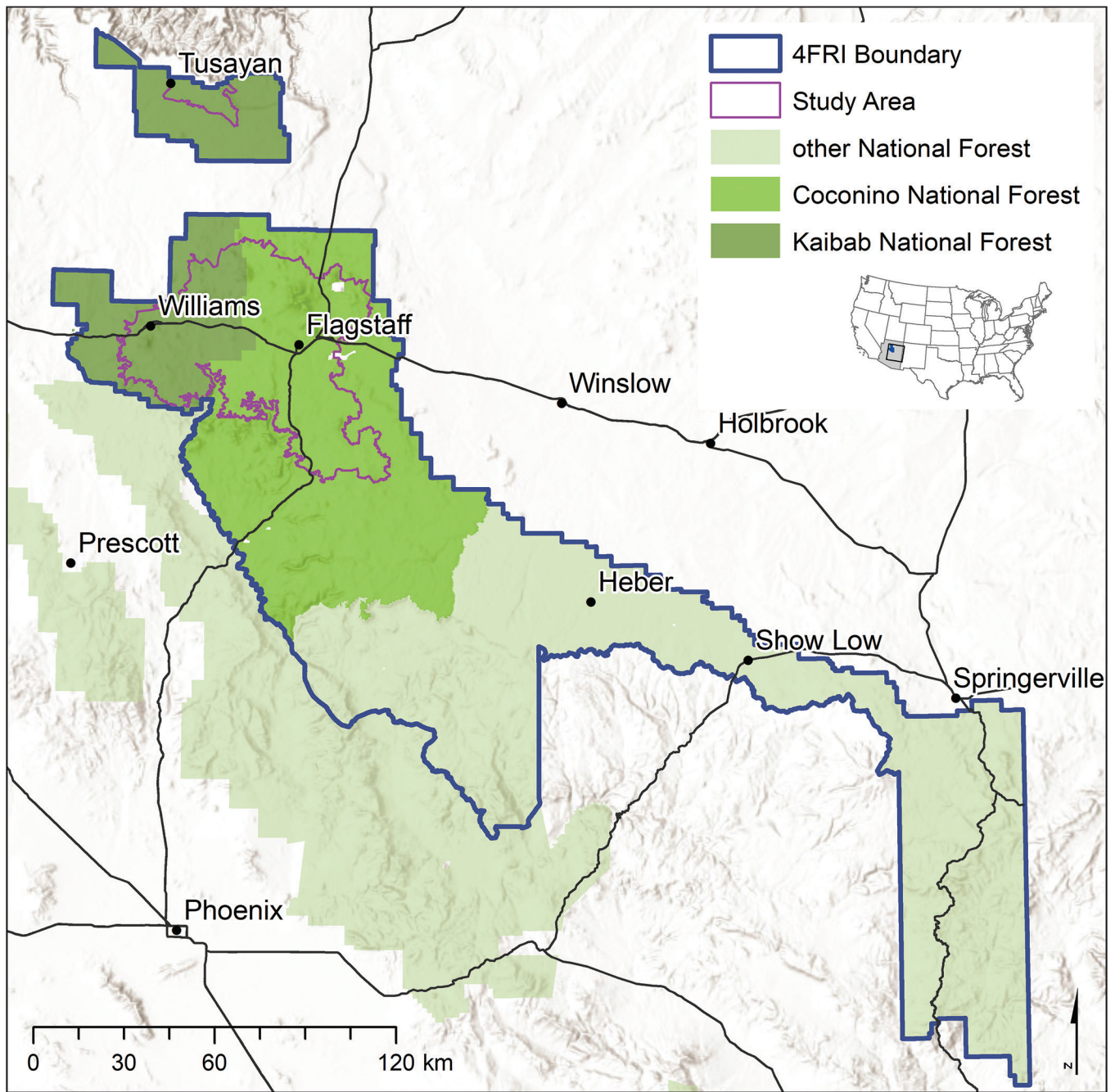


Figure 1—Location of the Four Forest Restoration Initiative (4FRI) area and the first environmental impact statement project study area within national forest land in Arizona.

restoration of priority forest landscapes” (Butler et al. 2015; USDA FS 2015a) and serves as a demonstration for effective restoration techniques and forest product utilization (Schultz et al. 2012). The study area contains 155,000 ha of treatments that were included in the first landscape scale environmental impact statement for 4FRI that had a decision signed in 2014 (USDA FS SW 2014). Stakeholders and a Forest Service planning team worked together for 4 years to incorporate multiple values into a comprehensive restoration plan. An economic viability assessment was not included in the planning process primarily because it was not required for planning under the National Environmental Policy Act (NEPA 1969). The 4FRI Stakeholder Group, including Forest Service staff, developed broad goals to achieve landscape-scale forest restoration, meeting multiple ecological objectives, while providing appropriately scaled, sustainable forest products to strengthen local economies. The stakeholder group has long recognized the need to strategically incorporate the multiple ecological values, including beneficial fire use, with community infrastructure and protection values across landscapes. However, working at landscape scales in the 4FRI project has highlighted the need to incorporate industry capacity and economic feasibility into strategic landscape planning—a concept not limited to northern Arizona (Blignaut et al. 2014; Iftekhar et al. 2017).

For this study we analyzed the western portion of the larger 4FRI planning area that was selected for the 1st phase of analysis (fig. 1). This first environmental impact statement project area covers approximately 240,000 ha located on the Williams and Tusayan districts of the Kaibab National Forest (NF) and on the Flagstaff and Mogollon Rim districts of the Coconino NF. We analyzed 155,000 ha (65 percent) that are available for mechanical treatments according to forest plans. Excluded areas include special management designations (wilderness, research natural areas, inventoried roadless areas, and experimental forest), areas included in previous projects, areas located on non-Forest Service administered lands, or areas that were designated to receive a nonmechanical thinning treatment (i.e., prescribed fire only).

The study area is dominated by ponderosa pine forests (*Pinus ponderosa* Laws.) at elevations ranging from 1,767 to 2,800 m including a mix of oak (*Quercus* spp.), juniper (*Juniperus* spp.) and pinyon pine (*Pinus edulis* Engelm.) with infrequent individuals or small groups of aspen (*Populus tremuloides* Michx.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Gordon & Glend.) Lindl. Ex Hildebr.), and blue spruce (*Picea pungens* Engelm.). Historically, ponderosa pine forests consisted of open park-line stands (Covington and Moore 1994), but current forest stands within the project area are more continuous, are more even-aged, and have higher densities with fewer nonforested openings than historical reference conditions (USDA FS 2014).

Historically, forest management in the 4FRI footprint was consistent with

broader FS management. Selective harvest of larger trees primarily started with the railroad infrastructure built in the 1880s. This continued until 1990; harvests were sometimes followed by planting and or precommercial thinning. In the last 30 years, however, forests have been managed primarily to thin small trees to reduce the risk of uncharacteristic fire effects and restoration goals, either through timber sales for material over 12.7 cm in diameter or through precommercial thinning of smaller diameter material. The use of fire varied across the national forests in the Southwest; on the Coconino and Kaibab NFs, fires were largely suppressed until the 1990s, with scattered pile and broadcast burning associated with harvesting activities. In the last 25 years, the use of prescribed fire has steadily increased each year (USDA Forest Service 2020). Wildfires managed to meet forest plan objectives have been utilized over the last 20 years on the Kaibab NF and the last 10 years on the Coconino NF. The two NFs harvest 156,000 m³ per year (USDA Forest Service 2017) on average and burn approximately 24,000 ha per year (12,500 ha in the wildland urban interface (WUI) and 14,000 ha outside the WUI).

Scenario Objectives

After preliminary discussions with stakeholders and 4FRI planning staff we selected two treatment objectives for analysis: 1) ecological, as measured as the relative potential for crown fire activity between untreated and treated stands (i.e. the efficacy of treatments to reduce potential passive and active crown fire); and 2) economic, measured as the total net value of treatments. The ecological indicator was developed by a small group of stakeholders and was intended as a surrogate for a number of linked ecological values including wildlife habitat for both the Mexican Spotted Owl (*Strix occidentalis lucida*) and pronghorn antelope (*Antilocapra americana*). Reduction in crown fire confers a number of other benefits to ecological conditions, and also paves the way for wildfires to be managed to meet forest plan objectives on a large-scale and prescribed fire to further build and maintain forest resiliency (Barros et al. 2018). The net value resulting from treatments was included as a priority since private entities that conduct harvesting operations are more inclined to bid on timber sales and implement the treatments proportional to financial incentives. Economic benefits such as avoided suppression costs are tangible, but not relevant in this specific prioritization since the purchaser of the contract to conduct the treatments is not compensated for anything other than wood products.

Stand and Inventory Data

We obtained stand polygon and inventory data from the Coconino and Kaibab NF data libraries, which included 11,788 stands. Stand polygons in the forest inventory data were delineated with aerial photos into areas based on similar characteristics such as vegetation type, slope, aspect, tree density, species composition, and management history. Stands varied in area from 4 to 80 ha. Approximately 34 percent of the ponderosa pine forest type within the study area had inventory data obtained within the last 5 years. Forest inventory estimates contained the number of trees per hectare by species and diameter at breast height (d.b.h., 1.37 m). Diameter was measured to the nearest 0.25 cm. Inventory data for the remaining stands were imputed using

a most similar neighbor process (Crookston et al. 2002) as implemented in the FS vegetation analysis system.

Calculating Potential Crown Fire

The potential for crown fire behavior was determined for each pixel using the fire simulation program FlamMap (Brittain 2015). We assessed both “passive” and “active” crown fire as indicators of high-severity effects. Passive crown fire is when the crowns of individual trees or small groups of trees burn without spreading to the adjacent forest canopy. Active crown fire is when the fire spreads through the canopy fuels but is dependent on the heat of surface fire for continued spread (Scott and Reinhardt 2001). Weather and fuel moisture conditions for the fire modeling were obtained based on the 2010 Schultz Fire that burned with mixed and high severity over about 6,000 ha within the 4FRI footprint. This fire represented potential fire behavior in a typical peak fire season, and weather conditions were based on the day the fire started (table 1). Fuel models were then calibrated to create fire behavior outputs representing the fire behavior observed in the Schultz Fire. Gridded 30-m FlamMap outputs (30 m) for crown fire, and surface fire, were used to attribute the stand polygons based on the majority count of the observed fire behavior.

To measure the potential for treatments to reduce the likelihood of crown fire we modeled silvicultural treatments and post-treatment wildfire behavior for each stand using the Forest Vegetation Simulator (FVS), Central Rockies Variant (Dixon 2002). FVS is a distance-independent, individual-tree model, where stands are the basic unit of management, and model projections are dependent on interactions among trees within stands (Dixon 2002). The model is widely used in research and empirically for a range of stand modeling priorities (Crookston and Havis 2002; Havis and Crookston 2008;

Table 1—Weather and fuel moisture parameters used for fire simulation based on the 2010 Schultz Fire.

Variable	Simulation value (percentile)	Schultz Fire value (percentile) ^a	97th percentile conditions ^b
Maximum temperature (°C)	25 (50th)	25 (50th)	32
Minimum RH (%)	11 (85th)	11 (85th)	7%
Maximum 6-m wind speed (km hr ⁻¹)	6 (95th)	~7 (98th)	6.7
1-hr fuel moisture (%) ^c	4 (74th)	3 (86th)	2%
10-hr fuel moisture (%) ^c	4 (90th)	3 (95th)	3%
100-hr fuel moisture (%) ^c	6 (90th)	6 (90th)	5%

^aWeather conditions change throughout the day and the effects of topography and surface heating produced gusts over twice as high on Schultz Pass as those shown above. At the RAWs station, wind speed averaged ~5.8 km hr⁻¹, gusting up to 8.5. We used 6 km hr⁻¹ in order to preserve the contrast in potential fire behavior.

^bPercentiles were determined using data from the Flagstaff RAWs from April 15th through September 15th, 1968–2012.

^cWhen fire behavior is modeled, fuel moistures are set for each fuel model. Fuel moistures above indicate what was applied to the majority of the acres modeled.

Keyser and Keyser 2017). FVS-Fire and Fuels Extension (FFE) (Rebain et al. 2010) outputs for surface and crown fuels data were then used to adjust the fuel models for rerunning FlamMap to produce post-treatment fire behavior under the same conditions run previously (Schultz Fire). The difference between pre- and post-treatment active crown fire was then calculated to determine treatment effectiveness to reduce crown fire hazard. This variable is hereafter referenced as Delta (Δ) Active Crown Fire. (fig. 2a; Appendix A, fig. A1).

Financial Analysis

We simulated treatment prescriptions in FVS to generate a list of harvested trees by species and d.b.h. The list of harvested trees echoes the information in the inventory plot to the outputs. A total of 34 unique FVS models were developed to mimic the individual treatment designs as they were proposed in the 4FRI 1st environmental impact statement analysis. Some prescriptions were two-stage and first simulated a thinning across the entire stand followed

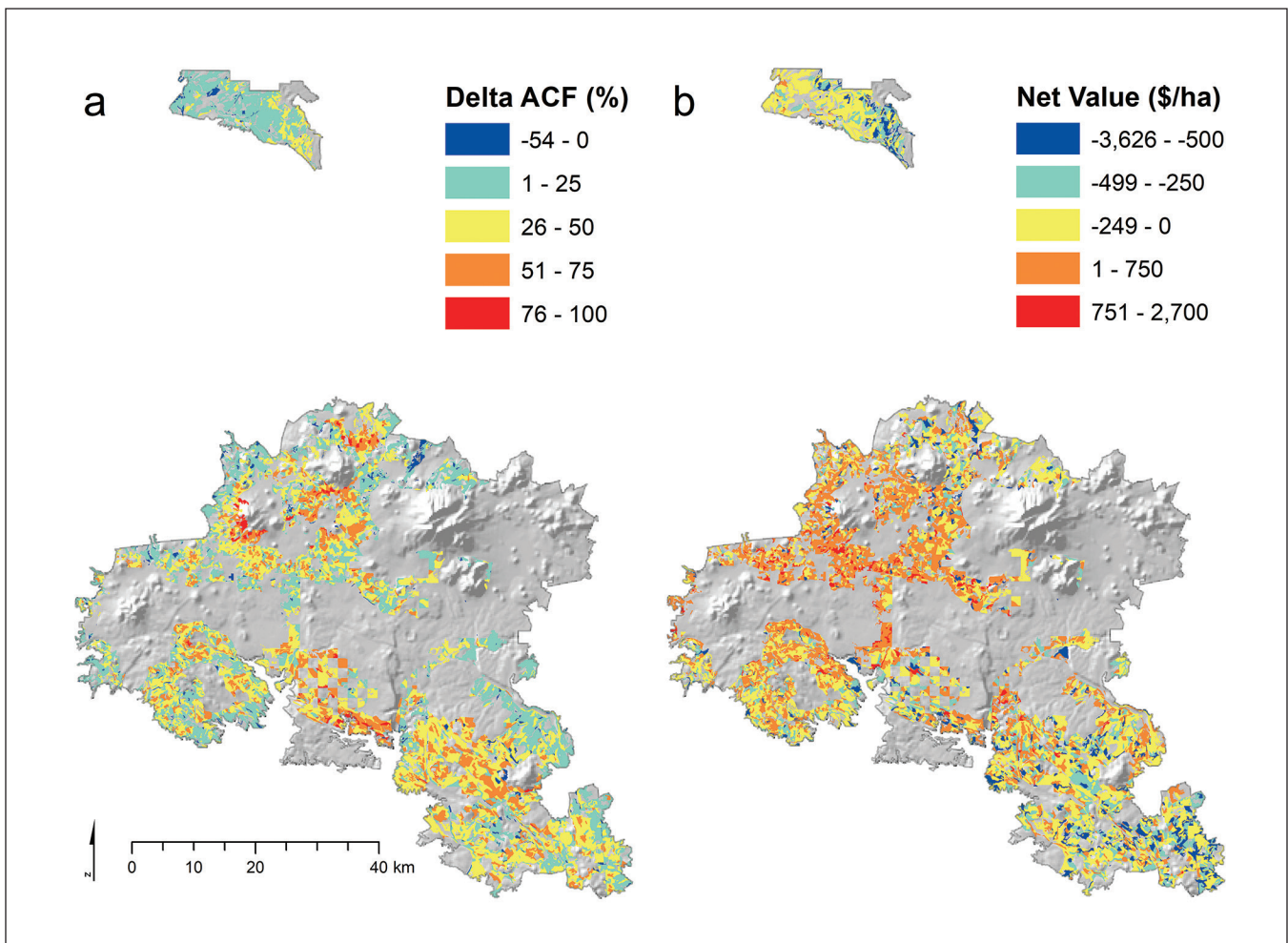


Figure 2—Restoration objective input variables used in the prioritization analysis: (a) change in active crown fire from pre- and post-treatment conditions, and (b) net value obtained from merchantable ponderosa pine as described in the financial analysis section. Note that only stands that were eligible for mechanical treatment were considered in prioritization. Stands that would receive either a burn-only treatment or a grassland restoration treatment were omitted from the prioritization process.

by a second stage that modeled group selection for regeneration openings in prescriptions developed to emulate a “patchy, clumpy” ponderosa pine structure. The outputs from these two-stage thinning prescriptions were averaged using an 85 percent and a 15 percent weighting. The harvested trees were then processed using the economics extension and custom FVS scripts to calculate the potential revenue from restoration treatments.

To estimate the net value of harvested material, we used a residual value appraisal approach (Ager et al. 2017) where harvest and transportation costs are subtracted from the projected revenue from the logs at the mill. The net value of treatments is shown in figure 2b and was calculated as:

$$\text{Net value} = \text{log pond value} - (\text{harvesting cost} + \text{hauling cost} + \text{ancillary costs}) \quad [1]$$

The *log pond value* was the amount a mill will pay for a log delivered to the mill location. The FVS economics extension was then used to convert harvested trees into 5-m logs and sum their value based on log price data (table 2, fig. 3c). Note that only ponderosa pine was valued in this analysis.

The *harvesting cost* included the cost associated with moving merchantable logs from the stump onto a logging truck and moving nonmerchantable material to a landing site. Harvesting costs were calculated based on tree size class consistent with previous studies (Rainville et al. 2008; Rummer 2008) (fig. 3a). Table 3 shows the values used to estimate the cost to move harvested material from stump to logging truck.

The *hauling cost* estimated the cost to move merchantable volume from the harvest landing to the nearest wood processing facility. Hauling cost calculations used the estimated travel time to the nearest mill and the number of truckloads of merchantable timber in the project area. Hauling cost was estimated using the following formula:

$$\text{Hauling cost} = \text{travel time} \times \text{cost per hour} \times \text{merchantable volume per truck} \quad [2]$$

Table 2—Log pond values used for the economic analysis.

Size class (cm)	\$ / m ³ ^a
12.7–20.3	25
20.4–30.5	34
30.6–45.7	39
45.7+	52

^aEstimates were provided to Mark Nigrelli.

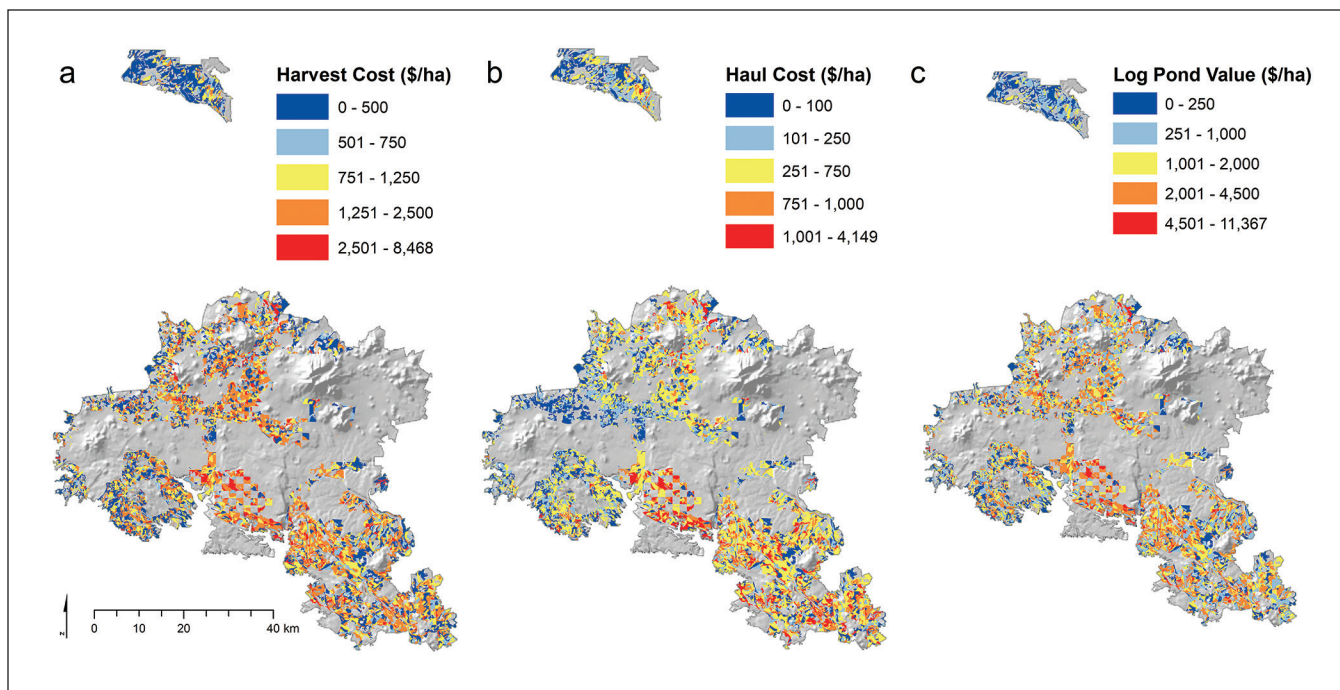


Figure 3—Stand-level spatial distribution of the economic input variables within the study area. Values are averages by stand.

Table 3—Assumed costs for ground-based logging activities used to estimate per hectare harvesting costs for each thinned forest stand.

Tree d.b.h. (cm)	Number of cut trees (ha ⁻¹)					
	12	50	124	247	494	988
	(\$/m ³) ^a					
0.25–15					35	32
> 15–18				28	26	24
> 18–23			22	20	19	18
> 23–41		14	13	13	12	12
> 41–53	13	13	13	13	12	12

^a Values given are costs in U.S. dollars per cubic meter removed, grouped by size class and number of trees cut per hectare. Harvest cost estimates stratification was adapted from Rainville et al. (2008).

Travel time was measured in hours at a cost of \$85 per hour and included to and from the mill (round-trip). It should be noted that only merchantable ponderosa pine was accounted for in the haul cost (fig. 3b). A value of 17 m³ was assumed for the merchantable volume per truck load. Travel time to the nearest mill was estimated using the cost distance function in ArcGIS Spatial Analyst (ESRI 2013). A digital map of roads on the national forests within the study area was obtained from the 4FRI project data library. Both road layers were converted to a 30 x 30 m pixel raster and reclassified based on FS road maintenance level designation (1–5). The time to traverse each pixel was estimated using travel speed assumptions in table 4. Each stand was attributed with the minimum travel time using ArcGIS zonal statistics (fig. 4)

Ancillary costs including planning and road construction were not included in the analysis. Road maintenance costs, based on discussions with the economics planning team, were set at \$1.00 per merchantable cubic meter and added to all stands to cover these costs. Estimation of additional treatment costs could be further refined by incorporating the cost to process and/or remove biomass material left on site. It should be noted that all stands that were designated as receiving a burn-only prescription or a grassland restoration treatment were not included in this FVS modeling effort.

Spatial Prioritization Model

We used ForSys (formerly the Landscape Treatment Designer) (Ager et al. 2016) to examine a range of scenarios that maximized either financial, ecological, or a mix of objectives. ForSys is similar to Marxan with Zones (Watts et al. 2009), although we incorporated many features specific to prioritizing forest management rather than designing conservation reserves. A scenario in our case is a priority sequence of project areas (n = 40) with treated area (1,000 ha) identified among the candidate stands in each one. Thus, the program replicates actual restoration planning where landscapes are partitioned into smaller project areas to meet logistical constraints related to implementing treatments. These 40 project areas would treat a total of 40,000 ha and represent a 5-year program of work. Scenarios were created by changing the priority weights for selecting treatment units (from 0 to 3) in all combinations in a linear objective function. Eliminating duplicate weightings (e.g., 1-1, 2-2, 3-3) resulted in nine unique weight combinations

Table 4—Assumed average haul speeds by road maintenance class.

Road maintenance class	Speed (km hr ⁻¹)
1	8
2	16
3	40
4	72
5	89
No road	3

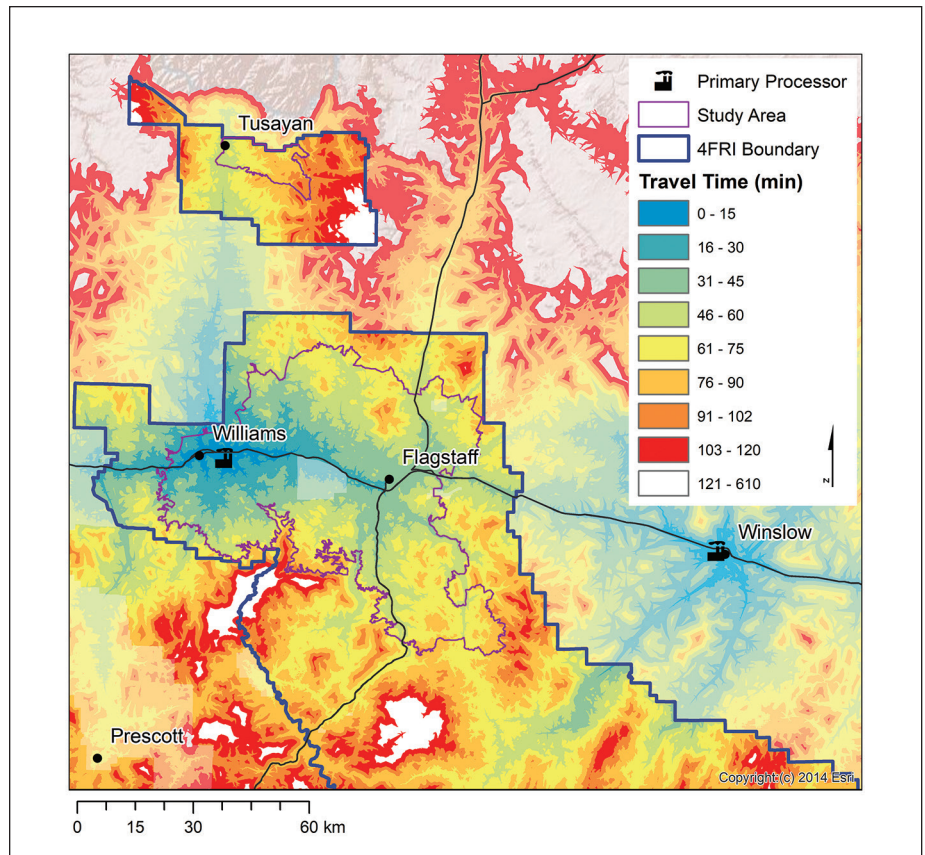


Figure 4—Map of travel time (minutes) to the nearest mill used to estimate haul costs. Estimates of travel time were used to calculate the total stand level haul cost to remove merchantable timber.

(scenarios). For each scenario the optimum project areas were identified and sequenced using a relatively simple neighborhood search algorithm (Feo and Resende 1995) (Appendix A, fig. A2). The algorithm tests each stand in the landscape as a potential centroid to build a project area by searching around that centroid for stands that are available to treat, meaning that some level of biomass or sawtimber is produced. The search distance is increased until the treatment area constraint (1,000 ha) is reached and the total objective value for that project area is stored in memory. The algorithm then moves to the nearest polygon that has yet to be included in a project area and repeats the process among the remaining unselected polygons. The process repeats until the specified number of project areas and treatment units within them have been identified.

The objective value is calculated as:

$$\text{Max } \sum_{j=1}^k (Z_j * \sum (W_i N_{ij})) \quad [4]$$

Subject to:

$$\sum_{j=1}^k (Z_j A_j) \leq C \quad [5]$$

where C is the area treated per project area, Z is a vector indicating whether the j th stand is treated (e.g., $Z_j = 1$ for treated stands and 0 for untreated

stands), N_{ij} is the contribution to priority i in stand j if treated, and A is the area of the j th treated stand. W_i is a weighting coefficient that can be used to weight one priority versus another.

We report results from all nine scenarios but focus on two specific benchmark scenarios: (1) maximize revenue, and (2) reduce crown fire, and a third scenario that is a balance between the two. To simplify comparison among the two priorities, we standardized the outputs by calculating the percentage that each stand potentially contributed to the total possible in the study area.

Results

Maps of the change in potential active crown fire and the net value from treatments are shown in figures 2a and 2b, respectively. The results showed that 98 percent of the treatable area could be effectively treated to reduce active crown fire (ACF) under the assumed weather conditions. By contrast, the area that generated positive net value from treatments was limited to 33 percent of the treatable area (51,208 ha) (fig. 5). High net value areas were clustered in stands along the I-40 corridor in the northwest part of the study area due to the impact of haul cost in net value calculations (fig. 3b).

Optimizing the two priorities generated a substantially different spatial distribution of project areas and treatment units (fig. 6). Prioritizing ACF generated a priority sequence that was distributed throughout the study area (fig. 6a), whereas optimal projects for revenue were clustered along the I-40 corridor between Flagstaff and Williams (fig. 6b). The impact of haul cost, as noted above, likely contributed significantly to this result. The balanced scenario prioritized about half of the top 10 projects near the I-40 corridor but showed less clustering than the revenue scenario (fig. 6c).

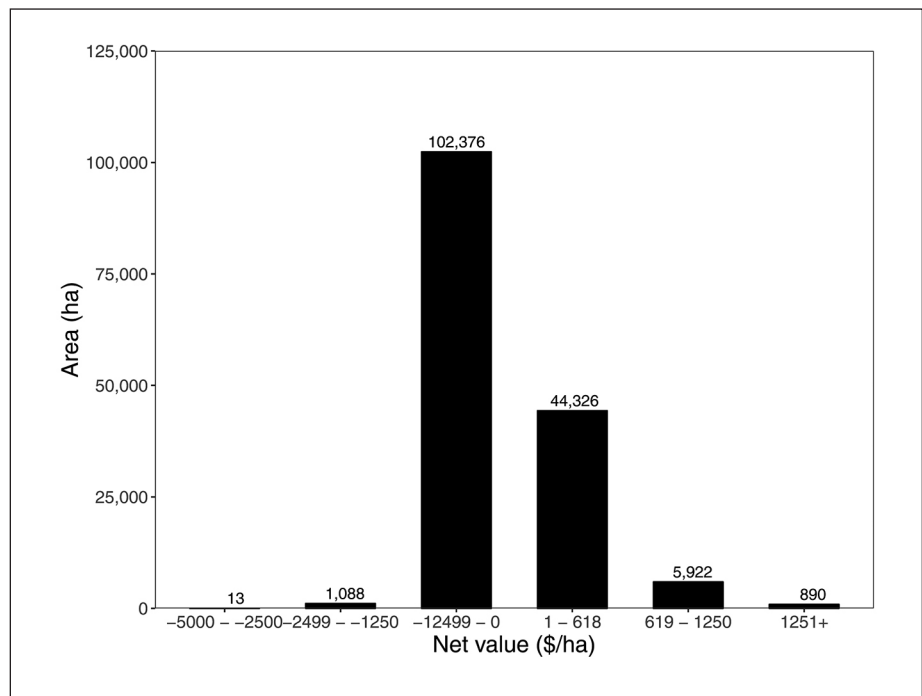


Figure 5—Distribution of treatable stand area according to net value in the study area.

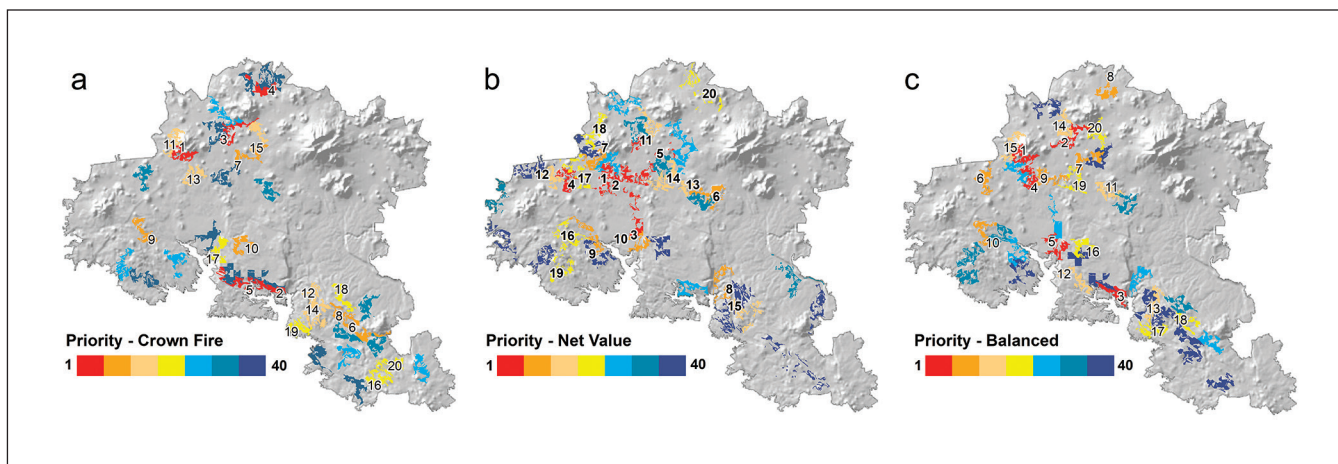


Figure 6— Location of priority projects for the two benchmark scenarios: (a) reducing active crown fire potential; (b) maximizing revenue; and (c) for the balanced scenario, simultaneously maximizing revenue and reduction in active crown fire potential.

For each project area we used the outputs to plot production frontiers (PFs, fig. 7) to illustrate priority tradeoffs. Results showed that prioritizing reduction in ACF negatively impacted potential net value (green dot, fig. 7). Similarly, maximizing net revenue showed a negative tradeoff in terms of treating areas with ACF (purple dot, fig. 7). The range in net value from all nine scenarios was -\$68,612 to \$661,272 while the range in reduction of ACF among the nine scenarios was less than 1 percent. Prioritizing even the third

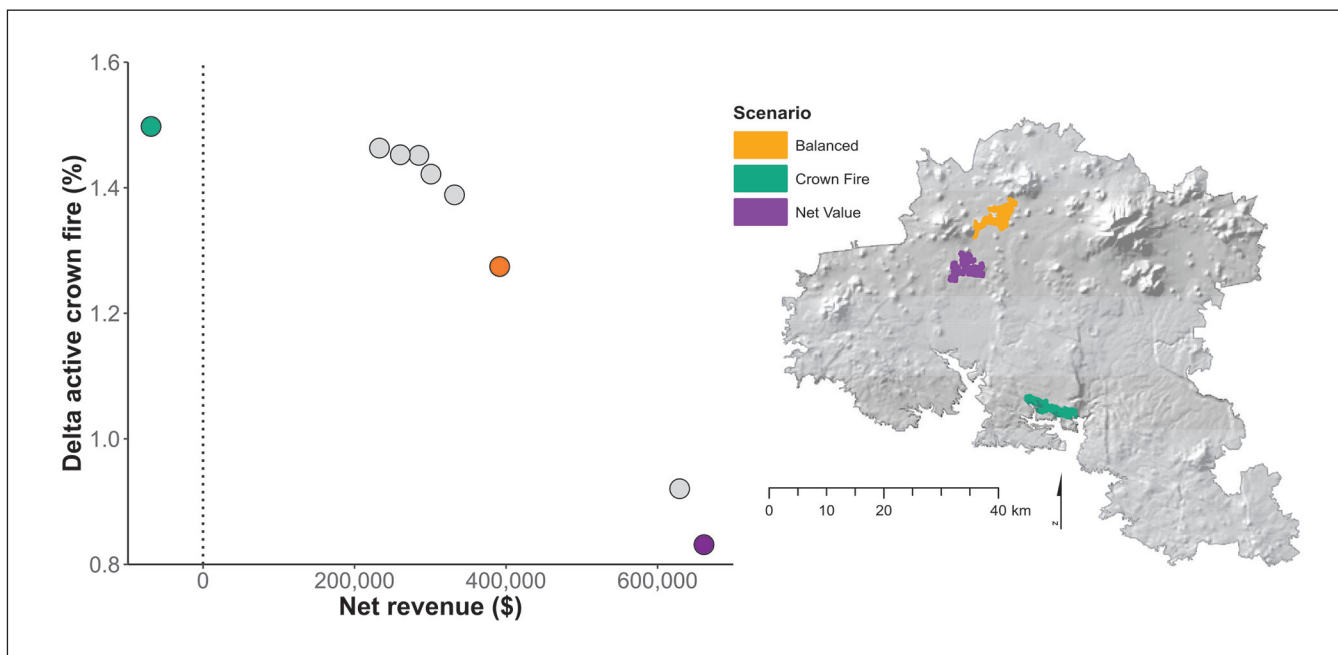


Figure 7—Production frontier curve (PF). The effect of prioritizing projects based on net revenue versus reduction in active crown fire potential on treatment location. Treatments were modeled for a total of 1,000 ha per project area. Treatment locations correspond to the associated points on the graph based on color. Each circle represents a distinct set of stands selected for treatment for a single 1,000-ha project. Prioritizing reduction in active crown fire for a single 1,000-ha project, for example, results in a selection of stands in the southern portion of the study area, but changing the objective weights to emphasize net revenue shifts treatment to the northwest.

best project in terms of net value in an effort to reduce ACF at 1.3 percent resulted in a significant opportunity cost (ca. \$269,694). This results from the scarcity of stands that have the potential to produce positive net value. The location of optimal project areas changed substantially when different restoration objectives were prioritized (fig. 7, right panel).

Contrasting the two benchmark scenarios with the balanced scenario for a 5-year plan of work treating roughly 45,000 ha (fig. 8, dashed vertical line), optimizing net value resulted in a 31 percent reduction in ACF (fig. 8a) while generating \$12,529,345 in revenue (fig. 8b). The balanced optimization

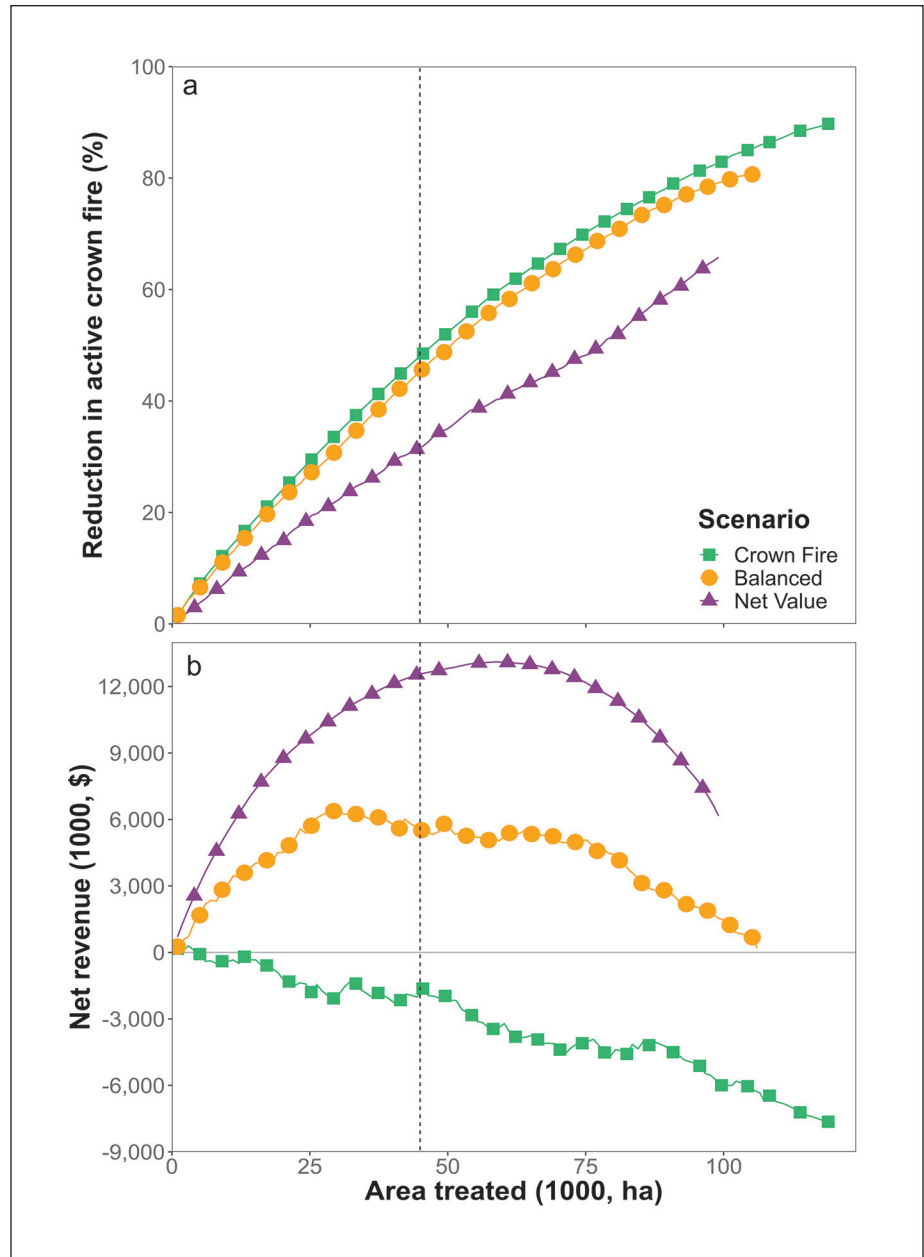


Figure 8—Cumulative attainment in (a) reduction in active crown fire, and (b) net value with increasing area treated for the two benchmark scenarios maximizing either reduction in active crown fire or net value with a third balanced scenario simultaneously maximizing revenue and reduction in active crown fire potential.

scenario reduced ACF 45 percent while generating \$5,676,058 in revenue. Alternatively, optimizing the reduction in ACF decreased ACF by 48 percent but required \$2,020,548 in additional subsidies. An additional 17 percent of the total ACF that is treatable would be reduced in the ACF scenario versus the net value optimized scenario. However, that reduction would come at an opportunity cost of \$10.5 million (fig. 8).

At increasing scales of implementation, the analysis suggested that prioritizing projects based on net revenue could generate increasing positive revenues for 58,810 ha of treatment (54 x 1,000 ha projects) (fig. 8b), after which the availability of stands with positive value has been exhausted leading to diminishing returns. By contrast, a scenario where projects are prioritized to reduce ACF would require additional subsidies after the first four projects (fig. 8). Even in the balanced scenario, 33 percent of the first 40 projects resulted in unprofitable solutions, and unprofitable solutions started showing up after 7 projects.

When we compare the top 40 restoration projects identified in our scenarios (based on objectives) with planned restoration projects as part of 4FRI, we showed that there are opportunities to better optimize net value and reduction in ACF (fig. 9). In particular, the “best” project provides opportunities to balance both net value and a reduction in ACF that exceed progress towards these restoration objectives in comparison to any proposed 4FRI project, and many perform better than the economic optimization scenarios. The majority of proposed projects, however, are clustered near or even below the 40th best project identified in the modeling. We expect the priorities to shift as users change the input variables or weights. ACF was used as a restoration surrogate here, and it is important to note that some of these proposed 4FRI projects were chosen based on different prioritization criteria, including wildland urban interface or watershed health, than the ACF indicator analyzed here.

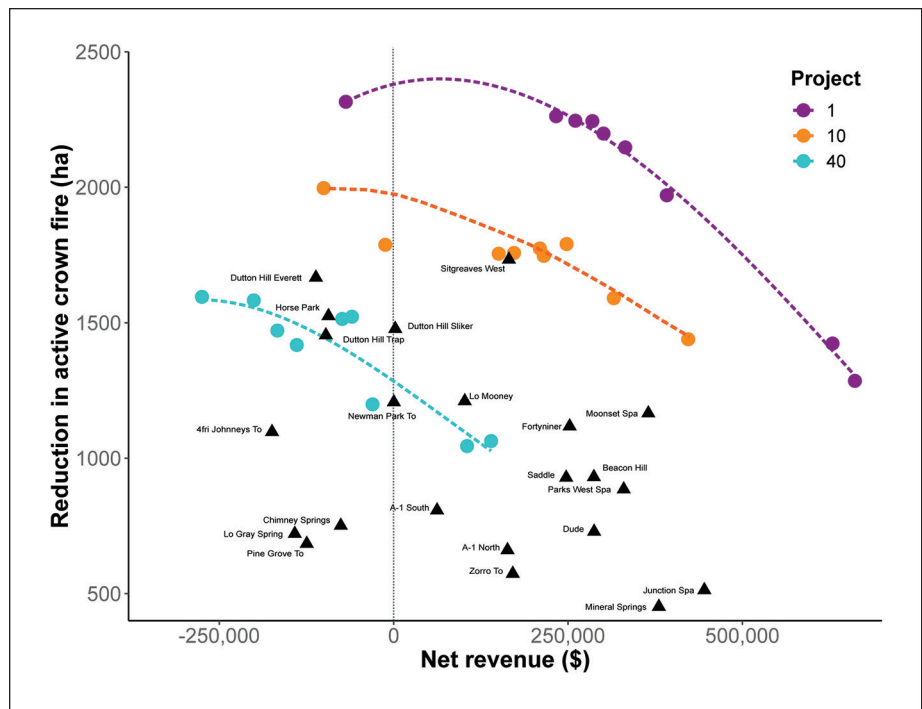


Figure 9—Comparison of the tradeoff in attainment for 3 of the top 40 optimal projects modeled in the study. Each line represents a separate project area, and the circular symbols represent separate 1,000-ha restoration scenarios and distinct sets of selected stands for treatment optimized to achieve reduction in active crown fire potential, maximize net revenue, or a blend of both priorities. The shorter the curve the fewer combinations of stands are available to optimize a given objective. The longer the curve, the more opportunities there are on the landscape to change a selection of treatment stands to emphasize one objective or another. In addition, we approximated attainment for 22 Forest Service projects where layout has been completed or nearly completed (2017–2020) for a comparison weighted to represent similar treatment area size (1,000 ha).

Discussion

Collaborative forest landscape restoration programs on western United States public lands face substantial challenges to sustain the pace and scale of treatments under current budgets and economic conditions. Given that financial constraints are a major factor that limit wider implementation of forest restoration activities in the western United States, and elsewhere (Aronson and Alexander 2013), the modeling demonstrated in this study has the potential to improve the current ad hoc treatment prioritization methods that use GIS overlays and various scoring templates. Our methods have been demonstrated on other landscapes in the United States (Ager et al. 2017) and elsewhere (Alcasena et al. 2018; Salis et al. 2016) to identify optimal project areas and examine financial and ecological tradeoffs among management objectives (Ager et al. 2010; Ager et al. 2016). Heretofore, optimization tools to study tradeoffs and prioritize landscapes have not been available as routine planning tools to guide Forest Service restoration investments, although various experimental systems that exceed the technical capacity of planning teams have been demonstrated (Schroder et al. 2016). Thus, decisions about restoration priorities have been made without a complete picture of the financial cost to emphasize one restoration objective versus another.

We found that reducing crown fire and restoring fire resiliency in the southwestern U.S. study area can be accomplished with positive net revenue for a substantial area of treatments. Among the three scenarios, treating about 44,000 ha and optimizing net value resulted in a 29 percent reduction in ACF (fig. 8a) and generated \$12,150,525 in revenue (fig. 8b). By contrast, the balanced scenario reduced ACF substantially more (by a third to 41 percent), while generating less revenue (\$5,759,525) but still showing a net return. Finally, optimizing ACF reduced crown fire area by 44 percent, a marginal increase from the balanced scenario, but required \$2,295,907 in investment. The results confirm that restoring expansive southwestern U.S. ponderosa pine forests to improve fire resiliency can pose significant financial challenges as in other restoration environments (Allen et al. 2002), but underscores that projecting revenue from harvested wood as part of the restoration planning ultimately improves the likelihood that projects will be implemented (i.e., contractors bid on the sale). Indeed, a portion of that revenue can be designated to fund restoration activities in locations where forest and fuel management do not generate a net positive value (Deal et al. 2012; USDA FS 2012).

Our economic analysis is consistent with earlier studies that demonstrated the financial challenge of forest restoration in the southwestern region and elsewhere in the western United States, and that subsidies will be required to scale up treatments (Barbour et al. 2008; Beck Group 2015; Rainville et al. 2008). More importantly, our large case study showed the importance of prioritization in the planning phase to develop scenarios that

are economically viable. The prioritization process is important at multiple scales; both the location of the project area and the stands selected within them determine financial and ecological outcomes. The relative importance of prioritization at these different scales in terms of achieving restoration outcomes over the long run has not been investigated.

The results of our study were used by the 4FRI implementation team to guide a 5-year plan of work in terms of the location of project areas and stands to treat within them. We are unaware of similar case studies on federal lands where the application of forest optimization models (Schroder et al. 2016) led to implementation decisions about priority landscapes for treatments. More importantly, the application of our model as part of the collaborative planning process cultivated a keen interest in further studies to add ecological indicators and performance measures. The modeling can also be widely extended to optimize the spatial implementation of natural and prescribed fire to address the fire deficit (Minas and Hearne 2016) and growing backlog of areas that are in need of fire treatments (Ager et al. 2013; Alcasena et al. 2018; Chung et al. 2013). These experiments can be conducted as part of prioritizing treatments on the additional 560 thousand ha in the 4FRI project once the final environmental impact statement is completed.

This work along with many other studies contributes to achieving long-term social and ecological goals for U.S. national forest restoration programs and collaborative efforts such as the National Cohesive Wildland Fire Management Strategy and Shared Stewardship (USDA FS 2014, 2018). Our framework could be expanded to other CFLRP project areas and other landscape restoration initiatives, including the USDA Forest Service and Natural Resources Conservation Service Joint Chiefs' Landscape Restoration Partnership. Spatial decision support tools beyond ad hoc GIS overlays and various scoring methods are largely lacking for the design of viable projects where the specific wood products mix generated from restoration activities (i.e., log size, species, value) is modeled over a simulated implementation. Moreover, the analysis contributes to the broader collaborative aspects of the CFLRP, which were funded specifically to build trust among private and public entities (Schultz et al. 2012).

Decision support tools presented in this study can build transparency among federal land managers and stakeholders by illustrating tradeoffs among social and economic objectives, as described in our previous work (Ager et al. 2017). Furthermore, it is an opportunity to include stakeholders in the planning process (Butler et al. 2015) rather than a body to review the decision and respective rationale. Although there is extensive research on the application of decision support to forest management issues (Nobre et al. 2016), most are concerned with regulated forests, and very few if any studies meet the needs of applied restoration planners in terms of applicability to either short- or long-term planning problems. For instance, spatial optimization has been applied to a wide range of forest management goals, including designing wildlife habitat reserves, locating fuel breaks, suppression activities, and harvest scheduling (Baskent et al. 2000; Borges et al. 2014; Rönnqvist et al. 2015; Schroder et al. 2016). However, the level of analytical support, especially for mathematical programming and heuristic

approaches (Hof and Bevers 2002; Rönnqvist et al. 2015), is not available to restoration planners within the CFLRP process, and it is in general scarce at all administrative levels of planning in the Forest Service and other U.S. federal land management agencies.

The need for scenario planning frameworks to address federal forest restoration issues is unprecedented in an era of climate change and the growing scale of natural disturbances such as wildfire. Scenario planning is a systematic approach to think creatively about possible complex and uncertain futures (Peterson et al. 2003; Spies et al. 2017; Star et al. 2016), rather than focusing on the accurate prediction of a single outcome. Although in its current form we did not analyze uncertainties associated with predicted outcomes, the model does provide the ability to examine many alternative outcome responses to different restoration priorities. Our model can be readily applied to participatory scenario planning exercises where research scientists, managers, policymakers, and other stakeholders explore and test scenarios in an iterative process. In this way the system functions as a multicriteria platform to explore landscape management scenarios that are optimized in terms of where and how to achieve different outcomes and outputs at different administrative scales. At present, national decision support models do not exist to examine alternative scenarios to allocate the approximately \$1 billion annual investment in forest and fuel management activities to the 10 regions and 154 U.S. national forests. In prior work we demonstrated application of the model at much larger scales (western United States) to understand production frontiers and tradeoffs among agency-wide targets and management goals (Ager et al. 2019) and assessed near-term progress towards nationally identified priorities and targets.

A particularly promising expansion of our work is to support the new FS emphases on cross-boundary management to increase the scale of active forest management (USDA FS 2018). Our planning model here can potentially have widespread application for coprioritizing investment decisions as outlined in the shared stewardship memorandums of understanding (MOU) (USDA FS 1999). Specifically, these call for “new mapping and decision tools to locate treatments where they can do the most good, thereby protecting communities, watersheds, and economies where the risks are greatest” (USDA FS 2019). The core idea in this initiative is to expand land treatments across boundaries to reduce the scale mismatch between wildfire risk and the current forest management footprint (Ager et al. 2015). However, the process will require spatial planning to coprioritize projects, meaning that respective federal and state assessments on land conditions (threats and opportunities) will require a multicriteria approach (Diaz-Balteiro and Romero 2008) to integrate the respective priorities identified in agency and state assessments and understand tradeoffs. This has been completed in the State of New Mexico as part of the State Forest Action Plan (Day et al. 2021; New Mexico State Forestry 2020). Assessments of cross-boundary risk (Ager et al. 2018) can be integrated into this process and used as a management priority to target forest treatments where wildfires are predicted to spread across federal and state boundaries.

Conclusions

We developed and applied a spatial forest planning model that can be used to improve the efficiency of collaborative and other planning efforts on U.S. public forests. The model can also be used to support the coprioritization efforts as part of the Forest Service Shared Stewardship initiative (USDA FS 2018) where boundary-spanning projects are being designed and implemented to expand the scale of treatments. The model is substantially less complex than typical spatial forest planning models, while providing adequate functionality for prioritizing restoration objectives and understanding multicriteria tradeoffs. In the current application we demonstrated the model to prioritize both an economic and an ecological objective for a large restoration project in the southwestern United States where forest management is constrained by low economic value of forest materials removed as part of restoration activities.

We examined a large number of scenarios that optimized ecological or economic objectives, plus we identified a scenario that adequately satisfied both objectives, thus ensuring the financial viability of the project. The methods also allowed comparison of proposed projects within scenarios to enable more optimal solutions and better understand the efficiency associated with current planning. The approach, therefore, has widespread application as part of collaborative forest landscape restoration on federal forests in the United States or where similar economic conditions prevent wider scale application of restoration activities.

Most importantly, such a modeling approach will be crucial as a scenario planning tool to enlarge the footprint of forest management activities and thus address the growing threat of wildfire across the West. Shared stewardship activities with interagency coprioritization will be necessary to identify scenarios that meet the respective interests of multiple landowners and stakeholders. Here, our model provides quantitative tradeoffs and clear production frontiers at multiple scales to help improve transparency in the multi-owner forest planning environment.

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Appendix A. Additional Modeling Details

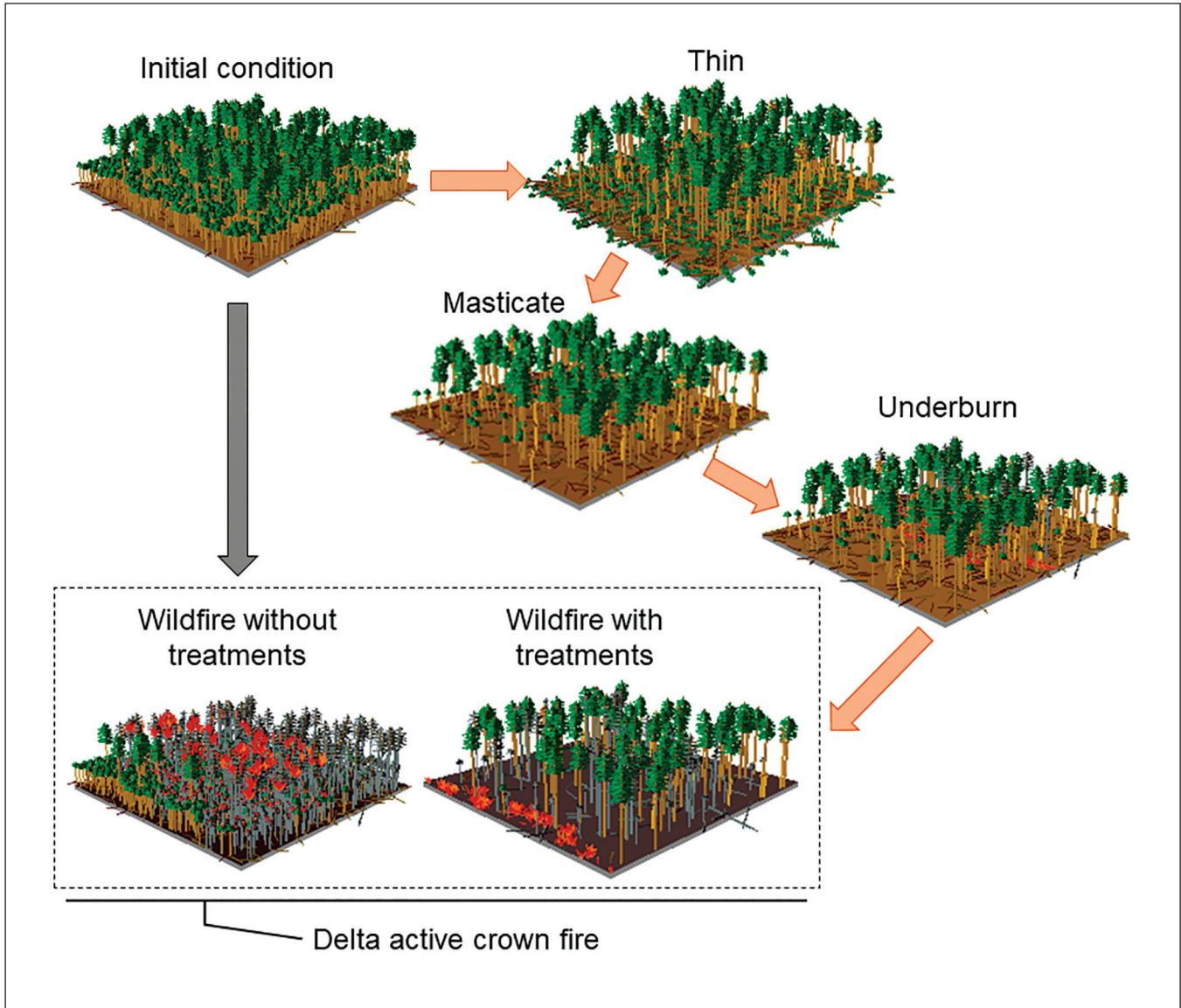


Figure A1—Illustration of how delta active crown fire was calculated from Forest Vegetation Simulator (Dixon 2002) outputs where stands receive silvicultural treatments (thinning, mastication and underburning) and post-treatment wildfire behavior is compared with stands that receive no treatments. Potential crown fire behavior was estimated with FlamMap (Brittain 2015). See text for more details.

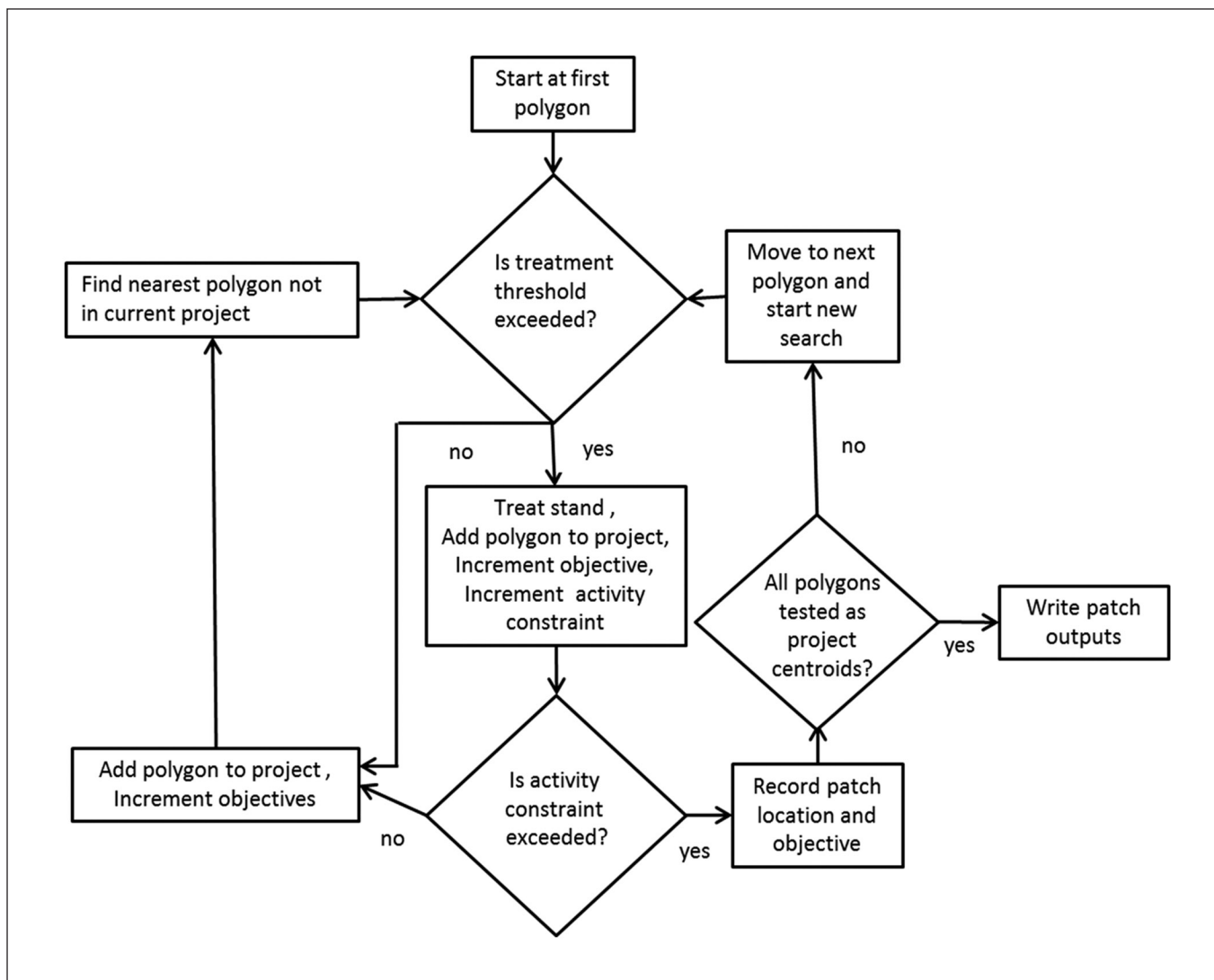


Figure A2—Decision logic for the optimization model used to locate project areas. The algorithm tests each stand as the seed location for a project, and absorbs adjacent stands until a total area treated constraint is met. The model identifies the aggregate of polygons that maximize the restoration objective and the polygons that require treatment. In the current study, polygons were defined as stands, treatment thresholds were measured by potential flame length, activity constraint was the total treatment allowance per project of 1000 ha, and restoration priorities were: 1) maximize revenue, 2) reduce crown fire, and 3) a balance between the two. Figure taken from Ager et al. (2013).

References

- 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. <http://dx.doi.org/10.1890/ES13-00007.1>.
- Brittain, S. 2015. Fire behavior FlamMap application interface. http://sbrittain.net/FB/FB_API.htm
- Dixon, G.E. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Fort Collins, CO: USDA Forest Service, Forest Management Service Center. 226 p.

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