



Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Rocky Mountain Research Station

General Technical Report RMRS-GTR-437

February 2024

Prioritizing Restoration and Risk Reduction Landscape Projects With the ForSys Planning System

Michelle A. Day, Alan A. Ager, Rachel M. Houtman, Cody R. Evers



Day, Michelle A.; Ager, Alan A.; Houtman, Rachel M.; Evers, Cody R. 2023.
Prioritizing restoration and risk reduction landscape projects with the ForSys planning system. Gen. Tech. Rep. RMRS-GTR-437. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 51 p. <https://doi.org/10.2737/RMRS-GTR-437>.

ABSTRACT

The ForSys spatial planning system was developed by USDA Forest Service Research and Development to modernize agency tools to prioritize forest and fuel management investments and understand tradeoffs among alternative scenarios. ForSys uses inputs on objectives, management restrictions, constraints, and treatment thresholds to organize stands into planning areas that are optimized for one or more objectives. The model has been used in five different countries resulting in published case studies at scales ranging from watersheds to the continental United States, and multiple Federal records of decisions and environmental management documents. Most recently, ForSys was used as the analytical tool to identify priority firesheds in the 2022 Wildfire Crisis Strategy, and to downscale priorities to field units as part of implementation. In this paper, we describe the ForSys model and then review selected case studies where the model was applied to a wide range of land management problems. We discuss the overall science findings, management implications, and future development with external technology partners as part of broader application of the model to optimize investments in landscape restoration and risk reduction.

Keywords: *spatial prioritization, conservation planning, scenario planning, forest restoration, decision support system*

AUTHORS

Michelle A. Day is a Biological Scientist in the Fire, Fuel, and Smoke Research Program, Rocky Mountain Research Station, Missoula, Montana.

Alan A. Ager is a Research Forester Emeritus in the Fire, Fuel, and Smoke Research Program, Rocky Mountain Research Station, Missoula, Montana.

Rachel M. Houtman is a Biological Scientist in the Fire, Fuel, and Smoke Research Program, Rocky Mountain Research Station, Missoula, Montana.

Cody R. Evers is a Research Associate in the Department of Environmental Science and Management at Portland State University in Portland, Oregon..

ACKNOWLEDGMENTS

We acknowledge funding from the National Fire Decision Support Center, State and Private Forestry, Washington Office to support our research efforts. John Phipps, Deputy Chief State and Private Forestry (Retired), provided valuable feedback on model design and functional requirements. Ken Bunzel and Stu Brittain provided programming support as part of the research on the ForSys spatial planning system. John Battles, Dave Schmidt (Spatial Informatics Group), and Ana Barros provided feedback that greatly improved this manuscript.

All Rocky Mountain Research Station publications are published by U.S. Forest Service employees and are in the public domain and available at no cost. Even though U.S. Forest Service publications are not copyrighted, they are formatted according to U.S. Department of Agriculture standards and research findings and formatting cannot be altered in reprints. Altering content or formatting, including the cover and title page, is strictly prohibited.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

COVER IMAGE: Composed by Cody R. Evers with photos from USDA Forest Service.

Contents

Introduction	1	Future System Development	31
ForSys	2	Program Distribution	32
Model Overview	2	References	32
Spatial Optimization Heuristics	4	Appendix A	37
Review of Science and Management Applications	11	Table A1. List of published spatial planning case studies using ForSys, and their science and management application, scale and key findings presented in alphabetical order by author.	37
Designing Efficient Dry Forest Treatment Strategies.....	11	Table A2. Decomposition of planning areas into treatment need, costs and revenues for the Umatilla National Forest for two example planning areas show in figure 13. Data outputs were taken from Belavenutti et al. (2021).	50
Incorporating Multiple Objectives in Scenario Planning	13	Table A3. Ownership composition in treated areas among the top 25 watersheds in the State of New Mexico when prioritizing only the reduction in risk to water supplies. Data accompanies the stacked bar chart in figure 14.	51
Prioritizing Prescribed Burning	16		
Tradeoffs Between Wood Production and Risk Reduction	20		
Cross-boundary Scenario Planning for Shared Stewardship	21		
Modeling a Scenario for the 2022 Wildfire Crisis Strategy	21		
Prioritizing the Construction of Fuel Break Networks	24		
Discussion	26		
Management Implications	27		
ForSys Versus Other Prioritization and Planning Systems	27		
Box 1—Prioritization decision support tools used in land management as reported in recent literature	29		
Future Applications	30		
Protect Sage Grouse Habitat	30		
Dynamic Strategic Fuel Breaks for the Desert Tortoise	30		
Co-prioritization of Restoration and Fuel Break Networks	30		
Integration of Additional Priorities into the Wildfire Crisis Strategy	31		
Assessing Social Equity of Management Projects	31		

Introduction

Defining priorities in restoration, risk reduction, and conservation programs has become increasingly important to address a wide range of emerging resource management issues on public lands in the United States and elsewhere (Brudvig 2017; Chazdon and Guariguata 2018; Kukkala and Moilanen 2013; Moilanen et al. 2011; Pohjanmies et al. 2019; Strassburg et al. 2020). Prioritization often involves multiple objectives and is constrained by limited resources and by restrictions on where management is directed. Ignored, these factors can have manifold impacts on expected outcomes from restoration, contributing to failed objectives and wasted financial resources (Brudvig 2017; Iftexhar et al. 2016). Successful prioritization plans help allocate limited resources, often at multiple scales, and communicate restoration plans and estimated outcomes to key stakeholders (Eaton et al. 2019; Riddell et al. 2019).

Data for prioritization are widely available in the numerous Federal, State, and local assessments that describe land conditions for a wide array of natural resource values including fire risk, watershed health, wildlife habitat, and terrestrial conditions (Cleland et al. 2017; Dillon and Gilbertson-Day 2020; USDA FS 2011, 2019). Yet the most commonly used approach for prioritizing programs of work typically involves overlaying maps of assessment layers and determining areas of overlap; this does not provide information on tradeoffs or predict outcomes at the multiple scales at which land management agencies allocate investments. Decision support tools are needed to transform assessments into projects on the ground based on priorities, budgets or workforce capacity, and constraints on where treatments are permitted.

There are two particular approaches in the operations research field that are widely used for experimenting with prioritization and have

contributed to more efficient and effective restoration planning: (1) spatial optimization and (2) scenario planning. Spatial optimization aggregates or arranges treatments on landscapes to optimize one or more objectives, and it can identify optimal project designs and explore tradeoffs while incorporating constraints (Adams et al. 2016; Mazziotta et al. 2017; Pohjanmies et al. 2019; Schroder et al. 2016; Triviño et al. 2017). Likewise, the science and literature on scenario planning emphasizes the importance of examining large arrays of management scenarios to reveal tradeoffs between different prioritization strategies and explore compromise solutions (Biggs et al. 2007; Star et al. 2016; Trammell et al. 2018) (fig. 1).

We developed the ForSys spatial planning system (ForSys Research Consortium 2024) in an effort to advance and combine the application of spatial optimization and scenario planning for prioritizing risk reduction and restoration investments. ForSys was designed as a tool to integrate assessments into prioritization strategies and predict outcomes. Many of the features in ForSys were designed to enhance the U.S. Department of Agriculture, Forest Service's ability to build optimized treatment plans and estimate outcomes. In this paper, we describe more than 10 years of research using ForSys across 27 published case studies. We first describe the ForSys model and then review selected case studies, highlighting forest and fuel management work in the western United States that supported state forest action plans and Forest Service national fuels reduction investment allocations. We then discuss overall science findings, management implications, and future development with external technology partners as part of broader application of the model to modernize current prioritization methods and technology.

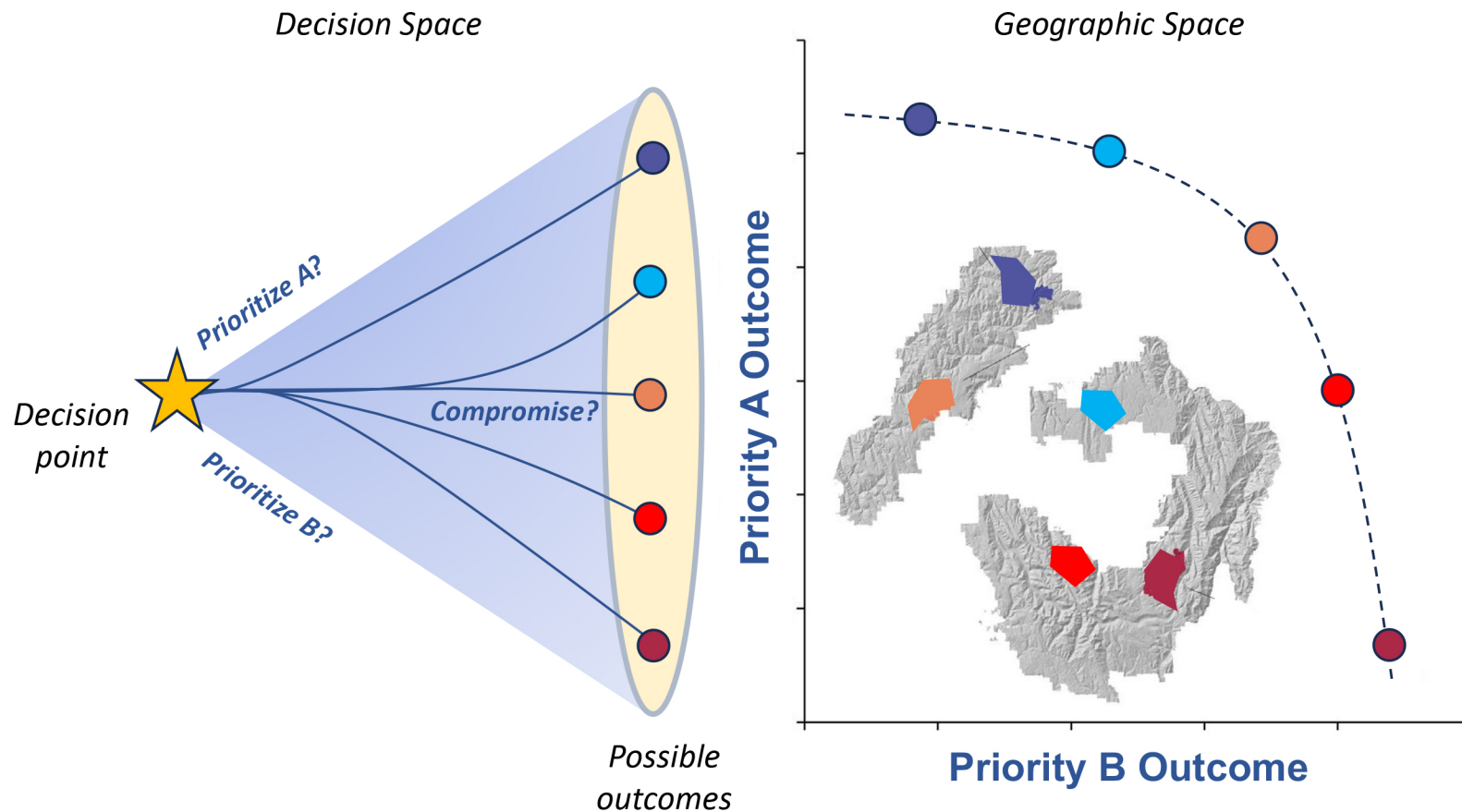


Figure 1—Scenario planning is a systemic method for thinking creatively about possible complex and uncertain futures. The central idea is to consider a variety of possible futures rather than to focus on the accurate prediction of a single outcome. Here multiple outcomes are modeled in ForSys based on two priorities, increasing the decision space and influencing where on the landscape treatments are targeted.

ForSys

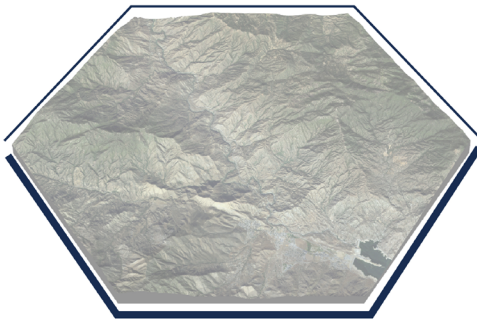
Model Overview

ForSys was designed to help managers create spatial prioritization plans that meet predefined goals and targets while accounting for constraints (fig. 2). The model was originally named the Landscape Treatment Designer (Ager et al. 2012) and in this paper we use ForSys as the naming convention for the earlier model version since it is

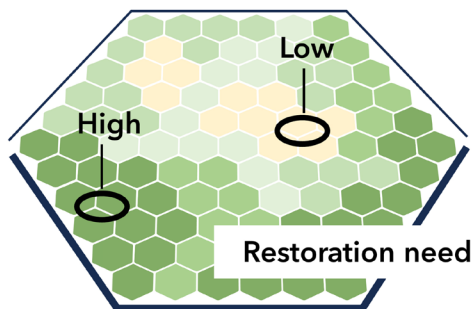
fundamentally the same model but with many enhancements. ForSys solves typical spatial planning problems where treatments are allocated to optimize one or more restoration objectives while accounting for multiple hierarchical spatial constraints and treatment thresholds. The model was developed with an emphasis on application by nontechnical users, and thus optimization is accomplished with a relatively simple greedy spatial heuristic instead of more complicated mathematical programming approaches (Beyer et al. 2016; Hof and Bevers 2002; Tóth 2020)

Opportunities

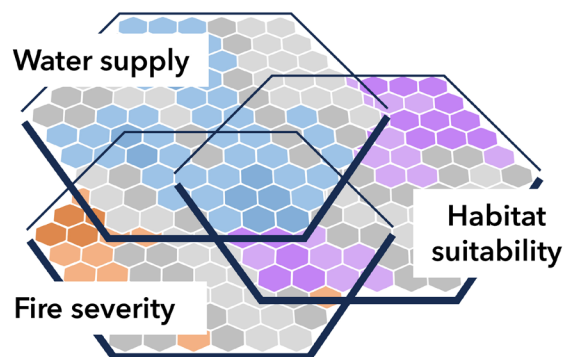
Study area?



Priorities?

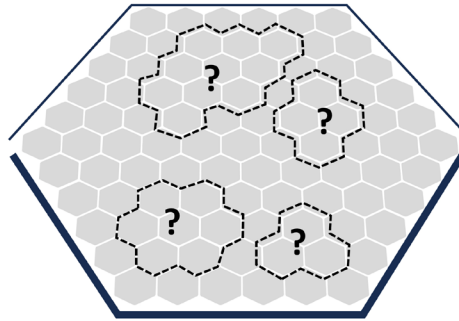


Outcomes?

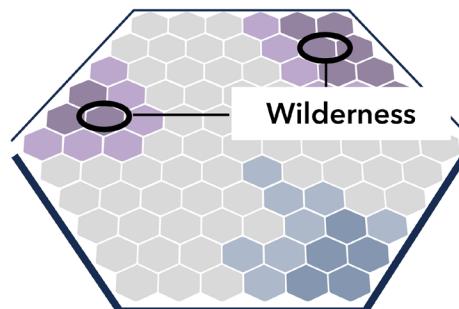


Constraints

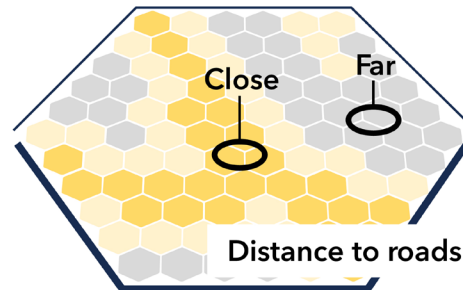
Project size?



Restrictions?



Treatment criteria?



Outputs

Project outcome/tradeoffs

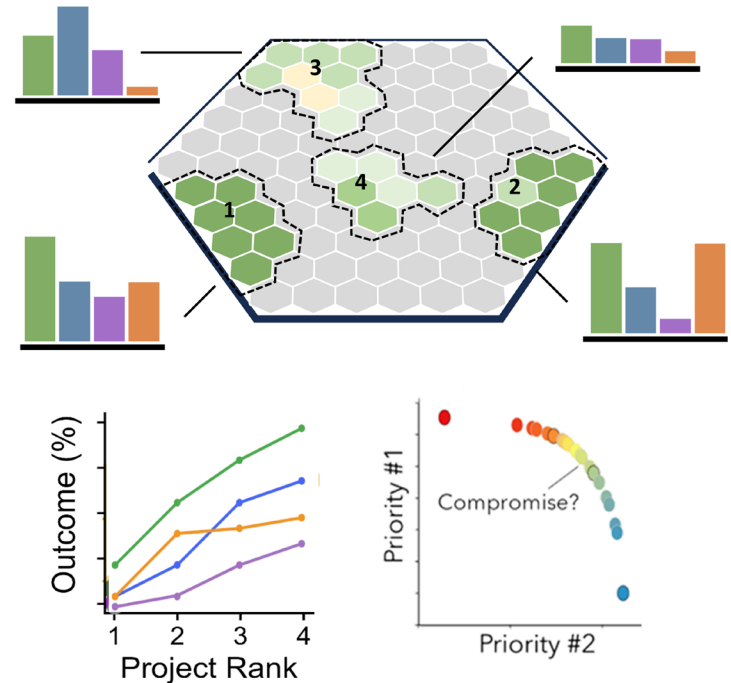


Figure 2—ForSys example workflow. Scenarios are designed by understanding spatially-explicit values and constraints on landscape management. It is not simply a matter of where priorities overlap but how treatment is limited to particular locations or conditions. In this example, a single objective is prioritized for treatment to treat 30% of the landscape in 500-acre projects. Treatments are prohibited from wilderness areas and “stands,” or treatment decision units, must be close to roads to be selected for treatment. Other values are of interest as treatment outcomes even though they were not priorities in the scenario. ForSys will determine where to locate projects and in what priority order, then assess outcomes. For multiple priorities, ForSys will also explore if there are opportunities for compromise solutions where projects can be located to target both objectives efficiently.

that are not feasible to implement in the field in large land management agencies. While mathematical programming methods are scientifically more elegant and achieve exact optimal solutions (Beyer et al. 2016), to our knowledge their application to the problem of prioritization on U.S. public lands has largely been in the research domain and they have failed to yield land management decisions based on their output (Colavito 2021). Moreover, the internal mechanics of these models are difficult to communicate to stakeholders. Additionally, the speed and simplicity of greedy heuristics allows for the exploration of hundreds of scenarios to fully explore the tradeoffs inherent in land management decisions, rather than finding an optimal solution.

ForSys is used for short-range tactical planning problems where invariant landscape conditions can be assumed, i.e., fire and forest succession are not going to significantly affect the outcome of the model run compared to prescribed management, although the potential impacts of treatment on the predicted outcomes are considered. Long-term planning problems are addressed with landscape disturbance and succession models (Scheller et al. 2007; Spies et al. 2017). ForSys was developed for multiple platforms including Windows desktop (ForSysX), R (ForSysR) (Evers et al. 2023), and R-Studio hosted on an Amazon cloud instance. Although most of the case studies have focused on forest and wildfire issues (table 1), the modeling framework can be applied to a wide range of restoration, rehabilitation, and risk reduction problems. Core model parameters and options are listed in tables 2 and 3 and include the commonly used inputs for many other landscape planning models including objectives, constraints, treatment thresholds, and spatial data on landscape attributes.

ForSys is designed around the concept that restoration and risk reduction activities occur at the stand polygon scale (1–20 ha; 2.5–50 acres) and need to be organized into project areas (5,000–25,000 acres) to achieve landscape scale management goals and meet logistical and administrative constraints. Prioritization of stands for treatments and their organization into landscape-scale projects can be accomplished with four spatial strategies: (1) stands are selected to optimize one or more

objectives within a predefined planning area; (2) stands are aggregated to create planning areas that optimize one or more objectives; (3) stands are maximally dispersed from a project centroid considering one or more objectives and distance from the centroid; and (4) project areas are maximally dispersed within a larger landscape considering both distance from other projects and one or more objectives (fig. 3). With these options the program can be used to create a wide range of spatially organized treatment patches within planning areas, and planning area distributions within larger spatial domains. The program was designed to replicate a wide range of optimal spatial treatment patterns, including treatments to optimize prescribed fire containers (Ager et al. 2013), build fuel break networks (Ager et al. 2023; Belavenutti et al. 2022b), or create various mixtures and variants thereof (fig. 4).

ForSys does not have embedded management response functions, thus it can incorporate any type of management prioritization problem from prescribed fire to culvert replacement. This, however, requires that outputs from management actions be modeled in advance and quantified in the input database. For instance, in an economic application, the predicted net revenue is calculated outside of ForSys and presented as choices to the model as part of a scenario that includes objectives, constraints, and treatment thresholds.

Spatial Optimization Heuristics

There are several alternative spatial optimization procedures available in ForSys and the optimization and options differ between the R (ForSysR) and desktop (ForSysX) versions in terms of the various algorithms. The primary optimization functionality used in ForSys is the aggregation of potential treatment pixels or stands (the treatment decision unit) into a landscape project. Note that in several case studies, the spatial optimization was not invoked since planning areas were predefined (e.g., Ager et al. 2017; Ager et al. 2019). In these cases, ForSys simply sorts the available stands and selects those that maximize the objective and meets constraints and treatment thresholds. Priority projects are based on those planning areas with the highest objective score

Table 1—List of published spatial planning case studies using ForSys.

No.	Published case study	Scale	Location	Citation
1	Optimizing the implementation of a forest fuel break network	National Forest (520,000 ha)	Oregon	Ager et al. (2023)
2	Development and application of the Fireshed Registry	National	Western U.S.	Ager et al. (2021a)
3	Production possibility frontiers and socioecological tradeoffs for restoration of fire adapted forests	Regional (four National Forests; 2.5 million ha)	Oregon	Ager et al. (2016)
4	Balancing ecological and economic objectives in restoration of fire frequent forests—Case study from the Four Forest Restoration Initiative	National Forest (970,000 ha)	Arizona	Ager et al. (2021b)
5	Planning for future fire: Scenario analysis of an accelerated fuel reduction plan for the western United States	Sub-national (59 million ha)	Western U.S.	Ager et al. (2021c)
6	Tradeoffs between U.S. National Forest harvest targets and fuel management to reduce wildfire transmission to the wildland urban interface	Sub-national (59 million ha)	Western U.S.	Ager et al. (2019)
7	Overview and example application of the Landscape Treatment Designer	National Forest (350,000 ha)	Oregon	Ager et al. (2012)
8	Restoration of fire in managed forests: A model to prioritize landscapes and analyze tradeoffs	Ranger district (14,000 ha)	Oregon	Ager et al. (2013)
9	Economic opportunities and trade-offs in collaborative forest landscape restoration	Regional (four National Forests; 2.5 million ha)	Oregon	Ager et al. (2017)
10	Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk	Regional (1.3 million ha)	Idaho	Alcasena et al. (2022)
11	Optimizing prescribed fire allocation for managing fire risk in central Catalonia	County (130,000 ha)	Spain	Alcasena et al. (2018)
12	Trends in wildfire risk at time-scale: Optimizing fuel treatments configurations in eucalyptus plantations in Portugal	Regional (150,000 ha)	Portugal	Ariza et al. (2015)
13	Designing forest restoration projects to optimize the application of broadcast burning	National Forest (520,000 ha)	Oregon	Belavenutti et al. (2022a)
14	Multi-objective scheduling of fuel treatments to implement a linear fuel break network	National Forest (520,000 ha)	Oregon	Belavenutti et al. (2022b)
15	The economic reality of the forest and fuel management deficit on a fire prone western U.S. National Forest	National Forest (520,000 ha)	Oregon	Belavenutti et al. (2021)
16	Addressing trade-offs among fuel management scenarios through a dynamic and spatial integrated approach for enhanced decision-making in eucalyptus forest	Local (3600 ha)	Portugal	Botequim et al. (2014)
17	Landscape-scale fuel treatment and wildfire impacts on carbon stocks and fire hazard in California spotted owl habitat	Landscape (55,398 ha)	California	Chiono et al. (2017)
18	An assessment of forest and woodland restoration priorities to address wildfire risk in New Mexico	State (24 million ha)	New Mexico	Day et al. (2021)
19	Cost-effective fuel treatment planning: A theoretical justification and case study	Ranger district (160,930 ha)	Oregon	Kreitler et al. (2019)

(Continued ...)

Table 1—(continued)

20	Temporal optimization of fuel treatment design in blue gum (<i>Eucalyptus globulus</i>) plantations	Local (1,449 ha)	Portugal	Martín et al. (2016)
21	Spatial optimization and tradeoffs of alternative forest management scenarios in Macedonia, Greece	National (3.4 million ha)	Greece	Palaiologou et al. (2021)
22	Coupling wildfire spread and erosion models to quantify post-fire erosion before and after fuel treatments	Landscape (68,000 ha)	Italy	Salis et al. (2019)
23	Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area	Landscape (68,000 ha)	Italy	Salis et al. (2016)
24	Comparing risk-based fuel treatment prioritization with alternative strategies for enhancing protection and resource management objectives	Regional (8.5 million ha)	New Mexico	Thompson et al. (2022)
25	Appendix E. Using landscape condition metrics and ForSys for the Social and Ecological Resilience Across the Landscape Project. Social and Ecological Resilience Across the Landscape (56500) Draft Environmental Impact Statement Stanislaus National Forest	Project (100,000 ha)	California	USDA FS (2021)
26	Prioritization of forest restoration projects: Tradeoffs between wildfire protection, ecological restoration and economic objectives	National Forest (915,000 ha)	Oregon	Vogler et al. (2015)
27	Forest Health Assessment and Treatment Framework 2020	Landscape	Washington	Washington State DNR (2020)

Table 2—Summary of features and capabilities of the ForSys model.

Feature	Explanation	ForSysX	ForSysR
Weighted objective function	Objectives and weights can be used for multi objective optimization	Yes	Yes
Objective iteration	Automates iterating through different weight combinations to analyze trade-offs among objectives	Yes	Yes
Hierarchical constraints	Constraints can be modeled at multiple hierarchical spatial units	Yes	--
Constraint iteration	Automates iterating through different constraint ceilings to analyze the effect of constraints on objectives	Yes	Yes *
Availability	Stand is available for treatment according to administrative restrictions on Land Management activities; non-available stands can be included in projects	Yes	Yes
Exclusion	Stand is within the study area but excluded from projects and treatments	Yes	Yes **
Treatment threshold	Specifies conditions under which an available stand can be treated	Yes	Yes
Treatment threshold iteration	Automates iterating through different treatment thresholds to analyze the effect of thresholds on objectives	Yes	Yes *
Zonation	Study areas can be partitioned to serially process subunits according to alternative scenarios and respective parameters	Yes	Yes
Seed stand percent	Controls how many of the stands are used as seeds to build optimized projects; a lower number can result in lower objective values but faster processing time	Yes	Yes
Distance weighting	Used in the optimization algorithm to adjust the relative value of distance versus objective when adding patches to a project	Yes	Yes
Maximize distance	Chooses patches that maximize distance from the project centroid	Yes	--
Project level tabular outputs	CSV output file that echoes input parameters and summarizes objective values	Yes	Yes
Project by group level tabular outputs	CSV output file that echoes input parameters and summarizes by both project and specified grouping levels (e.g., forest type)	No	Yes
Graphical outputs	JPG files with solution images showing treated and non-treated stands	Yes	--
Save option	Writes scenario parameters and input/output files to an XML format; file pathways can be edited within a text editor when sharing setup files across users	Yes	Yes
Archiving option	Saves both input data and run parameters in a zip or RData file	Yes	Yes
Graphics post processor	Creates attainment graphs and production frontiers from CSV project outputs	Yes	Yes
ForSys with Fire	R extension analyzes planning risk under future fire scenarios by overlaying future fire perimeters derived from simulation outputs	No	Yes
Annual targets	Sets the number of planning years and annual treatment target to simulate annual treatment goals	Yes	Yes
Spatial optimization	Optimizes stand aggregation based on spatial location, objective weight and distance	Yes	Yes
Spatial dispersion	Disperses project locations across the study area	Yes	--
Patchbuster	Recursive optimization to disperse treatments or projects in a planning area	Yes	--

* Easily applied as loop in ForSysR

** ForSysR excludes stands that do not meet the `global_threshold`

** Can be achieved with nested constraints

-- Indicates not currently available in published code

Table 3—Key inputs to formulate a scenario in ForSys.

Input variable	Explanation	Examples	ForSysR	ForSysX
Stand	Spatial treatment decision unit	Hexagons, raster cells, delineated stands	stand_id_field	Stand ID
Predefined planning areas	Subunit used to define treatment selection	Subwatershed, PODs*, firesheds	proj_id_field	Subunit
Treatment threshold	Metric to trigger treatment	Slope < 35%; board feet per acre	stand_threshold	Treatment threshold
Effects of treatments	Metrics to summarize treatment outcome	Volume, acres of risk treated	scenario_output_fields	Effects
Management objectives	Priorities for selecting stands for treatment	Wildfire risk reduction, forest health, resiliency	scenario_priorities	Priorities
Targets or constraints	Maximum level of activity	Treat 40% of the area; treat 5,000 acres within each POD	proj_target_field; patchmax_proj_size	Constraints
Availability	Variable to define if stand can be treated	All non-wilderness	global_threshold	Available for management

* POD = potential operational delineation

ForSys Spatial Algorithms



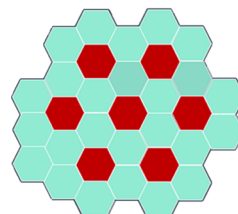
Predefined planning areas



Adjacency : Find veins of high objective



Adjacency with inverse distance weighting: create more compact projects



Patchbuster: treatments are dispersed from patch edge



Disperse projects: Maximize distance between projects

High Low

Figure 3—ForSys spatial algorithms to identify stands for treatment based on objective value scaled from high to low.

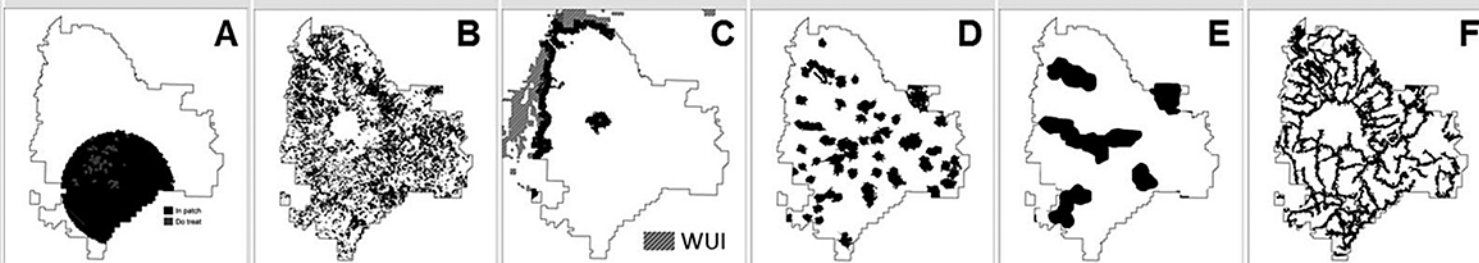
	Spatial Strategies for Fuel Management					
	Restoration of low severity fire regime	Broad landscape protection	Localized protection	Protection of dispersed values	Restoration of mixed severity fire regime	Strategic containment
Spatial pattern of values	High density, dispersed	Low density, dispersed	Variable density, clumpy	Clumpy	Any	Low or none
Landscape goal	Low hazard fire containers	Disrupt spread, facilitate containment	Localized defensible fuel breaks	Dispersed defensible fuel breaks	Restoration of dispersed natural fire barriers	Contain large fires at defensible locations
Performance measure	Area burned by prescribed and natural fire	Reduction in landscape burn probability	Local reduction in exposure near values at risk	Reduced exposure to fire	Landscape reduction in hazard and burn probability	Area burned by natural fire
Treatment goal	Reduce fire severity	Reduce fire spread rate	Facilitate suppression	Facilitate suppression	Reduce fire spread rate	Facilitate suppression
Example map						

Figure 4—ForSys was developed to model different types of spatial fuel management strategies. Figure from Ager et al. (2013).

and sequenced from highest to lowest. In many applications of ForSys, however, project boundaries do not exist. Here, the analyst looks to bundle together treated stands into organically assembled patches. To do so, ForSys uses a “greedy heuristic” to aggregate stands into projects to maximize a single or weighted objective function (Ager et al. 2016). The term “greedy” describes the process by which projects are assembled while the term “heuristic” is used to distinguish this from modeling approaches that seek true optima. We have developed several heuristics. Three are described in more detail below.

Project building mechanism in ForSysX

The algorithm starts with a random stand in the input spatial dataset, and a list of adjacent candidate stands are identified using an adjacency matrix that is computed prior to the optimization process. The candidate stand with the highest objective value is added to the project. A new list of candidates is identified that now contains stands that are adjacent to the seed stand as well as stands that are adjacent to a prior selected candidate. Again, the patch with the highest objective is added to the project. Each time a candidate stand is selected, it is removed from the candidate list. This iteration continues, adding stands to the project, until either the specified project diameter or one of the constraints is exceeded. When all stands (or all available stands) have been tested as a seed for a project, the project with the highest objective is identified and stands included are removed from consideration in subsequent projects. The project building process repeats until the number of projects specified by the user has been created.

Note that the process of identifying the optimal adjacent candidate stand can either be based solely on the objective value, or the objective values can be adjusted based on their distance to the seed stand using a user-defined inverse distance power weighting value. The inverse distance power setting controls the relative importance of distance vs. objective value. When this is greater than zero, inverse distance weighting of the objective value is used in the stand selection process. A higher value will produce more tightly clumped stands in a project area but can potentially result in a lower total project objective value (fig. 3).

The spatial optimization section of ForSysX allows the user to enter the maximum project diameter, which controls the potential size of the project. The default value of -1 specifies an unlimited project size, which allows ForSys to find veins of high objective (fig. 3). When the project size is unlimited, the constraint value (e.g., budget constraint) will terminate the project building process. Using the default project diameter of -1 often results in much longer processing time depending on landscape size. The Max Number Projects setting controls how many projects will be created. Each successive project assumes previous projects have been identified and those stands are unavailable for treatment. The adjacency file stores adjacency relationships between stands and is generated with the Generate Adjacency option. Adjacency files are stored and can be loaded in subsequent program sessions.

Project building approach in ForSysR using Patchmax

In ForSysR, the project prioritization is accomplished using a patch-building algorithm called Patchmax (Belavenutti et al. 2022b). Patchmax works in similar fashion to the project building described directly above: every stand is evaluated as a potential seed for a patch grown to a specific size given specific constraints; the patch with the highest objective score is selected; and subsequent patches are built from the remaining stands. Projects are built similar to ForSysX by searching through a stand adjacency matrix to ensure contiguity. The specific algorithm applied by ForSysR, however, is based on the well-known Dijkstra’s algorithm (Dijkstra 1959) to identify the shortest travel distance between stands and all other stands in the study area. Distances between adjacent stands are shortened to favor higher quality stands or lengthened to avoid excluded stands based on a spatial priority weight (SPW) and an exclusion penalty weight (EPW). Both parameters control the search behavior much like the inverse distance power in ForSysX and allow balancing the relative importance of distance against objective value. The SPW parameter increases the distance between adjacent stands with poor objective quality, causing patches to grow towards areas where the objective values are higher. For example, a SPW setting of 1 penalizes the distance cost of

adding the stand with the lowest priority score by 10x, leading the algorithm to search elsewhere for stands to include within the project perimeter (fig. 5A–B). The EPW parameter, by contrast, applies a similar distance penalty if one or both adjacent stands have been excluded from treatment based on the treatment threshold. An EPW setting of 1 penalizes the distance cost by 10x, thus encouraging the algorithm to search for patches that minimize the number of excluded stands (fig. 5C–D). The final parameter, the exclusion limit (EL), invalidates patches where the total percent of excluded stands exceeds some value. The impact of SPW and EPW are illustrated in figure 5.

Patch busting with ForSysX

An alternative to aggregation is the dispersion algorithm in ForSysX, which can be used either to disperse treated stands within a project or projects within a study area. The process was originally designed for the latter, where projects are located to optimally fragment large (e.g., 10,000– 50,000 acres) areas that have predicted high severity fire behavior (fig. 6). The explanation of the algorithm uses this application context, although other uses are possible. Given a landscape that has contiguous areas of expected high severity fire, the patchbuster algorithm works recursively to locate treatments that maximum distance to the high-severity patch edge (or to non-high severity areas), which breaks or “busts” up these large, contiguous areas. The patch identifier field is used to designate if a stand is high severity or not (coded as one if true, zero if false). Distance to the nearest non-high severity fire area is averaged for all stands and used to calculate the total project objective. All stands are used as a seed for this process, as in the aggregation process described above. Note that this algorithm executes recursively as each project is identified to recalculate the distance between each remaining patch of high severity and non-high severity fire. The result is a distribution of projects that fragment the contiguous portions of the landscape with high severity fire behavior. The patchbuster weight setting specifies the relative importance of distance versus other objectives. The average distance (kilometers) is multiplied by this weight before being

added to the calculated total patch objective. Projects will be selected to maximize the distance between these stands and stands that are treated in previous projects. Note that successive program sessions can be used to aggregate and disperse treatments at different scales, although case studies demonstrating this functionality have not been completed.

Review of Science and Management Applications

Designing Efficient Dry Forest Treatment Strategies

One of the early applications of the ForSys system focused on optimizing treatment locations to restore fire resiliency in the dry pine forests in central Oregon. The study was conducted on the 245,000 ha Bend-Fort Rock District of the Deschutes National Forest (Ager et al. 2013). Forest composition was dominated by large areas of dry ponderosa pine (*Pinus ponderosa*) that over time had become overstocked and were in need of various restoration treatments to improve fire resiliency. The questions addressed in this study were where can fuel treatment projects be located to maximize the improvement in resiliency per area treated (meaning reduction in potential wildfire mortality of large ponderosa pine trees), and what is the tradeoff between treatment intensity (amount of fuel removed) and total project area on predicted total mortality. Expected mortality for the before and after treatment conditions was estimated by combining landscape and stand-level fire simulation outputs. Specifically, FlamMap (Brittain 2015) was used to estimate burn probability by flame length category, and the Forest Vegetation Simulator (FVS) was used to estimate tree mortality as a function of flame length. Expected mortality was then estimated as the cross product of burn probability for each flame length class and the predicted mortality at that flame length. The simulated treatment scenarios used the difference in expected mortality between the treated and non-treated stands as the objective, and project areas were created using the spatial optimization routine in ForSys. The scenarios identified optimal project areas where treatments could maximize the reduction in potential

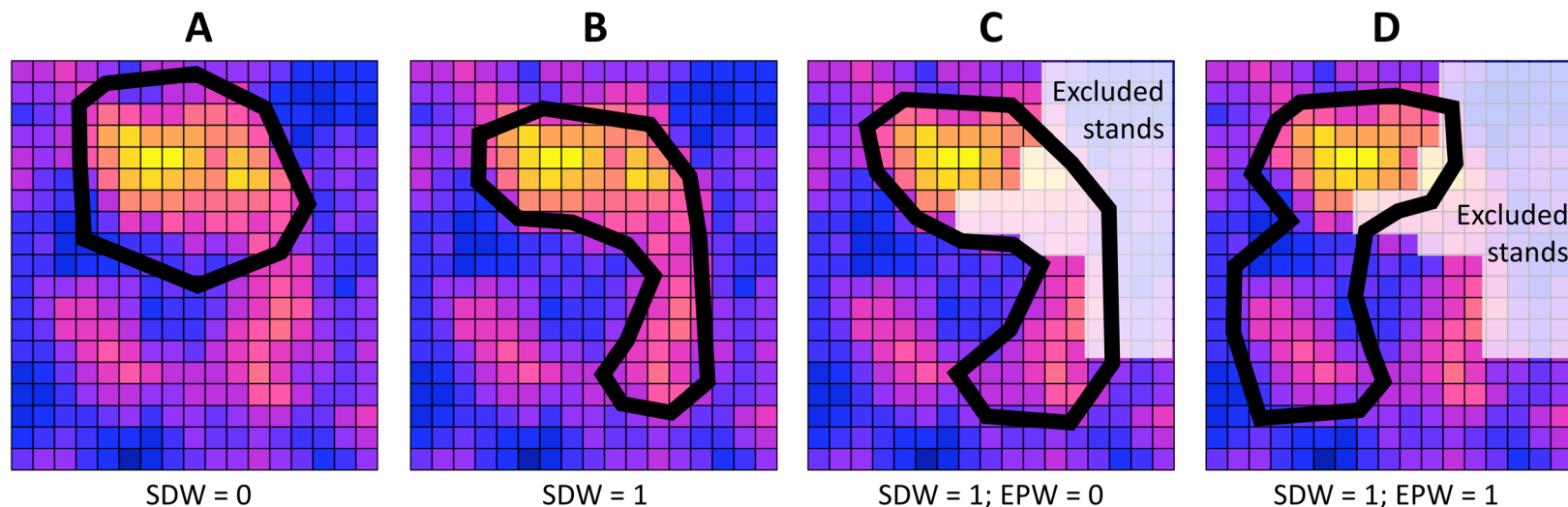


Figure 5—ForSysR patchmax algorithm. Projects are built as patches that maximize an objective score while minimizing the distance travelled. The distance cost used in the search process can be modified so that the patch follows ‘veins’ of high-quality stands throughout the landscape and/or avoids other areas where treatment is restricted. Lighter yellow colors are high objective value stands, and darker blue are low value. Figures A-D show alternative patch configurations using the same seed stand after altering spatial distance weight (SDW) and exclusion penalty weight (EPW) parameters. Figure A shows a project with a low SDW that results in a compact shape. Figure B shows the effect of a SDW of 1, causing a more sinuous final project shape. Figures C-D hold SDW constant but Figure C excludes some stands for treatment that fall below a specified treatment threshold (shown in white). The proposed projects expand relative to the previous panel to reach the targeted constraint while the overall project shape remains the same. Setting the EPW to 1 in Figure D causes the lower right lobe of the project to shift left to avoid excluded stands.

Patchbuster Recursive Algorithm

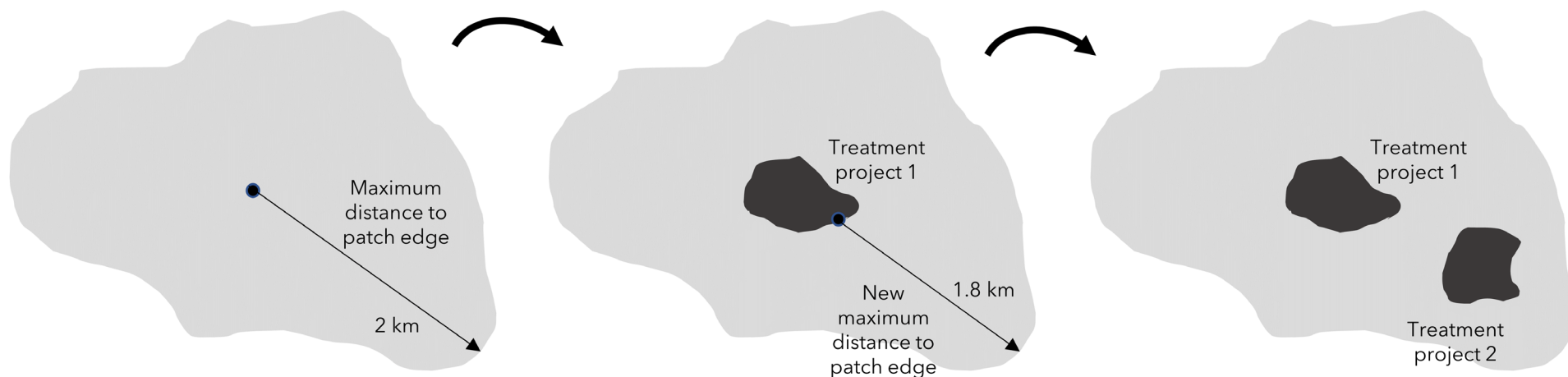


Figure 6—ForSys patchbuster algorithm. The light gray “patch” in the figure is an area predicted to be at risk for high severity fire. The patchbuster algorithm calculates the maximum distance to the patch edge to create its highest priority treatment project. It records this project then iteratively recalculates the new maximum distance to patch edge to place additional projects, “busting” up the landscape to break up large areas of expected high severity fire.

wildfire mortality of large ponderosa pine, resulting in large contiguous restored landscapes that could then be maintained with broadcast burning or using lightning fires and other “unplanned ignitions” to return fire to the landscape. However, by simulating many scenarios and adjusting fire behavior thresholds for treatment, the total treated area per project revealed significant project design tradeoffs. For instance, under strict treatment thresholds for low flame length (< 4 feet or 1.2 m), a high percentage of stands required treatment in each project (e.g., 80 percent), and the resulting project area was relatively small compared to scenarios where treatment thresholds were less stringent, leaving the surrounding landscape at risk for high severity fire. Conversely, a threshold of > 8 feet (or 2.4 m) flame length resulted in treating fewer stands (20 percent) and larger projects with reduced resiliency (fig. 7). From the simulations it was possible to identify the optimal treatment density that maximized the reduction in potential mortality to old growth ponderosa pine. The study demonstrated new methods to explore different landscape treatment configurations and identify optimal project parameters that maximize restoration goals, including the reintroduction of prescribed and natural fire. To our knowledge, this study was the first of its kind that applied spatial optimization to the problem of dry forest restoration to improve fire resiliency at landscape scales.

Incorporating Multiple Objectives in Scenario Planning

We expanded the scale and scope of the modeling described above in a series of studies, where ForSys was used to examine alternative prioritization strategies and analyze tradeoffs among land condition assessments commonly used in collaborative forest restoration and risk reduction programs (HFRA 2003; Schultz et al. 2012). This work was initially focused at the scale of an individual national forest (500,000 ha) and was in part motivated by the publication of many new and existing assessments of forest conditions (Haugo et al. 2015), as well as the emergence of forest collaboratives where the Forest Service had the opportunity to articulate restoration priorities to formally established stakeholders. For instance, where are the management priorities given

multiple objectives, and do the areas targeted for restoration change depending on the objective, or do all the assessments point to the same location? In this management system, restoration and resiliency objectives are achieved with investments in forest and fuel treatments that include thinning, broadcast burning, mastication and pile burning.

The first case study was built off a request from the Wallowa-Whitman National Forest (WAW) in eastern Oregon to create a 10-year action plan that identified priority landscapes for restoration and risk reduction (Vogler et al. 2015). This project prioritized five different land condition assessments selected by managers including vegetation departure, insect risk, timber volume, wildfire hazard, and wildfire exposure to the wildland urban interface (WUI) (Vogler et al. 2015). Stand polygons based on aerial photo interpretation were obtained from the WAW and used as the treatment decision units. We leveraged this work to examine how prioritization methods used in Vogler et al. (2015) could be improved by spatially optimizing project boundaries rather than using predefined planning areas. Ager et al. (2016) used ForSys to build 12,000-acre projects by aggregating adjacent stands with high objective scores rather than using predefined planning areas and applied it on 2.5 million ha encompassing the four Blue Mountain National Forests in eastern Oregon. ForSys was used to identify the top 20 projects on each national forest. The same five objectives were used: wildfire hazard, insect and disease risk, ecological departure, and potential harvest volume (Ager et al. 2016). The latter metrics were derived using the same methods as in Vogler et al. (2015) described above. The study also used a newer regional assessment by Haugo et al. (2015) that mapped forest departure from historical range of variability (HRV) in the Pacific Northwest as a way to estimate the backlog of areas needing restoration. Significant tradeoffs were observed among some of the prioritization variables studied, and optimizing one objective resulted in low attainment for the other objectives (10–30 percent reduction). For example, compromise solutions were found between prioritizing both harvest volume and forest departure, but harvest volume was still four times more responsive to treatments than forest departure (figs. 8–9), owing to the fact that forest

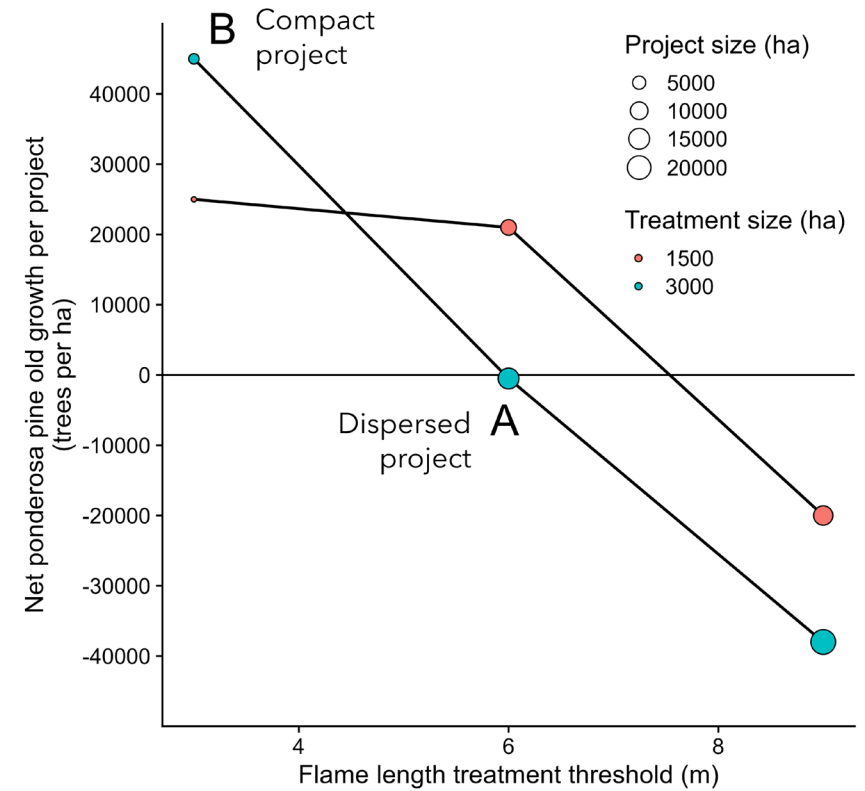
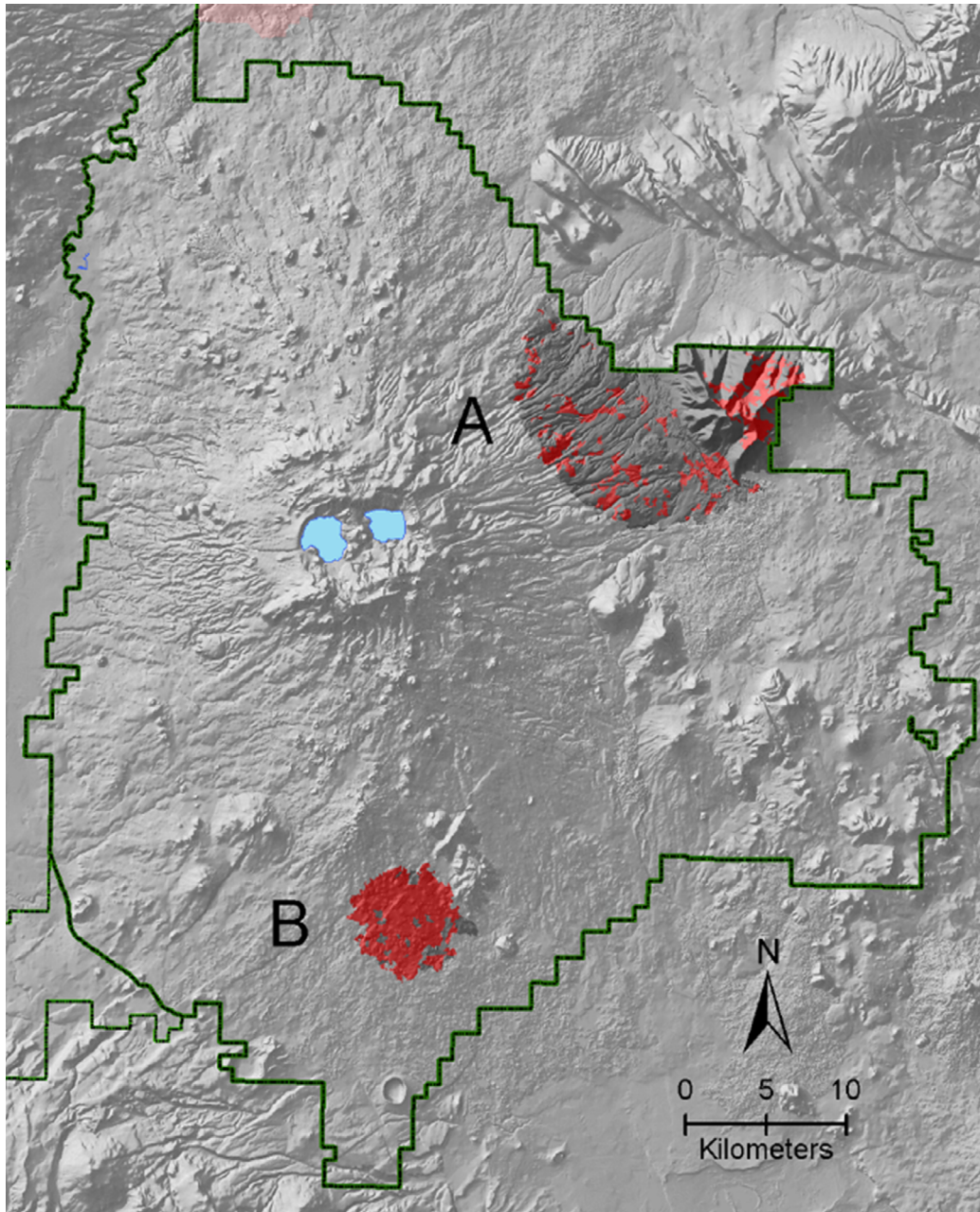


Figure 7—Scenario planning was used to explore how compact versus dispersed treatments would affect the efficiency of treating to restore old growth ponderosa pine to more resilient conditions on the Deschutes National Forest. Treatment size (total treated area within a project boundary) and treatment thresholds (flame length class that triggered treatment) were varied to explore the net effect on ponderosa pine survival. Compact projects at low flame length thresholds (A) were the most effective, but at higher flame lengths with smaller treatment area, opportunities existed to minimize ponderosa pine loss to wildfire. The map on the left shows the spatial arrangement of compact versus dispersed projects. Red areas indicate treated stands. Colors of points on the graph indicate treatment size, while the size of the points indicates total project size (including treated and untreated stands).

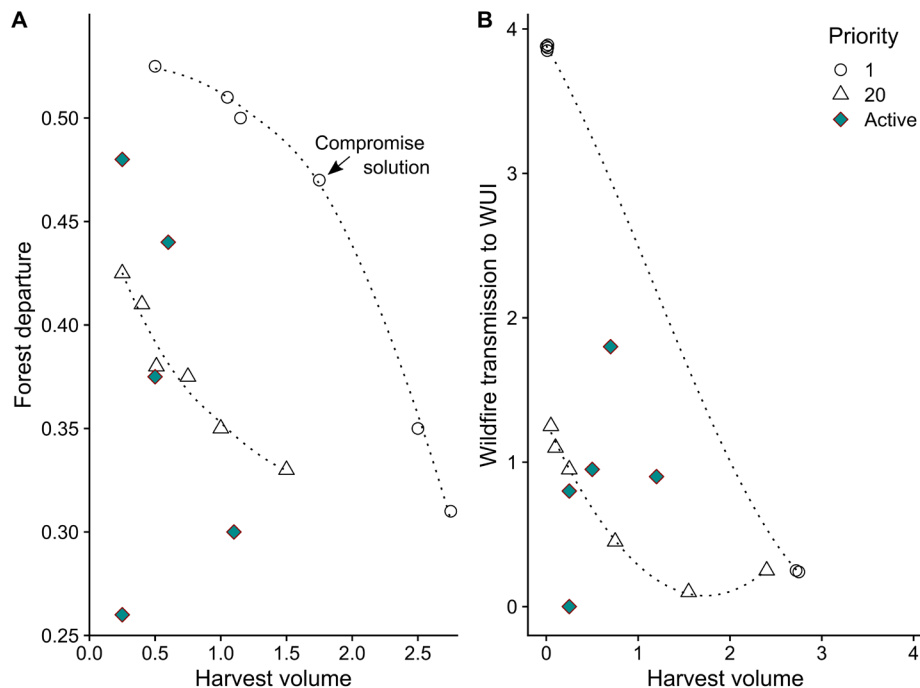


Figure 8—Ager et al. (2016) ran ForSys to prioritize multiple land management objectives by creating roughly 12,000-acre projects. Each unfilled point represents either the top- or the 20th-ranked project under different weightings of the two objectives. Each endpoint on the curves is the product of a single-objective scenario while the other points were produced by multi-priority scenarios. In this way, tradeoff curves created from prioritizing pairs of objectives allow for the exploration of compromise solutions as seen in panel A. But note the scale differences in the x- and y-axes. These values have been normalized to a percent of the total of each priority that exists on the manageable lands, so they are comparable. While a compromise solution exists, four times more harvest volume is produced compared with treated forest departure. The tradeoff between treating to reduce wildfire transmission to the wildland urban interface (WUI) and producing harvest volume shows no compromise solutions; these two objectives are not co-located on this study landscape (B). Active Forest Service projects (either implemented or near completion at the time of the study) of similar size are shown in comparison to those output from the model, revealing opportunities on the landscape to better maximize these particular objectives. Figure was derived from data outputs from Ager et al. (2016). Note that this figure was simplified for clarity; not all the multi-priority scenarios (unfilled points) were included.

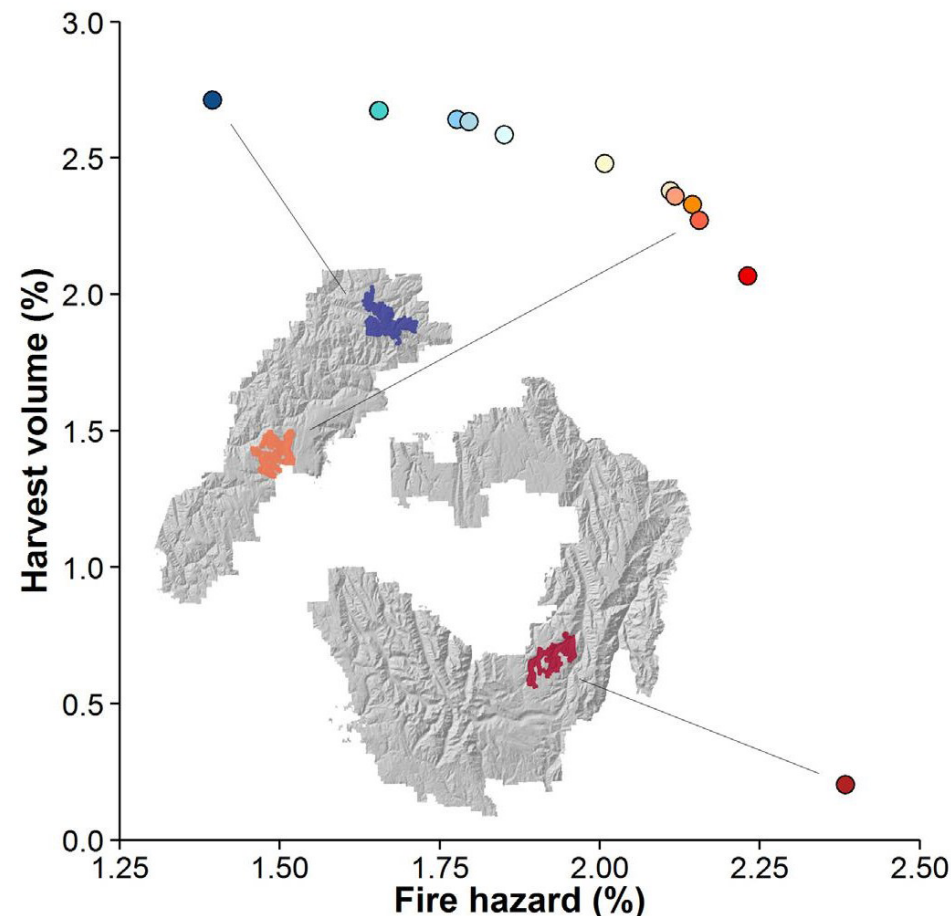


Figure 9—Tradeoffs at the national forest scale between treating fire hazard and harvest volume. Points show optimal project designs generated with ForSys when prioritizing two objectives. The blue dot represents a single scenario where only harvest volume is prioritized, while the red dot represents the scenario prioritizing only fire hazard. The orange dot and project represent the compromise solution in terms of attainment and spatial location, respectively. Changing the priority dramatically shifts the location on the forest targeted for treatment because the objectives are not co-located. Figure from Ager et al. (2016)

departure is a condition dispersed throughout the study area, making it easy to incorporate into optimized projects, although not at high levels. Other treatment targets such as wildfire transmission to the WUI showed high tradeoffs with harvest volume, meaning that the optimization was effective at designing highly efficient projects to treat either exposure or harvest volume, but not both. This study also compared optimal project areas derived from modeling with 14 restoration projects either implemented or near completion at the time of the study. These were plotted on the tradeoff curve to examine the optimality of actual restoration projects compared with model results (fig. 8). This showed that the bulk of the Forest Service projects examined were suboptimal compared to those generated by the ForSys optimization algorithm. This is the only known study where treatments from actual restoration projects were compared with a modeled optimal treatment design.

A followup study (Ager et al. 2017) used the same five management objectives but incorporated projected net revenue from density reduction thinning treatments to analyze the effect of social (WUI risk reduction) and ecological (departure from HRV) objectives on project scale economics within the same four national forests in eastern Oregon. Net revenue was calculated as the residual value of logs delivered to local mills after subtracting transportation and logging costs (Ager et al. 2017). The empirical data used by the model were derived from lengthy workshops with Forest contracting officers and planners that manage the financial accounting process for timber sales. We found that optimizing revenue, which makes large-scale restoration projects viable to contractors, resulted in a sharp reduction in treatments that address other priorities, and prioritizing three of the management objectives would require active investment (figs. 10–11). Only treating insect and disease risk generated enough revenue to be economically viable for the first 600,00 acres treated across all four national forests. The value of understanding these economic impacts was discussed in the paper, especially as it relates to collaborative planning, and underscores the reality of restoring many degraded systems, where the biggest challenge to restoration is paying for it. This work represented one of the first spatially explicit, economic

tradeoff analyses of national forest restoration programs, and reveals the relative cost of different restoration strategies, as well scale-related changes in tradeoffs (production frontiers) associated with restoration investments.

Prioritizing Prescribed Burning

Decision support tools to schedule and optimize the implementation of prescribed broadcast burning blocks have received relatively little attention despite the backlog that potentially exceeds several million acres on western U.S. national forests and in other fire-prone regions globally. Belavenutti et al. (2022a) expanded on the work of Alcasena et al. (2018) by optimizing project areas to maximize revenue while also including a minimum area of dry forests in need of broadcast burning, as opposed to the earlier approach which prioritized prescribed fire by differing fuel treatment objectives such as facilitating fire suppression. The problem is that most of the prescribed fire backlog exists in projects areas that have marginal commercial thinning opportunities, yet maintenance prescribed fire treatments are needed to reduce surface fuels. ForSys was used to create projects in and around areas in need of prescribed fire treatments, bending the project boundaries along the ecological gradients of dry and moist mixed conifer forest types where the latter provided commercial thinning opportunities that could create a financially viable project while including substantial area where broadcast burning could be applied in conjunction with other treatments (Belavenutti et al. 2022a). A detailed forest and fuel management decision tree was generated and applied to each stand in the modeling (fig. 12). Inclusion of costs and benefits yielded financial treatment profiles for each planning area (fig. 13). A new measure of resiliency was created that measured the excess stand density index as a proportion of the site potential as defined in Powell (2010), similar to that proposed in a later study by North et al. (2022). In general, we found that restoration treatments in dry forests that included density reduction thinning and broadcast burning resulted in a net projected cost that ranged from \$110 to \$8,000 per ha. By contrast, density reduction thinning in moist mixed

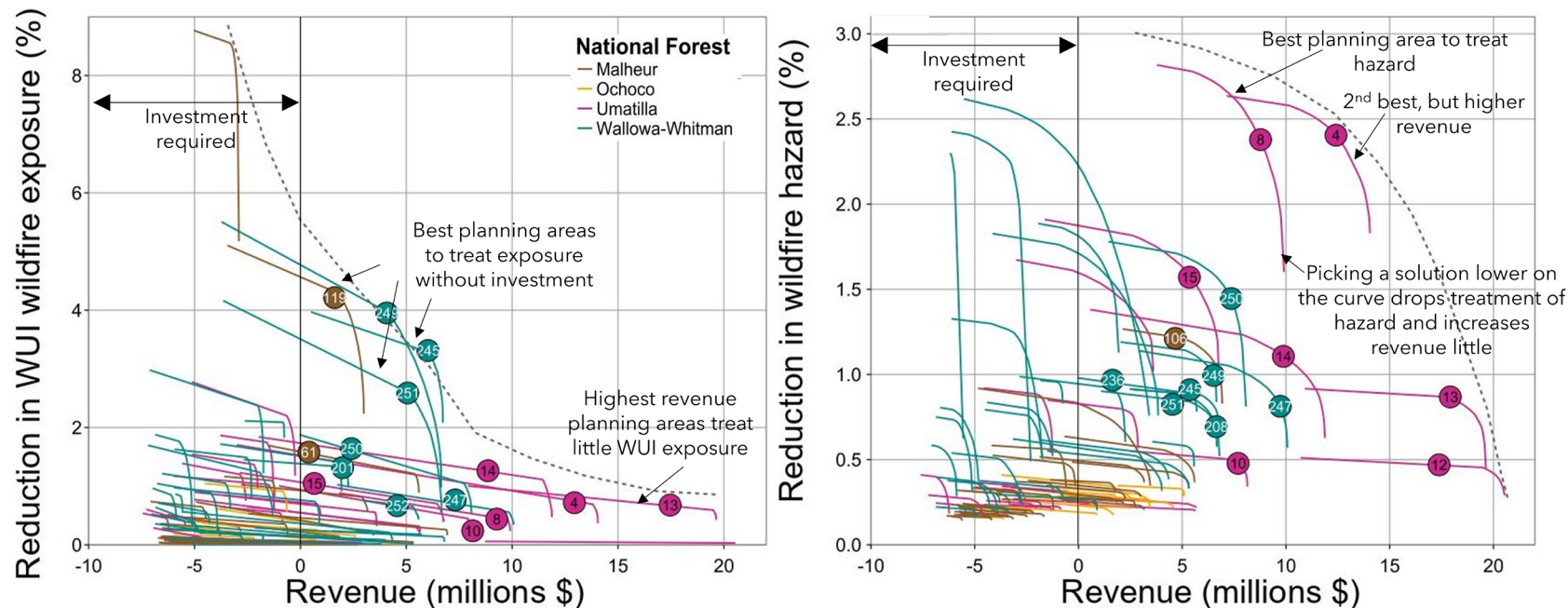


Figure 10—Tradeoffs between two restoration objectives and revenue on the four national forests in the Blue Mountains, Oregon. Each curved line represents an individual planning area, where points on the line represent different treatment solutions to prioritize one or the other objective, or a mix of both if possible. Curves in the upper right portion of the panels are the best planning areas to treat to achieve both objectives. Figure modified from Ager et al. (2017).

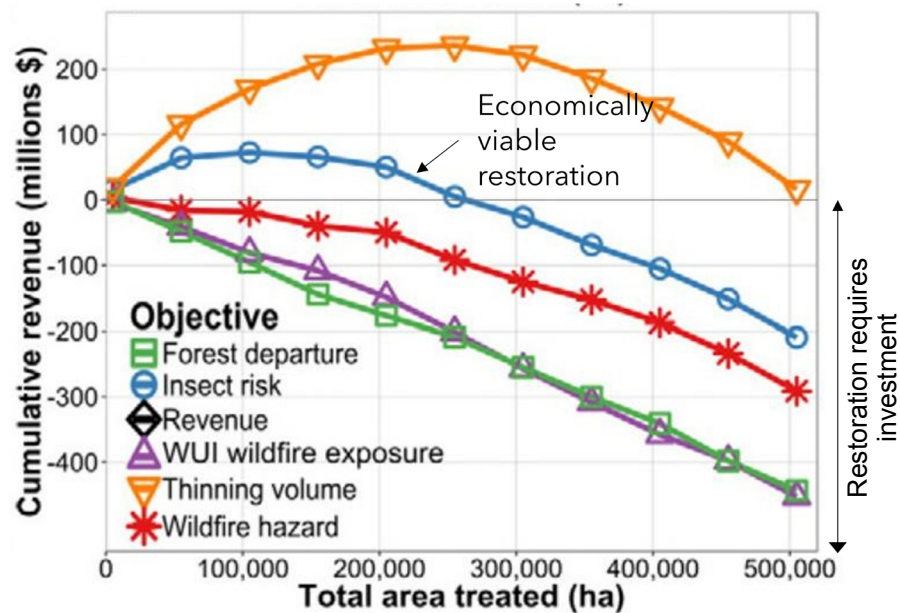


Figure 11—Impacts of alternative prioritization variables on net revenue. Three of the five restoration objectives would require investment when prioritized individually. Only insect risk generated revenue, breaking even at roughly 250,000 ha (600,000 acres) treated across all four national forests. Figure modified from Ager et al. (2017).

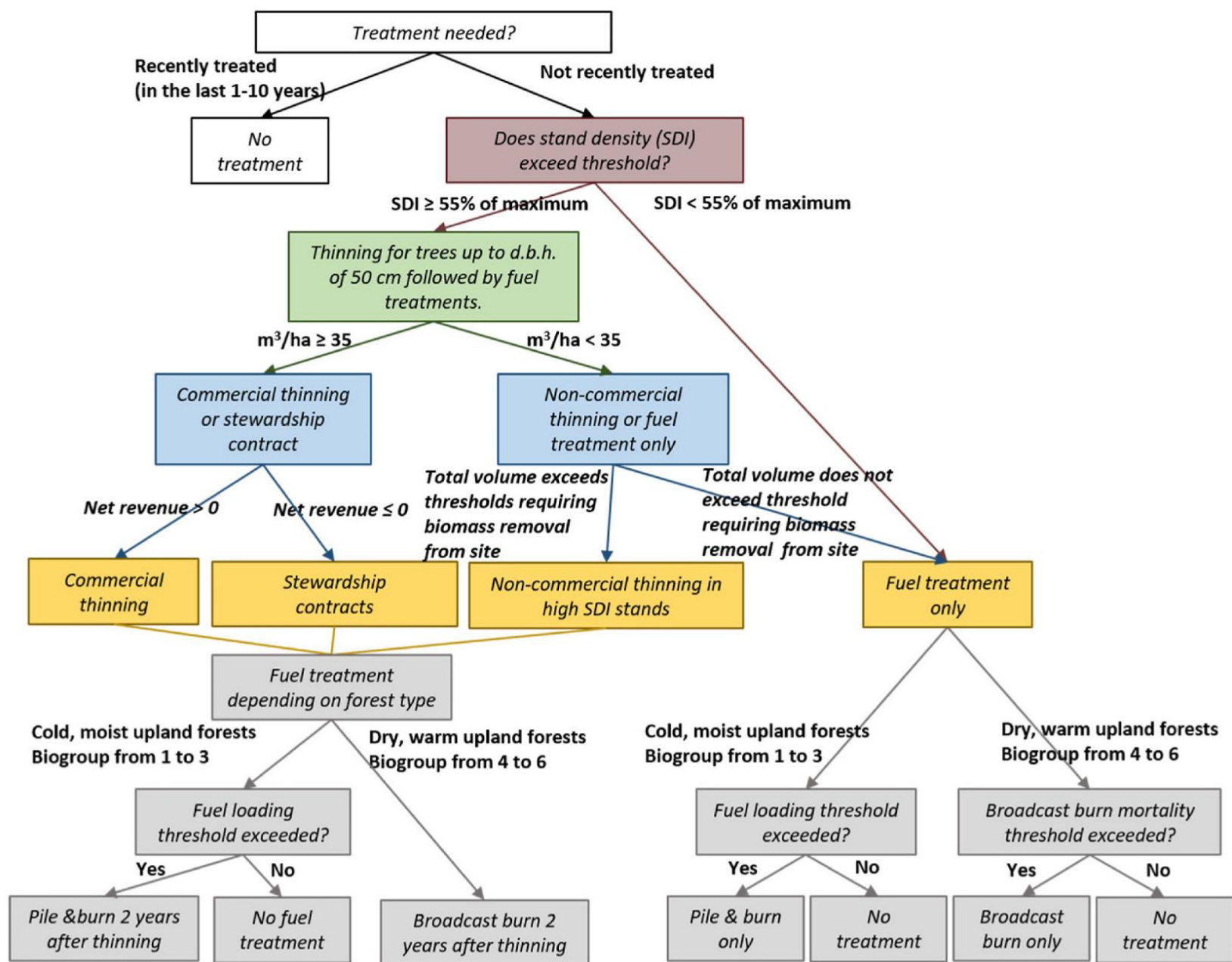


Figure 12—Example forest and fuel management decision tree for the Umatilla National Forest that determines treatment needs by treatment type based on potential natural vegetation, stand conditions, and potential thin volume. Figure from Belavenutti et al. (2021).

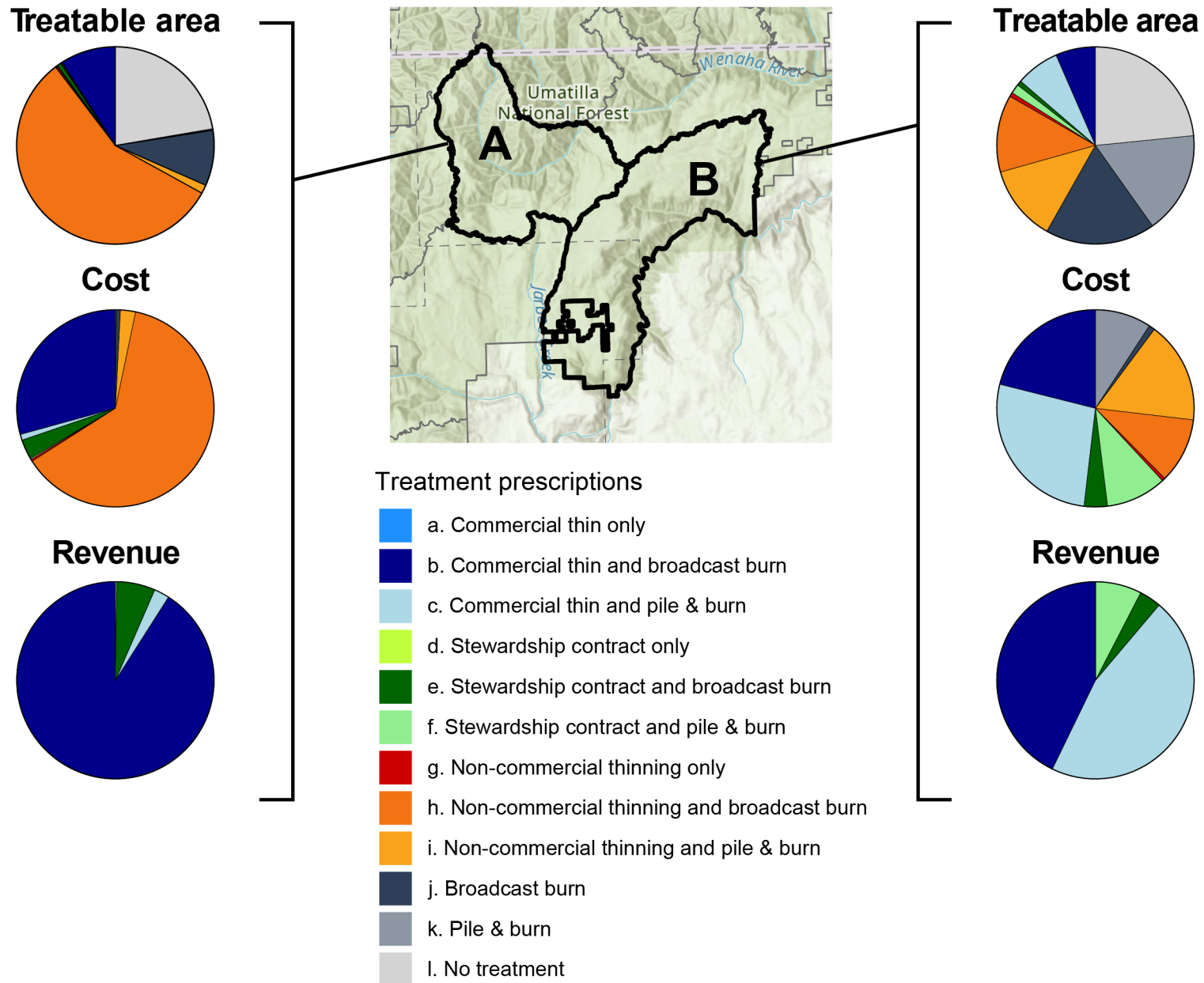


Figure 13—Decomposition of planning areas into treatment need, costs and revenues for the Umatilla National Forest for two example planning areas. Treatment prescriptions are derived from the decision tree shown in fig. 12. The northwest planning area (A) needed a majority non-commercial thinning and broadcast burn treatment, yet most revenue was generated from the small portion of commercial thin mixed with broadcast burn. The southeast planning area (B) had a much more diverse mix of treatment needs. The economic reality of treatment needs on the ground must be understood in order to increase the restoration footprint in western U.S. forests. Figure was generated from data outputs from Belavenutti et al. (2021). Data corresponding to pie charts can be found in appendix table A2.

conifer forests on more productive microsites generated significant commercial timber volume and projected revenue that ranged from \$4,000 to \$20,000 per ha. Multiple project area sizes were also explored to understand the effect of restoration scale on financial outcomes. We found that optimal projects in terms of generating revenue to subsidize density reduction and broadcast burning were 810 ha and contained > 50 percent of dry forest area. Larger projects and those with a higher percentage of dry forest area resulted in lower revenue, eliminating revenue when projects reached 2,700 ha. Forest restoration programs can use these methods to plan and design restoration projects that are financially viable while addressing the broadcast burn backlog in dry forests that require relatively expensive fuel reduction treatments prior to reintroducing fire.

Tradeoffs Between Wood Production and Risk Reduction

Fuel policy discussions between the National Fire Decision Support Center and Forest Service leadership over the period 2018–2021 led to an interest in understanding how agency timber targets conflicted with direction to allocate fuel treatment investments in and around the WUI. Although prior studies discussed above identified economic tradeoffs of this type on selected national forests, a larger systematic analysis for the western United States was needed to quantify tradeoffs at a scale meaningful in a policy context. Hence the sample size was increased to 79 western U.S. national forests and the methods used in the prior study were used to quantify timber harvest-WUI tradeoffs with the ForSys model (Ager et al. 2019). The study used SILVIS polygon-based spatial data (Radeloff et al. 2005) to create a WUI layer around national forests, and wildfire simulation outputs generated from the large fire simulator, FSim (Finney et al. 2011; Short et al. 2016), to quantify the area of WUI burned and structures affected by ignitions. Timber harvest estimates were derived from tree lists interpolated from forest inventory data (Riley et al. 2021) and FVS. Harvest prescriptions were generalized from operational practices by forest silviculturists and removed smaller, fire intolerant species to reduce ladder fuels and create fire resilient

conditions (Jain et al. 2012). The results showed strong tradeoffs and scale effects on tradeoffs, and more importantly substantial variation among planning areas and national forests (Ager et al. 2019). Prioritizing treatments to reduce fire transmission to the WUI resulted in an average harvest volume reduction of about 248 m³ per ha treated. The analysis also identified opportunities where both management objectives can be achieved. This work represents the first large-scale tradeoff analysis for key management goals in forest and fuel management programs on national forests and introduced Forest Service leadership to scenario planning applications to forest management policies.

A subsequent and more detailed study to examine the economics with alternative WUI treatment strategies was reported by Alcasena et al. (2022). Here, tradeoffs between treating in the WUI versus surrounding landscape in terms of financial efficiency were analyzed on a large fire-prone area of central Idaho (USA). The study area consisted of 20 rural communities and resorts for a 1.4 million ha landscape. Simulation modeling was used to estimate expected structure loss based on burn probability, intensity, and characteristics of the home ignition zone (HIZ). Three fuel treatment scenarios were explored that targeted treatments to: (1) the landscape surrounding communities predicted to be the source of exposure from large fires, (2) fuel treatments in the HIZ, and (3) a combination of landscape and HIZ. Each scenario was evaluated in terms of expected structure loss compared to a no-treatment scenario. The potential revenue from wood products was estimated to assess the cost-efficiency of each scenario. The results indicated that the combined landscape and HIZ treatment scenario, which treated 5.7 percent of the study area, resulted in the highest overall reduction in predicted exposure (47.5 percent, 100 structures yr⁻¹) and predicted loss (69.1 percent, 57 structures yr⁻¹). By doing both, the landscape treatments generated revenues that subsidized the HIZ treatment costs. However, HIZ treatments provided the best per area treated outcome (treatment efficiency) where exposure and loss were reduced by one structure by treating 89 and 111 ha per year, respectively, with an annual cost of \$33,645 and

\$73,672. Revenue from thinning was the highest for landscape fuel treatments and covered 16 percent of the required investment. This work highlighted economic and risk tradeoffs associated with alternative fuel treatment strategies to protect developed areas from large wildland fires.

Cross-boundary Scenario Planning for Shared Stewardship

States are required by the USDA Forest Service (as authorized by the Federal Farm Bill) to develop a Forest Action Plan on a recurring 10-year plan cycle. In 2020 when the state of New Mexico was required to revise their existing 2010 plan, the state forester made the decision to develop the revised plan collaboratively with the Forest Service to aid in the implementation of the Agreement for Shared Stewardship signed by New Mexico Governor Michelle Lujan Grisham and USDA Forest Service Chief Vicki Christiansen in 2019. The plan would contain a vision and next steps for collaboration between agencies and organizations, not just guide the actions of the Forestry Division alone. The Vision included a framework to coordinate forest and watershed management via a strategy that addresses key issues in forest and watershed management in a changing climate. Scenario planning was utilized as a framework to build consensus among the agencies involved in planning. The primary goal was to identify where activities could achieve multiple restoration objectives, including reducing risk from wildfire and postfire impacts to water supply and water quality, communities, infrastructure, and biodiversity, and assessing tradeoffs between these objectives. Details of the methods used to build these metrics can be found in Day et al. (2021). We then used ForSys to build optimal projects under the multiple objectives and examined the outputs to identify where forest management could achieve multiple shared restoration objectives to reduce wildfire risk to water supply and quality; communities and infrastructure; and biodiversity.

The results showed clusters of planning areas that were sources of substantial wildfire risk that span ownerships and forest types. Within a planning area there was a tradeoff between locating treatments to address wildfire risk to communities versus locating them in areas that will

best reduce wildfire risk to water quality and supply. However, among planning areas the potential to treat two restoration priorities was often correlated, meaning that an area of high risk for water quality and supply was also an area of high risk to communities (fig. 14A). The results also showed that risk was concentrated on particular ownerships within planning areas rather than spread out across multiple jurisdictions in terms of the areas identified for treatment in the modeling (fig. 14B). Thus, planning areas were not necessarily compromised for not crossing boundaries. This report was intended as a decision support framework to prioritize planning areas, identify cross-boundary opportunities, and provide a wide array of maps and graphical outputs upon which to further develop active forest management programs.

In addition, given the collaborative nature of this multi-agency effort, the Scenario Investment Planning Platform (SIPP) analytical approach provided a framework for a more collaborative prioritization process. Members of the coordinating group noted that the opportunity to assess multiple restoration objectives in a single model, and to examine tradeoffs among them, created an integrated approach to identify priority landscapes. It also helped identify opportunities to leverage financial, technical, and labor-based resources to achieve desired management outcomes.

Modeling a Scenario for the 2022 Wildfire Crisis Strategy

The Wildfire Crisis Strategy (WCS) and associated implementation plan were released in January of 2022 and present a blueprint for a 10-year accelerated fuels treatment program focused on treatment areas on national forests that are potential sources of wildfire risk to communities. The goals of the WCS are to treat 20 million acres of national forest (on top of current levels of treatment) and 30 million acres of non-national forest land, and to develop a plan for the long-term maintenance of treated areas past the next 10 years.

The plan targeted wildfire transmission to communities, meaning directed treatments to areas that modeling suggested were the source of large fires that exposure communities. There were several reasons for

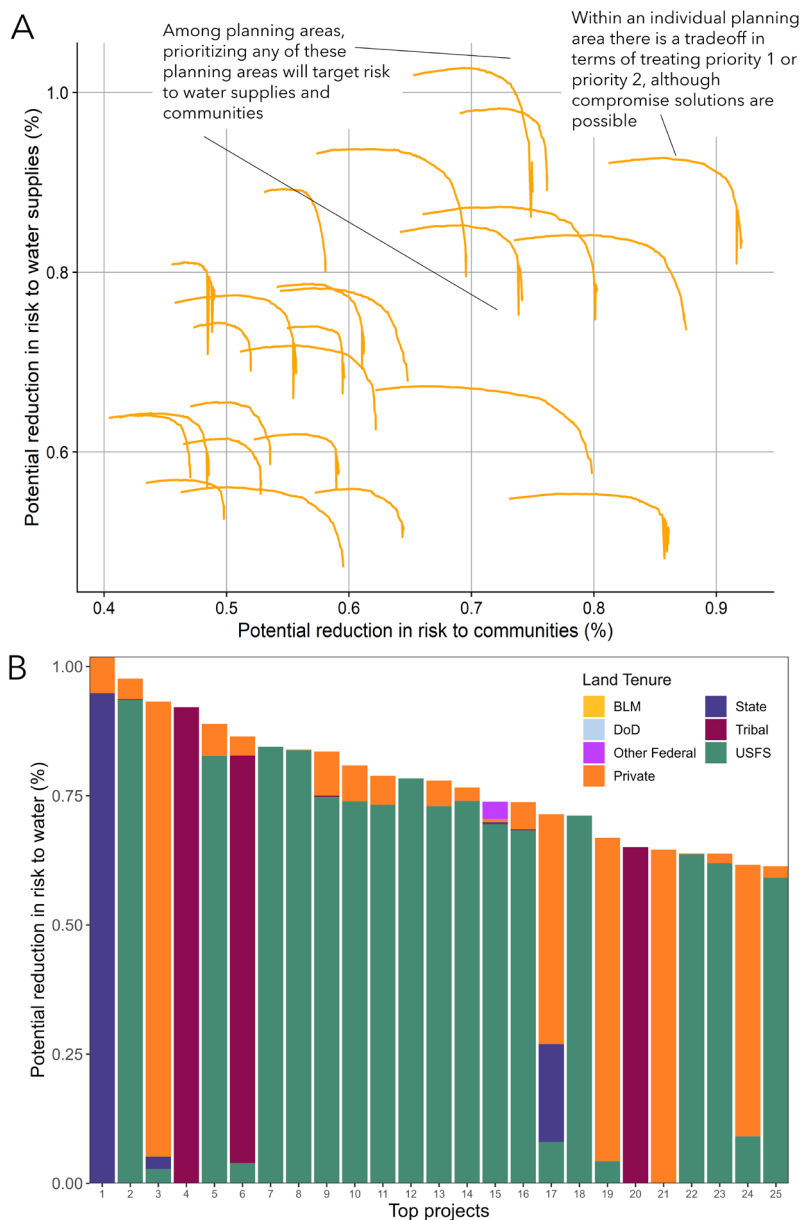


Figure 14—A) Tradeoff between prioritizing to treat wildfire risk to communities versus water supply in the state of New Mexico for the top 25 watersheds, and **B)** the ownership composition of the treated areas when prioritizing only the reduction in risk to water supplies for the top 25 watersheds. Data corresponding to bar charts can be found in appendix table A3. Figure modified from Day et al. (2021).

focusing the scenario on wildfire exposure transmission to communities, including: (1) areas where exposure originates encompass a wide range of other important values (biodiversity, water, recreation, etc.) that would benefit from forest restoration activities; (2) prior work suggested that the bulk of the problem (80 percent) was on a fraction of national forest lands, meaning this program “could make a difference”; and (3) exposure transmission was already mapped in detail and was a key component of prior shared stewardship strategies (fig. 8 in USDA FS 2018).

The work was initiated by first building a planning framework that defined discrete planning areas at the scale of most projects (ca. 25,000 acres) and to organize these into larger areas that were at the scale that exposure is organized. In this way scale mismatches are avoided. The resulting fireshed framework contained a nested system of treatment units, planning areas, and firesheds used to model the 10-year treatment plan (Ager et al. 2021a; Ager et al. 2021c).

We then used ForSys to prioritize each planning area based on predicted exposure, treating 80 percent of the treatable area on national forest land in each planning area where fires ignite and expose communities. A treatment ramp up was modeled to reflect capacity and related issues at the initiation of the plan. The results showed that treating about 40 percent of each planning area addressed 80 percent of the treatable national forest exposure. The outputs from the model were used to develop a treatment schedule over 10 years by national forest and region (fig. 15). The resulting 10-year plan was then extended to the eastern U.S. national forests and used as the foundation to develop the WCS (USDA FS 2022).

A novel aspect to this work that was not described in the WCS was the characterization of wildfire future uncertainty and its effect on the schedule of projects and treatments. A sample of 30 future fire scenarios was constructed by sampling from the national FSim library (Short et al. 2020) and assembling 20 sequential fire years for each of the replicate scenarios. Fires were not allowed to burn the same place twice in each 20-year scenario which was achieved by eliminating fire overlap. The

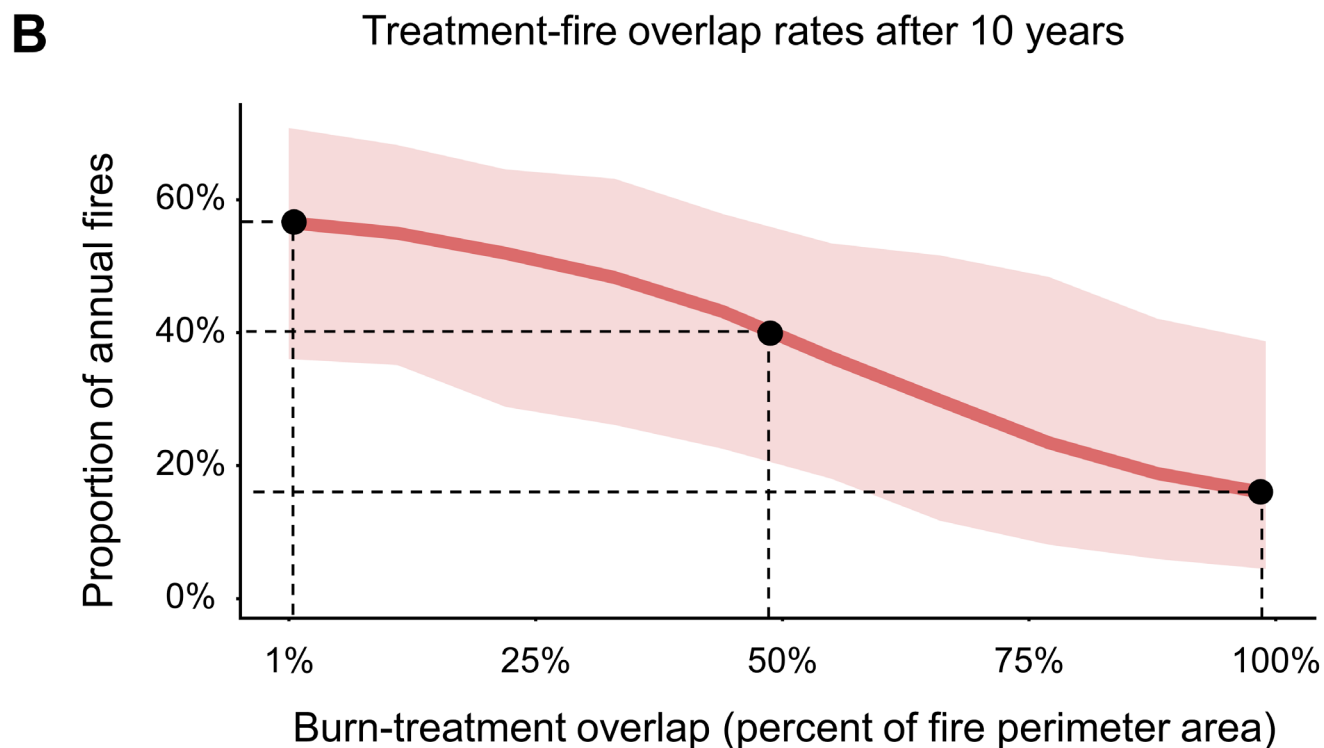
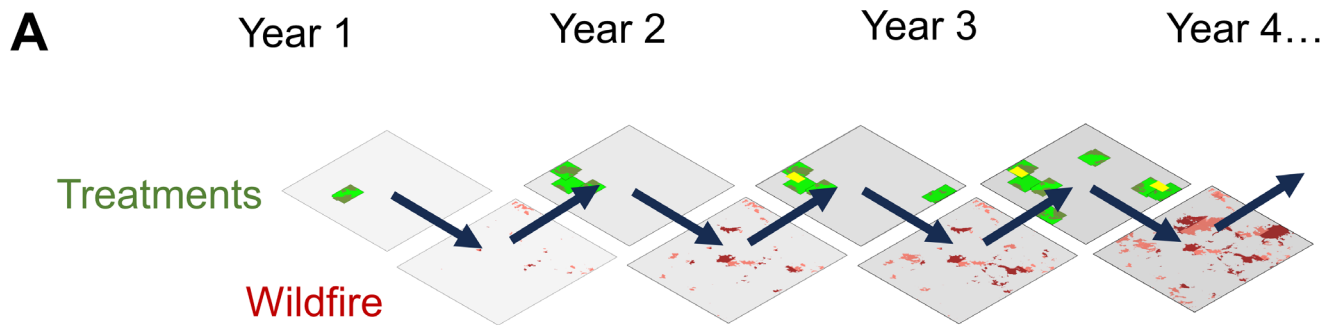


Figure 15—The process for combining ForSys treatment priorities with simulated fire seasons to estimate the wildfire-treatment overlap after 10-years of accelerated fuel treatments. Panel A illustrates how treated and burned areas accumulate over time within the study area. Panel B shows the degree of wildfire-treatment overlap once treatments are fully implemented within high-priority landscapes. For example, after 10-years of the proposed fuel treatments, 60% of wildfires in a given year within targeted forests are expected to at least touch treated acres, while 40% of wildfires will have at least 50% coverage, and 17% of wildfires will be 100% treated. The colored ribbon shows the variability in overlap due to the stochastic nature of wildfire.

study reported that once fully implemented more than 20 percent of simulated fires on national forests overlapped fuel treatments, and that roughly 20 percent of the projects were burned prior to their implementation, suggesting that any plan will undergo significant revision during implementation (Ager et al. 2021c). Treated areas intersected by wildfire accounted for twice the exposure of non-treated areas that also burned. Although approximate, these methods pave the way for expanded use of scenario planning to analyze and communicate future fire uncertainty in new policy initiatives regarding fuel management.

Prioritizing the Construction of Fuel Break Networks

Proposals to build new and expand existing linear fuel breaks networks (FBN) have emerged as part of several national initiatives in the United States and elsewhere (AGIF 2020; Pilliod et al. 2021; USDA FS 2022; Zong et al. 2021). FBNs are typically built on a core of existing roads and rights-of-way to minimize cost and maximize ingress, egress, and safety (Laschi et al. 2019; Oliveira et al. 2016). Natural barriers are also used including low-flammability vegetation (Cui et al. 2019), and non-vegetated features such as lakes and rivers. A key question facing managers is how to organize treatments into manageable project areas that meet operational and administrative constraints and prioritize investments over time to maximize fire management outcomes. In 2021 the SIPP team was contacted by the Umatilla National Forest staff, and asked for a plan to identify where treatments were needed along an existing network of fuel breaks and to identify priorities to start the treatment program. The original plan for the network did not consider how linear segments would be packaged into projects and how projects would be prioritized for treatments through time as the network is constructed.

We expanded the application of both the ForSysX and ForSysR applications to prioritize linear fuel breaks (versus scattered treatment blocks in a landscape) with modifications to both the input data structure and source code and conducted two studies, both on the Umatilla National

Forest. The proposed network extended over 3,538 km, both on the forest and on adjacent lands, and will require extensive forest and fuel management treatments to implement with current budgets and workforce. The long length of the fuel break network combined with the logistics of conducting forest and fuel management requires that treatments be partitioned into a sequence of discrete projects individually implemented over the next 10–20 years.

In the first study (Belavenutti et al. 2022b), we analyzed 13 implementation scenarios where optimized projects were built with ForSysR and prioritized based on predicted wildfire encounter rate, treatment cost, and harvest revenue. We found that among the scenarios, predicted net revenue ranged from \$-3,495 to \$6,642 ha⁻¹, and that prioritizing wildfire hazard significantly reduced net revenue and harvested timber. We demonstrate how the tradeoffs could be minimized using a multi-objective optimization approach. The multi-objective scenario resulted in the highest treatment of hazard, highest timber volume, and revenue except when compared to the scenarios that prioritized each of those objectives individually. We found the most efficient implementation scale was a sequence of relatively small projects that treated 300 ha ±10 percent, versus larger projects with additional treated area. The study demonstrated a decision support model for multi-objective optimization to implement large fuel break networks and provided initial high-priority fuel breaks for the national forest.

We then segmented the network into 2,766 treatment units (1000 m long x 300 m wide segments) and modified the ForSysX spatial optimization model to maximize linear distance of treated projects to examine alternative project implementation geometries, linear versus radial (Ager et al. 2023). We hypothesized that linear projects (long stretches of fuel break) were more efficient at intercepting a large number of individual fire events over larger spatial domains, whereas radial projects (semi-circular web of treatments that radiate from the project centroid) conferred

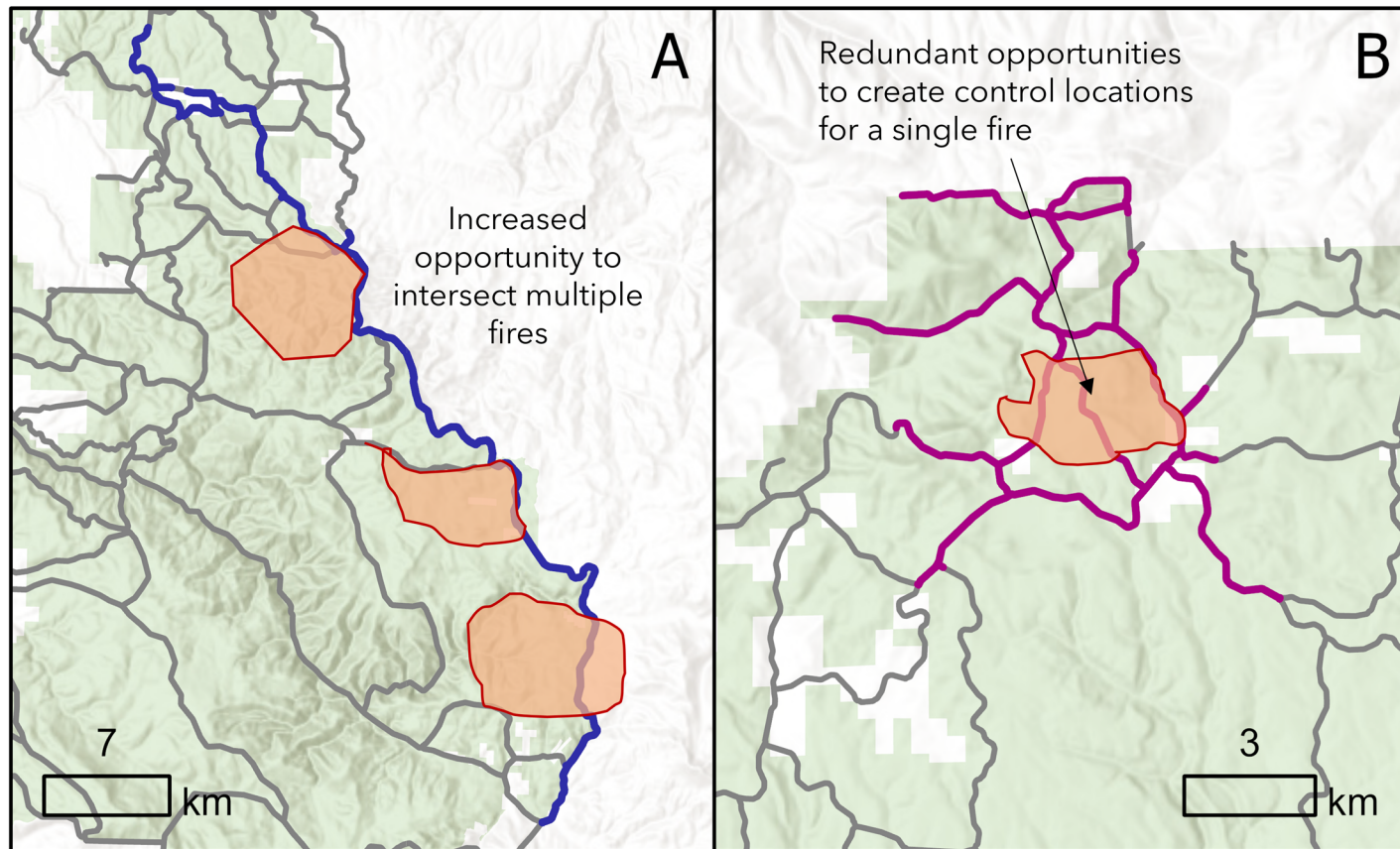


Figure 16—Example fuel break project geometries on the Umatilla National Forest (shaded green) with conceptual fires that intersect them: A) long linear stretches of fuel break maximize the contiguous linear distance to intercept more unique fires, versus B) radial projects, a semi-circular web of treatments that radiate from the project centroid, confer a higher level of network redundancy. Forests need to prioritize how they will implement treatments to harden potential control locations within designed fuel break networks (FBN). On the Umatilla National Forest, 97% of the FBN needed treatment according to managers. Figure modified from Ager et al. (2023).

a higher level of network redundancy in terms of the length of the fuel break exposed to fires (i.e., more chances to stop the same fire event; fig. 16). We simulated implementation of the alternative project geometries and then examined fuel break-wildfire spatial interactions using a library of simulated fires (Short 2020). The results supported the hypothesis. Linear projects exhibited substantially greater efficiency in terms

of intercepting fires (providing potential control locations) over larger areas. On the contrary, radial projects had a higher interception length given a fire encountered a project providing multiple opportunities to control the same fire. Adding economic objectives made it more difficult to find long stretches of linear fuel break, but substantially increased net revenue from harvested trees.

Discussion

We summarized research and application of a landscape spatial planning system built by the authors for decision support related to restoration and risk reduction. Additional studies are listed in table 1 and include several applications in the Mediterranean region that used similar objectives and methodologies as the studies discussed above. These include a study of management tradeoffs in Macedonia, a treatment design study in Sardinia, and an analysis of fuel treatments given budget constraints in eucalyptus forests in Portugal (Martín et al. 2016; Palaologou et al. 2021; Salis et al. 2016). A common finding among the studies described in the previous section is competing objectives among the many goals in risk reduction and restoration programs, especially between reducing risk to developed areas and economic outputs from forest management. Many ecological goals in restoration programs, such as reducing departure from historical conditions have weaker tradeoffs because the conditions targeted in assessments are spatially diffuse, and most project locations can capture these conditions within them. Although most studies found some level of tradeoffs among restoration and risk reduction goals, these were highly variable among planning landscapes within and among national forests. Tradeoffs also were highly scale dependent, where sharp tradeoffs within planning areas were manifested as complementary goals at larger scales (fig. 14A). The social and ecological tradeoffs described in the studies have heretofore not been quantified and mapped at the level of detail provided in many of the studies presented here, and have implications for collaborative planning. All of the studies support rigorous quantitative prioritization as evidenced by the finding that when treatment units are organized into landscape projects, the variation in attainment among optimized projects is substantial, often on the order of three- to four-fold or more on a typical national forest. Variation in assessment conditions is not surprising, especially at the stand scale, but the fact that metrics vary substantially at the scale that landscapes are selected for projects supports prioritizing to capture variation in landscape conditions relative to restoration and risk reduction goals. This is the key difference between a typical assessment and

a landscape scenario analysis where in the latter the assessment conditions are organized into landscape-scale management projects and take into consideration areas available for treatment (exclude protected lands).

In the process of analyzing many land assessments and using them in prioritization experiments, we found that most do not filter lands for where mechanical management investments are possible, making it difficult to use for most restoration and risk reduction planning. For instance, the Watershed Condition Framework (USDA FS 2011), Terrestrial Condition Assessment (Cleland et al. 2017), and Insect and Disease Risk (FHTET 2014) all suggest priorities but do not filter where management investments are possible to target the issues identified in the assessment and prescribe specific restorative treatments. In Law et al. (2021) an assessment of Forest Service lands allocated to conservation excluded nonforested areas, yet these account for 30–40 percent of the area of many national forests that are in roadless and wilderness and have protected status. Filters on landscapes that parse them into identifiable areas where management investments are needed and permitted are required to correctly identify the location of management priorities. Creation of the new national forest planning layer will make it possible to correct this issue on national forest lands (Jamie Barbour, Assistant Director of Adaptive Management, USDA Forest Service, personal communication).

We found that, in general, prior Forest Service projects in the Blue Mountain National Forests were generally suboptimal in terms of achieving treatment objectives. We quantified this by using tradeoff curves and compared these past projects with outputs from ForSys (fig. 8) (Ager et al. 2016). This study never investigated the causal factors for this result, and there are many possible explanations that need to be explored in future work. One unproven hypothesis is that collaborative planning can produce a solution that is optimal for none of the individual assessments.

More work is needed to introduce stochastic wildfire to quantify risk in conservation and disaster mitigation planning (Avin and Goodspeed 2020; Langford et al. 2009) that heretofore has received little attention

in the realm of wildfire policy planning in the United States and in other countries. For instance, estimates of future wildfire variability have not been incorporated into prior large-scale wildfire risk assessments (Calkin et al. 2010; Cleland et al. 2017; Dillon and Gilbertson-Day 2020; USDA FS 2011) or in Federal forest planning processes and systems (IFTDSS 2021; NFMA 1976; Trammell et al. 2018). Despite extensive agency investments in wildfire risk assessments, interpreting red versus green pixels is left to the manager's imagination, since quantities like expected loss are mostly meaningless without some interpretation of uncertainty. We devised a relatively simple approach to examine the effect of variability in fire regimes on fuel treatment scenarios using FSim simulation libraries (Short et al. 2020) to build future fire scenarios and intersect them with treatment plans (Ager et al. 2021c). This work exposed the weakness in arguments made in several papers that fuel treatments were not effective because a fire rarely encounters them (Barnett et al. 2016; Dunn et al. 2020; Schoennagel et al. 2017). From the fire side, an individual fire was highly likely to encounter a fuel break, while an individual fuel break may not encounter a wildfire in a given fire season. Our work suggests that variability in future fire seasons can obscure effects of fuel treatments on reducing exposure when examined over large spatial scales and short time frames (e.g., 2–5 years), despite treatments that are effective at local scales (Ager et al. 2021c).

Management Implications

The broad management implications from the development and application of the ForSys model for the National Forest System is that an established framework is now available for planners to rapidly prioritize management activities using existing agency assessments and geospatial data. ForSys fills a gap in multiscale flexible planning tools that can help planners and managers optimize investments in land management and define spatial priorities for a range of planning problems. The results of all the studies reviewed here support the use of landscape scenario planning for quantitative prioritization to carefully plan restoration and risk reduction investments. Careful prioritizing is warranted to capture variation in landscape conditions relative to restoration and risk reduction

goals. Prioritization affects outcomes; poor prioritization leads to poor outcomes (Hannah et al. 2020). As demonstrated in the case studies, the application framework is easily applicable to a range of resource and conservation planning problems and makes it possible for field units to use spatial optimization as part of the planning process without complicated commercial software. A co-benefit of the system is this analytical capacity can motivate national forests to improve and maintain forest vegetation and related spatial data sets that are a key component for project planning and forest-scale prioritization. A clear example of the potential management benefits was demonstrated in case studies completed on the Blue Mountain National Forests (Ager et al. 2016; Ager et al. 2017; Belavenutti et al. 2022a; Belavenutti et al. 2022b; Belavenutti et al. 2021) where a comprehensive and detailed projection of future management activities was modeled to achieve desired conditions in terms of risk and resiliency, while considering costs, revenues, and harvest volume (figs. 11–13). These plans can be effective products to communicate budget and workforce capacity needs to higher levels in the agency, and clearly communicate the backlog of management investments needed to achieve management goals. These same products are also of value for the kind of collaborative and cross-boundary planning (Charnley et al. 2020) that has been established as a core principle by multiple agency initiatives (USDA FS 2018).

ForSys Versus Other Prioritization and Planning Systems

There are several differences and similarities between ForSys and other approaches to the problem of prioritizing and scheduling treatments over space and time and measuring response. The simplest approach used for prioritizing management areas is the widely used practice of overlaying condition assessments in GIS and tallying up the scores. The drawback to this approach is that outcomes are not predicted, and priorities are generated as pixels, not projects which is the unit of landscape change in typical restoration and risk reduction projects. In other words, assessments of pixels need to be translated to actions at the scale of projects on U.S. public lands, which is the core functionality of ForSys.

At the other end of the complexity spectrum are the traditional operations research models developed to optimize management activities using mathematical programming methods (Hof and Bevers 2002; Murray et al. 2022; Murray and Church 2023; Tóth 2020). Despite their important contribution to decision theory, their application for land management decisions and contribution to environmental planning is sparse to nonexistent, with the exception being the use of the forest planning model, FORPLAN, in the 1980s and 1990s for the development of national forest plans (Kent et al. 1991). In this case a multiperiod linear optimization model was required to demonstrate nondeclining allowable timber sale quantities as required by Federal statute (the Multiple Use Sustained Yield Act). The model was nearly abandoned by the Forest Service after forest plans were completed and it was never applied at scales smaller or larger than national forests. Most analysts tasked with application of the model were overwhelmed at the complexity despite the full-time support of agency staff at a centralized help desk. One of the most serious drawbacks of the model was landscapes were represented as land strata attributed with strata average conditions. Another drawback was the difficulty of including stochastic wildfire disturbances and impacts as part of long-range predictions of harvest volumes and other outputs.

Various mathematical programming models are still developed and tested by researchers (Borges et al. 2017; Murray and Church 2023; Schroder et al. 2016) and advocated as a superior approach to identifying optimal solutions to the problem of aggregating land parcels into projects or conservations areas (Beyer et al. 2016; Murray and Church 2023; Murray et al. 2022). For instance, Murray et al. (2022) report that the ForSys heuristic was found to be up to 6.69 percent less efficient (4.56

percent average across the 23 planning problems). However, the largest landscape tested was 1,403 parcels, whereas a typical prioritization problem at the scale of a national forest ranges from 50,000 to 150,000 parcels (Murray et al. 2022). Note that that even at this size processing times were growing exponentially longer and optimal solutions were not achieved after an hour of processing. Likewise, Beyer et al. (2016) found a mathematical programming approach superior to the heuristics used in Marxan for conservation reserve design and argued that the former should be considered the preferred approach. Our application of the relatively simple ForSys model and associated heuristic approach has shown that the model can find solutions that are 5 to 10 times more optimal than actual project designs implemented by the Forest Service (Ager et al. 2016), and the program is readily implemented (and explained) by field units for local planning, which is not the case with mathematical programming models. Therefore, the marginal suboptimality of a model that can be widely applied is not significant when its simplicity can lead to application on hundreds of projects per year in agencies such as the USDA Forest Service (Colavito 2021).

After FORPLAN, many forests turned to state and transition models for long-range planning, specifically the Tool for Exploratory Landscape Scenario Analyses or TELSA model that incorporated disturbance, management, and successional processes (Kurz et al. 2000). A myriad of other models has been developed and applied since that era, including notably the Ecosystem Management Decision Support (EMDS) System (Reynolds 2001). It is beyond the scope of this review to catalog these other models and provide detailed comparisons of their functionality, although we have briefly surveyed these tools (Box 1).

Box 1—Prioritization decision support tools used in land management as reported in recent literature

ForSys (U.S. Department of Agriculture, Forest Service):

Optimization Method: Greedy heuristic

Key features:

- Spatially optimizes planning areas from treatment parcels
- Replicates U.S. federal planning
- No dependencies on specific data sets
- Application resulted in U.S. federal land management decisions
- Portable and optimization not dependent on commercial linear program solvers
- Scalable from thousands to millions of acres
- Open source R and windows desktop versions

Link: <https://www.forsysplanning.org/>

Land Tender (Vibrant Planet):

Optimization Method: ForSys (greedy heuristic)

Key features:

- Uses similar planning framework as ForSys
- Standardized data set provided to users
- Cloud hosted geospatial interface
- Toolkit to compare scenarios based on treatment area overlap

Link: <https://www.vibrantplanet.net/landtender>

Marxan (Marxan Conservation Solutions):

Optimization Method: Simulated annealing

Key features:

- Primary application is conservation planning and the design of conservation reserves
- Aggregates parcels into reserves
- Freely available, C program

Link: <https://marxansolutions.org/>

Planscape (California Natural Resources Agency, Google.org, Spatial Informatics Group):

Optimization Method: ForSys (greedy heuristic)

Key features:

- Uses similar planning framework as ForSys
- Uses California Regional Resource Kit data incorporating USFS and other datasets
- Cloud hosted geospatial interface
- Open source and open science

Link: <https://www.planscape.org/>

prioritizR (research team):

Optimization Method: mixed integer linear program

Key features:

- Similar purpose and functionality as Marxan
- Open source, R program
- Dependent on mixed-integer linear solver
- Commercial solver required for best performance

Link: <https://prioritizr.net/>

WePlan-Forests (International Institute for Sustainability Australia and International Institute for Sustainability Rio):

Optimization Method: linear program

Key features:

- Informs restoration planning and implementation within tropical and subtropical forest ecosystems at national scales
- Uses the PLANGEA framework
- Metrics defined by developers with 1 km² resolution
- Centralized system—scenarios executed by development team

Link: <http://weplan-forests.org/index.html>

Future Applications

Protect Sage Grouse Habitat

To date, most of the case studies using ForSys were conducted in forested systems; however, ForSys can prioritize any type of treatment in any system (e.g., prioritizing culvert replacement along road networks). ForSys is being applied to evaluate the effects of fuel treatments in sagebrush and pinyon-juniper (PJ) ecosystems to estimate treatment effects on fuels, fire behavior, fire effects, and economic tradeoffs. For example, how do treatments affect fire risk overall and in the different sagebrush response groups? How is fire risk affected by placing operational constraints on the landscape, and what are the effects of treating protected core sagebrush as well as the surrounding landscape? In this study, ForSys will be used to optimize fuel reduction treatments to protect sage grouse habitat using wildfire simulation outputs and maps of critical habitat.

Dynamic Strategic Fuel Breaks for the Desert Tortoise

Agassiz's desert tortoise (*Gopherus agassizii*) was placed on the Federal threatened species list 25 years ago. This species roams across millions of acres in Arizona, California, Nevada, and Utah and is considered an indicator of the health of the desert environment. Over 250,000 acres of desert tortoise habitat have burned in southern Nevada since 2005, including huge swaths of critical habitat, fueled by climate change and nonnative grass invasions in an ecosystem ill-adapted to wildfire. One species, the invasive red brome (*Bromus rubens*), provides ample fuel for large wildfires in the Mojave Desert when sufficient precipitation allows. Red brome cures about 3 months after precipitation events to a relatively low fuel moisture when it can then propagate fire. Red brome fuel loadings can be predicted in advance using real-time weather monitoring and the RMRS Fuel casting system (Reeves et al. 2020). Thus, levels of wildfire likelihood are highly dynamic over space and

time as is the risk to the desert tortoise. Coupling this system with wildfire risk simulation platforms built by scientists at RMRS can potentially map wildfire likelihood and risk to the tortoise in space and time to target optimized fuel breaks around critical habitat at risk. Systems of strategically placed fuel breaks in southern Nevada will improve firefighter safety, provide anchor points for fire suppression activities, expand opportunities to control wildfires, and create buffers for maintaining desert tortoise habitat. Fuel breaks will also offer protection to nonfire adapted species within the Mojave ecosystem as well as protect ongoing habitat restoration investments and reduce invasive plant species expansion due to fire disturbance. Desert fuel breaks can be dynamic and spatially attuned to the location of predicted wildfire risk, and can be established using a variety of techniques including mowing and pre-emergent herbicides. In this project we are coupling fuel prediction systems with ForSys to build a dynamic fuel break optimization system that can be used to direct wildfire mitigation investments in areas where the desert tortoise is threatened by wildfire.

Co-prioritization of Restoration and Fuel Break Networks

In 2017 the Washington Department of Natural Resources (DNR) presented the “20-Year Forest Health Strategic Plan: Eastern Washington,” which lays out a strategy and goals for restoring forested landscapes using forest and fuel management treatments in several priority landscapes. The plan sets a goal of 1.25 million acres restored by 2037. The priority areas are mixed-ownership landscapes in eastern Washington selected based on landscape departure from historical conditions and fire risk. The SIPP team and DNR scientists initiated a project to pilot a collaborative scenario planning system to allow for DNR to develop management plans with stakeholders. The hypothesis is that restoration projects built on partnerships that explore a diversity of objectives and scenarios results in projects with a higher degree of success when navigating the implementation process on mixed owner landscapes.

Integration of Additional Priorities into the Wildfire Crisis Strategy

After the initial development and implementation of the Wildfire Crisis Strategy (WCS) in 2020, the Forest Service was tasked with expanding the underlying priorities based on five additional considerations as part of Climate Resilience and Carbon Stewardship of America's National Forests and Grasslands (Secretary's Memorandum 1077-004 Section 2A): carbon stocks, wildlife habitat, biodiversity, water, and environmental justice (USDA 2022). Over the next year, Forest Service teams were assembled to deliver spatially explicit risk information to inform decision making. However, these new Section 2A1 assessments were not rendered into priorities using the same framework and methods used for building exposure as originally published in the 10-year plan and implemented in the WCS (Ager et al. 2021c; USDA FS 2022). Thus, the authors are analyzing how to optimize management investments according to these new assessments and understand priority tradeoffs within the existing fireshed framework. In addition, we are assessing the potential impacts of climate change on wildfire exposure to buildings using midcentury climate using RCP8.5 climate change scenarios from multiple global circulation models. This work will provide a novel analysis describing tradeoffs among a wide range of wildfire risk management objectives (carbon stocks, wildlife habitat, biodiversity, water, and environmental justice), in effect integrating other assessments into the same decision framework as used in the formulation of the WCS, and setting the stage for supporting future initiatives aimed at curbing wildfire impacts on national forests.

Assessing Social Equity of Management Projects

Integration of the Secretary's Memorandum (as noted above) into the WCS included a key consideration for social equity, an important dimension for many scenario planning problems. Not only do many projects directly sustain or restore ecosystem products and services for local communities, but they also contribute to local economies and job creation. Recognizing this, the 2020 Justice 40 initiative directed agencies

to ensure that at least 40 percent of Federal funds were received by or contributed to economically marginalized populations. This applies to the WCS and associated priority landscapes. Regional land managers must choose where to prioritize fuel reduction projects, but in doing so, particular communities benefit from reduced wildfire risk. ForSys is being applied to this social equity question by showing how project priorities shift when targeting treatments that could benefit marginalized populations. The social equity is being assessed by attributing the wildfire transmission layers used for the Fireshed Registry with the 2020 census data describing income estimates. In this way firesheds can be ranked in terms of the extent to which treatments are meeting the Justice 40 initiative.

Future System Development

This is a dynamic time for scenario investment planning given the increase in funding to dramatically increase fuels and forest health treatments by up to four times the current treatment levels in the West (USDA FS 2022). To advance scenario planning models and application for decision support at a range of scales in the Forest Service and partner agencies, the authors created the Scenario Investment Planning Platform in 2019. As the application of the model began to expand into educational institutions, nonprofit, for profit, and state agencies, the authors created the ForSys Research Consortium (2024) as a collaborative environment for development and technology exchange. The ForSys Research Consortium and the associated GitHub repositories were created to build a laboratory that includes educators, researchers, and practitioners with interests in the application of ForSys for scenario landscape planning. In the long run, this consortium will help migrate the system into a cloud platform that can access data in online databases (e.g., the Forest Service's Enterprise Data Warehouse), and can be accessed by Forest Service planners. In this way the system can be used for near real-time scenario planning with stakeholder input as part of collaborative planning processes sponsored by the agency. In the meantime, members of the consortium are deploying variants of

ForSys. For instance, the ForSysR code for the Patchmax algorithm was incorporated into the Vibrant Planet Land Tender planning system (Vibrant Planet 2023). Land Tender is being deployed by Vibrant Planet in a number of California planning venues at the time of this writing. In addition, the California Natural Resources Agency (CNRA) contracted Google.org and later Spatial Informatics Group to build Planscape (California Natural Resources Agency 2023), a cloud-based planning system that calls ForSysR for targeted application in California as part of California's Million Acre Initiative. Achieving the goal of building a cloud-based ForSys platform accessible within agency firewalls with the full functionality of ForSys could potentially accelerate and improve prioritization and planning for a wide range of natural resource management issues on national forests and partner agency lands.

Program Distribution

ForSysR is available via GitHub repositories (Evers et al. 2023) and ForSysX is available at <https://www.forsysplanning.org/>.

References

- Adams, V.M.; Pressey, R.L.; Álvarez-Romero, J.G. 2016. Using optimal land-use scenarios to assess trade-offs between conservation, development, and social values. *PLoS ONE*. 11: e0158350. <https://doi.org/10.1371/journal.pone.0158350>.
- Ager, A.A.; Day, M.A.; Aparicio, B.A.; Houtman, R.; Stinchfield, A., 2023. Optimizing the implementation of a forest fuel break network. *PLoS ONE* 18, 12, doi: 10.1371/journal.pone.0295392. <https://www.fs.usda.gov/research/treesearch/67187>.
- Ager, A.A.; Day, M.A.; Ringo, C.; [et al.]. 2021a. Development and application of the Fireshed Registry. Gen. Tech. Rep. RMRS-GTR-425. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 47 p. <https://doi.org/10.2737/RMRS-GTR-425>.
- Ager, A.A.; Day, M.A.; Vogler, K. 2016. Production possibility frontiers and socioecological tradeoffs for restoration of fire adapted forests. *Journal of Environmental Management*. 176: 157–168.
- Ager, A.A.; Day, M.A.; Waltz, A.; [et al.]. 2021b. Balancing ecological and economic objectives in restoration of fire frequent forests—Case study from the Four Forest Restoration Initiative. Gen. Tech. Rep. RMRS-GTR-424. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 30 p. <https://doi.org/10.2737/RMRS-GTR-424>.
- Ager, A.A.; Evers, C.R.; Day, M.A.; [et al.]. 2021c. Planning for future fire: Scenario analysis of an accelerated fuel reduction plan for the western United States. *Landscape and Urban Planning*. 215: 104212. <https://doi.org/10.1016/j.landurbplan.2021.104212>
- Ager, A.A.; Houtman, R.; Day, M.A.; [et al.]. 2019. Tradeoffs between U.S. National Forest harvest targets and fuel management to reduce wildfire transmission to the wildland urban interface. *Forest Ecology and Management*. 434: 99–109.
- Ager, A.A.; Vaillant, N.; Owens, D.E.; [et al.]. 2012. Overview and example application of the Landscape Treatment Designer. Gen. Tech. Rep. PNW-GTR-859. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 11 p.
- 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. <https://doi.org/10.1890/ES13-00007.1>.
- Ager, A.A.; Vogler, K.C.; Day, M.A.; [et al.]. 2017. Economic opportunities and trade-offs in collaborative forest landscape restoration. *Ecological Economics*. 136: 226–239.
- AGIF. 2020. National plan for integrated wildfire management 2020–2030. Lisbon: Agency for Integrated Rural Fire Management. 166 p.
- Alcasena, F.J.; Ager, A.A.; Belavenutti, P.; [et al.]. 2022. Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk. *Journal of Environmental Management*. 114650. <https://doi.org/10.1016/j.jenvman.2022.114650>.

- Alcasena, F.J.; Ager, A.A.; Salis, M.; [et al.]. 2018. Optimizing prescribed fire allocation for managing fire risk in central Catalonia. *Science of The Total Environment*. 4: 872–885.
- Ariza, A.M.; Pirotti, F.; de Oliveira, M.T.M.; [et al.]. 2015. Trends in wildfire risk at time-scale: Optimizing fuel treatments configurations in eucalyptus plantations in Portugal. Padua, Italy: University of Padua.
- Avin, U.; Goodspeed, R. 2020. Using exploratory scenarios in planning practice: A spectrum of approaches. *Journal of the American Planning Association*. 86: 403–416.
- Ball, I.R.; Possingham, H.P.; Watts, M. 2009. Marxan and relatives: Software for spatial conservation prioritisation. In: Moilanen, A.; Wilson, K.A.; Possingham, H.P., eds. *Spatial conservation prioritisation: Quantitative methods and computational tools*. Oxford: Oxford University Press: 185–210.
- Barnett, K.; Parks, S.; Miller, C.; [et al.]. 2016. Beyond fuel treatment effectiveness: Characterizing interactions between fire and treatments in the U.S. Forests. 7: 237.
- Belavenutti, P.; Ager, A.A.; Day, M.A.; [et al.]. 2022a. Designing forest restoration projects to optimize the application of broadcast burning. *Ecological Economics*. 201: 107558.
- Belavenutti, P.; Ager, A.A.; Day, M.A.; [et al.]. 2022b. Multi-objective scheduling of fuel treatments to implement a linear fuel break network. *Fire*. 6: 1. <https://doi.org/10.3390/fire6010001>.
- Belavenutti, P.; Chung, W.; Ager, A.A. 2021. The economic reality of the forest and fuel management deficit on a fire prone western U.S. National Forest. *Journal of Environmental Management*. 293: 112825.
- Beyer, H.L.; Dujardin, Y.; Watts, M.E.; [et al.]. 2016. Solving conservation planning problems with integer linear programming. *Ecological Modelling*. 328: 14–22.
- Borges, J.G.; Marques, S.; García-Gonzalo, J.; [et al.]. A multiple criteria approach for negotiating ecosystem services supply targets and forest owners' programs. *Forest Science*. 63: 49–61.
- Botequim, B.R.; Ager, A.; Pacheco, A.C.P.; [et al.]. 2014. Addressing trade-offs among fuel management scenarios through a dynamic and spatial integrated approach for enhanced decision-making in eucalyptus forest. In: Viegas, D.X., ed. *Advances in Forest Fire Research*. Coimbra, Portugal: Coimbra University Press.
- Brittain, S. 2015. Fire behavior FlamMap application interface. http://sbrittain.net/FB/FB_API.htm.
- Brudvig, L.A. 2017. Toward prediction in the restoration of biodiversity. *Journal of Applied Ecology*. 54: 1013–1017.
- California Natural Resources Agency. 2023. Planscape: A planning tool to maximize wildfire resilience and ecological benefits. <https://www.planscape.org/>.
- Calkin, D.E.; Ager, A.A.; Gilbertson-Day, J.; [et al.]. 2010. Wildfire risk and hazard: Procedures for the first approximation. Gen. Tech. Rep. GTR-RMRS-235. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 62 p. <https://doi.org/10.2737/RMRS-GTR-235>.
- Charnley, S.; Kelly, E.C.; Fischer, A.P. 2020. Fostering collective action to reduce wildfire risk across property boundaries in the American West. *Environmental Research Letters*. 15: 025007.
- Chazdon, R.L.; Guariguata, M.R. 2018. Decision support tools for forest landscape restoration: Current status and future outlook. Occasional Paper 183. Bogor, Indonesia: Center for International Forestry Research.
- Chiono, L.A.; Fry, D.L.; Collins, B.M.; [et al.]. 2017. Landscape-scale fuel treatment and wildfire impacts on carbon stocks and fire hazard in California spotted owl habitat. *Ecosphere*. 8: e01648. <https://doi.org/10.1002/ecs2.1648>.
- Cleland, D.; Reynolds, K.; Vaughan, R.; [et al.]. 2017. Terrestrial condition assessment for National Forests of the USDA Forest Service in the continental U.S. *Sustainability*. 9: 2144. <https://doi.org/10.3390/su9112144>.
- Colavito, M., 2021. The human dimensions of spatial, pre-wildfire planning decision support systems: A review of barriers, facilitators, and recommendations. *Forests* 12, 483.

- Cui, X.; Alam, M.A.; Perry, G.L.; [et al.]. 2019. Green firebreaks as a management tool for wildfires: Lessons from China. *Journal of Environmental Management*. 233: 329–336.
- Day, M.A.; Houtman, R.; Belavenutti, P.; [et al.]. 2021. An assessment of forest and woodland restoration priorities to address wildfire risk in New Mexico. Gen. Tech. Rep. RMRS-GTR-423. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. <https://doi.org/10.2737/RMRS-GTR-423>.
- Dijkstra, E.W. 1959. A note on two problems in connexion with graphs. *Numerische mathematik*. 1: 269–271.
- Dillon, G.K.; Gilbertson-Day, J. 2020. Wildfire Hazard Potential (WHP) for the conterminous United States (270-m), version 2020 (3rd edition). [Database]. <https://doi.org/10.2737/RDS-2015-0047-3>.
- Dunn, C.J.; O'Connor, C.D.; Abrams, J.; [et al.]. 2020. Wildfire risk science facilitates adaptation of fire-prone social-ecological systems to the new fire reality. *Environmental Research Letters*. 15: 025001.
- Eaton, M.J.; Yurek, S.; Haider, Z.; [et al.]. 2019. Spatial conservation planning under uncertainty: adapting to climate change risks using modern portfolio theory. *Ecological Applications*. 29: e01962. <https://doi.org/10.1002/eap.1962>.
- Evers, C.; Houtman, R.; Day, M.A.; [et al.]. 2023. ForSysR: A scenario planning platform for modeling multi-criteria spatial priorities in R. <https://github.com/forsys-sp/forsysr>.
- FHTET. 2014. 2013–2027 National Insect & Disease Forest Risk Assessment. FHTET-14-01. https://www.fs.usda.gov/foresthealth/technology/pdfs/2012_RiskMap_Report_web.pdf.
- Finney, M.A.; McHugh, C.W.; Grenfell, [et al.] 2011. A simulation of probabilistic wildfire risk components for the continental United States. *Stochastic Environmental Research and Risk Assessment*. 25: 973–1000.
- ForSys Research Consortium. 2024. The ForSys Research Consortium. <https://www.forsysplanning.org/>.
- Hannah, L.; Roehrdanz, P.R.; Marquet, P.A.; [et al.]. 2020. 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*. 43: 943–953.
- Haugo, R.; Zanger, C.; DeMeo, T.; [et al.]. 2015. A new approach to evaluate forest structure restoration needs across Oregon and Washington, USA. *Forest Ecology and Management*. 335: 37–50.
- HFRA. 2003. Healthy Forest Restoration Act of 2003.
- Hof, J.; Bevers, M. 2002. Spatial optimization in ecological applications. New York: Columbia University Press.
- IFTDSS. 2021. Fuel Treatment Effectiveness Monitoring (FTEM) [Database]. https://www.fs.usda.gov/adaptivemanagement/projects_main_fbat_fueltrat_effectiveness.php.
- Iftekhar, M.S.; Polyakov, M.; Ansell, D.; [et al.]. 2016. How economics can further the success of ecological restoration. *Conservation Biology*. 31: 261–268.
- Jain, T.B.; Battaglia, M.A.; Han, H.-S.; [et al.]. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States. Gen. Tech. Rep. RMRS-GTR-292. Fort Collins, CO: USDA, Forest Service. <https://www.fs.usda.gov/research/treesearch/42150>.
- Kent, B.; Bare, B.B.; Field, R.C.; [et al.]. 1991. Natural resource land management planning using large-scale linear programs: The USDA Forest Service experience with FORPLAN. *Operations Research*. 39: 13–27.
- Kreitler, J.; Thompson, M.P.; Vaillant, N.M.; [et al.]. 2019. Cost-effective fuel treatment planning: A theoretical justification and case study. *International Journal of Wildland Fire*. 29: 42–56.
- Kukkala, A.S.; Moilanen, A. 2013. Core concepts of spatial prioritisation in systematic conservation planning. *Biological Reviews*. 88: 443–464.
- Kurz, W.A.; Beukema, S.J.; Klenner, W.; [et al.]. 2000. TELSA: The tool for exploratory landscape scenario analyses. *Computers and Electronics in Agriculture*. 27: 227–242.
- Langford, W.T.; Gordon, A.; Bastin, L. 2009. When do conservation planning methods deliver? Quantifying the consequences of uncertainty. *Ecological Informatics*. 4: 123–135.
- Laschi, A.; Foderi, C.; Fabiano, F.; [et al.]. 2019. Forest road planning, construction and maintenance to improve forest fire fighting: A review. *Croatian Journal of Forest Engineering*. 40: 207–219.

- Law, B.E.; Berner, L.T.; Buotte, P.C.; Mildrexler, D.J.; Ripple, W.J. 2021. Strategic forest reserves can protect biodiversity in the western United States and mitigate climate change. *Communications Earth & Environment*. 2: 254.
- Martín, A.; Botequim, B.R.; Oliveira, T.M.; [et al.]. 2016. Temporal optimization of fuel treatment design in blue gum (*Eucalyptus globulus*) plantations. *Forest Systems*. 25(2): eRC09-eRC09. <https://doi.org/10.5424/fs/2016252-09293>.
- Mazziotta, A.; Podkopaev, D.; Triviño, M.; [et al.]. 2017. Quantifying and resolving conservation conflicts in forest landscapes via multiobjective optimization. *Silva Fennica*. 51: 1778. <https://doi.org/10.14214/sf.1778>.
- Moilanen, A.; Leathwick, J.R.; Quinn, J.M. 2011. Spatial prioritization of conservation management. *Conservation Letters*. 4: 383–393.
- Murray, A.T.; Church, R.L. 2023. Spatial optimization of multiple area land acquisition. *Computers & Operations Research*. 153: 106160. <https://doi.org/10.1016/j.cor.2023.106160>.
- Murray, A.T.; Church, R.L.; Pludow, B.A.; [et al.]. 2022. Advancing contiguous environmental land allocation analysis, planning and modeling. *Journal of Land Use Science*. 17: 572–590.
- NFMA. 1976. National Forest Management Act of 1976. 16 U.S.C. §§ 1600–1687.
- North, M.P.; Tompkins, R.E.; Bernal, A.A.; [et al.]. 2022. Operational resilience in western U.S. frequent-fire forests. *Forest and Ecology Management*. 507.
- Oliveira, T.M.; Barros, A.M.G.; Ager, A.A.; [et al.]. 2016. Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission. *International Journal of Wildland Fire*. 25: 619–632.
- Palaiologou, P.; Kalabokidis, K.; Ager, A.A.; [et al.]. 2021. Spatial optimization and tradeoffs of alternative forest management scenarios in Macedonia, Greece. *Forests*. 12: 697. <https://doi.org/10.3390/f12060697>.
- Pilliod, D.S.; Jeffries, M.A.; Welty, J.L.; [et al.]. 2021. Protecting restoration investments from the cheatgrass–fire cycle in sagebrush steppe. *Conservation Science and Practice*. 3.
- Pohjanmies, T.; Eyvindson, K.; Mönkkönen, M. 2019. Forest management optimization across spatial scales to reconcile economic and conservation objectives. *PLoS ONE*. 14: e0218213.
- Powell, D. 2010. Range of variation recommendations for dry, moist, and cold forests. White Paper F14-SO-WP-Silv-03. Pendleton, OR: USDA Forest Service, Pacific Northwest Region.
- Radeloff, V.C.; Hammer, R.B.; Stewart, S.I.; [et al.]. 2005. The wildland-urban interface in the United States. *Ecological Applications*. 15: 799–805.
- Reeves, M.C.; Hanberry, B.B.; Burden, I. 2020. Rapidly quantifying drought impacts to aid reseeding strategies. *Rangelands*. 42: 151–158.
- Reynolds, K.M. 2001. EMDS: Using a logic framework to assess forest ecosystem sustainability. *Journal of Forestry*. 99: 26–30.
- Riddell, G.A.; van Delden, H.; Maier, H.R.; [et al.]. 2019. Exploratory scenario analysis for disaster risk reduction: Considering alternative pathways in disaster risk assessment. *International Journal of Disaster Risk Reduction*. 39: 101230. <https://doi.org/10.1016/j.ijdr.2019.101230>.
- Riley, K.L.; Grenfell, I.C.; Finney, M.A.; [et al.]. 2021. TreeMap 2016: A tree-level model of the forests of the conterminous United States circa 2016. [Database]. <https://doi.org/10.2737/RDS-2021-0074>.
- Salis, M.; Del Giudice, L.; Robichaud, P.R.; [et al.]. 2019. Coupling wildfire spread and erosion models to quantify post-fire erosion before and after fuel treatments. *International Journal of Wildland Fire*. 28: 687–703.
- Salis, M.; Laconi, M.; Ager, A.A.; [et al.]. 2016. Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area. *Forest Ecology and Management*. 368: 207–221.
- Scheller, R.; Domingo, J.B.; Sturtevant, B.R.; [et al.]. 2007. Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. *Ecological Modelling*. 201: 409–419.
- Schoennagel, T.; Balch, J.K.; Brenkert-Smith, H.; [et al.]. 2017. Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences, USA*. 114: 1582–4590.

- Schroder, S.A.K.; Tóth, S.F.; Deal, R.L.; [et al.]. 2016. Multi-objective optimization to evaluate tradeoffs among forest ecosystem services following fire hazard reduction in the Deschutes National Forest, USA. *Ecosystem Services*. 22: 328–347.
- Schultz, C.A.; Jedd, T.; Beam, R.D. 2012. The Collaborative Forest Landscape Restoration Program: A history and overview of the first projects. *Journal of Forestry*. 110: 381–391.
- Short, K.C.; Finney, M.A.; Vogler, K.; [et al.]. 2nd edition. 2020. Spatial datasets of probabilistic wildfire risk components for the United States (270m). [Database]. <https://doi.org/10.2737/RDS-2016-0034-2>.
- Spies, T.; White, E.; Ager, A.; [et al.]. 2017. Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. *Ecology and Society*. 22: 25. <https://doi.org/10.5751/ES-08841-220125>.
- Star, J.; Rowland, E.L.; Black, M.E.; [et al.]. 2016. Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods. *Climate Risk Management*. 13: 88–94.
- Strassburg, B.B.; Iribarrem, A.; Beyer, H.L.; [et al.]. 2020. Global priority areas for ecosystem restoration. *Nature*. 586: 724–729.
- Thompson, M.P.; Vogler, K.C.; Scott, J.H.; [et al.]. 2022. Comparing risk-based fuel treatment prioritization with alternative strategies for enhancing protection and resource management objectives. *Fire Ecology*. 18: 26. <https://doi.org/10.1186/s42408-022-00149-0>.
- Tóth, S.F. 2020. The 17th symposium on systems analysis in forest resources: An introduction and synthesis. *Forest Science*. 66: 424–427.
- Trammell, E.J.; Thomas, J.S.; Mouat, D.; [et al.]. 2018. Developing alternative land-use scenarios to facilitate natural resource management across jurisdictional boundaries. *Journal of Environmental Planning and Management*. 61: 64–85.
- Triviño, M.; Pohjanmies, T.; Mazziotta, A.; [et al.]. 2017. Optimizing management to enhance multifunctionality in a boreal forest landscape. *Journal of Applied Ecology*. 54: 61–70.
- United States Department of Agriculture [USDA]. 2022. Secretary's Memorandum 1077-004: Climate Resilience and Carbon Stewardship of America's National Forests and Grasslands. Department Directive. <https://www.usda.gov/sites/default/files/documents/sm-1077-004-climate-resilience-carbon-stewardship.pdf>.
- USDA Forest Service [USDA FS]. 2011. Watershed Condition Framework: A framework for assessing and tracking changes to watershed condition. FS-977. https://www.fs.usda.gov/biology/resources/pubs/watershed/maps/Watershed_Condition_Framework2011FS977.pdf.
- USDA Forest Service [USDA FS]. 2018. Towards shared stewardship across landscapes: An outcome-based investment strategy. FS-118. Washington, DC: USDA Forest Service.
- USDA Forest Service [USDA FS]. 2022. Confronting the wildfire crisis: A 10-year implementation plan. FS-1187b. Washington, D.C. <https://www.fs.usda.gov/managing-land/wildfire-crisis>.
- USDA Forest Service, Pacific Southwest Region [USDA FS, PSR]. 2019. Conservation strategy for the California Spotted Owl in the Sierra Nevada Version 1.0. R5-TP-043. USDA Forest Service, Pacific Southwest Region. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd624135.pdf.
- USDA Forest Service, Stanislaus National Forest [USDA FS]. 2021. Appendix E. Using landscape condition metrics and ForSys for the social and ecological resilience across the landscape project. Draft Environmental Impact Statement Stanislaus National Forest 56500. Sonora, CA.
- Vibrant Planet. 2023. Land Tender: A platform for landscape restoration. <https://www.vibrantplanet.net/landtender>.
- Vogler, K.C.; Ager, A.A.; Day, M.A.; [et al.]. 2015. Prioritization of forest restoration projects: Tradeoffs between wildfire protection, ecological restoration and economic objectives. *Forests*. 6: 4403–4420.
- Washington State DNR. 2020. Forest health assessment and treatment framework 2020. RCW 76.06.200. https://www.dnr.wa.gov/publications/rp_2020_fh_report.pdf.
- Zong, X.; Tian, X.; Wang, X. 2021. An optimal firebreak design for the boreal forest of China. *Science of the Total Environment*. 781: 146822.

Table A1. List of published spatial planning case studies using ForSys, and their science and management application, scale and key findings presented in alphabetical order by author.

Published Case Study 1: Ager et al. (2023) Optimizing the implementation of a forest fuel break network. PLoS ONE. 18: e0295392. DOI: 10.1371/journal.pone.0295392.

Science and Management Application: Prioritizing Fuel Break Networks

Spatial Algorithm: Spatial optimization

Scale: National forest (520,000 ha)

Key Findings:

- Alternative spatial scenarios examined to prioritize and schedule the construction of a large-scale fuel break network
- Results illustrated how different prioritization strategies for implementing fuel break projects can affect performance and cost, and are relevant for both pre-defined and mapped networks yet to be implemented

Abstract: Methods and models to design, prioritize and evaluate fuel break networks have potential application in many fire-prone ecosystems where major increases in fuel management investments are planned in response to growing incidence of wildfires. A key question facing managers is how to scale treatments into manageable project areas that meet operational and administrative constraints, and then prioritize their implementation over time to maximize fire management outcomes. We developed and tested a spatial modeling system to optimize the implementation of a proposed 3,538 km fuel break network and explore tradeoffs between two implementation strategies on a 0.5 million ha national forest in the western US. We segmented the network into 2,766 treatment units and used a spatial optimization model to compare linear versus radial project implementation geometries. We hypothesized that linear projects were more efficient at intercepting individual fire events over larger spatial domains, whereas radial projects conferred a higher level of network redundancy in terms of the length of the fuel break exposed to fires. We simulated implementation of the alternative project geometries and then examined fuel break-wildfire spatial interactions using a library of simulated fires developed in prior work. The results supported the hypothesis, with linear projects exhibiting substantially greater efficiency in terms of intercepting fires over larger areas, whereas radial projects had a higher interception length given a fire encountered a project. Adding economic objectives made it more difficult to obtain alternative project geometries, but substantially increased net revenue from harvested trees.

Published Case Study 2: Ager, A. A., et al. (2021). Development and application of the Fireshed Registry. Gen. Tech. Rep. RMRS-GTR-425. Fort Collins, CO, USDA Forest Service, Rocky Mountain Research Station: 47. <https://www.fs.usda.gov/research/treesearch/62641>

Science and Management Application: Target the Source of Wildfire Transmission to Communities

Spatial Algorithm: Predefined planning areas

Scale: National

Key Findings:

- In corporation of ForSys scenario planning model into the fireshed planning framework
- Takes a systems approach to the wildfire problem by moving from a descriptive (assessments) to predictive (risk models) to prescriptive (scenario modeling) environment

Abstract: The Fireshed Registry is an interactive geospatial data portal providing access to data describing past, present, and future trends regarding wildfire exposure to communities and forest and fuel management. The registry employs a nested spatial framework that organizes landscape variation in wildfire risk to developed areas into containers or "firesheds" and displays these data on a background of maps on management and disturbances, including past and predicted wildfire events and their potential impacts. It was built in close cooperation with USDA Forest Service staff and establishes a nationally consistent, all-lands, scalable framework for classifying fireshed conditions in terms of underlying wildfire transmission and the potential to mitigate exposure and risk. Foremost, the framework provides a foundation for communication and coordination with external agencies and partners for cross-boundary collaboration and can potentially improve agency national reporting and monitoring of programs. The registry provides the Forest Service with a planning framework for tracking changes in fireshed conditions with respect to wildfire exposure at forest, regional, and national scales. We describe the process of building the system, sources of data, and its application within the agency for decision support and reporting for multiple ongoing programs related to forest and landscape management.

Published Case Study 3: Ager, A. A., et al. (2016). Production possibility frontiers and socioecological tradeoffs for restoration of fire adapted forests. *Journal of Environmental Management* 176: 157-168. <https://www.fs.usda.gov/research/treesearch/52994>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Spatial optimization; multiple objectives

Scale: Regional (four national forests; 2.5 million ha)

Key Findings:

- Clear tradeoffs among the various restoration goals revealing the lack of spatial covariance among different stressors and ecosystem services
- Production frontiers combined with empirical data on ongoing projects can establish targets and monitoring benchmarks that are needed for restoration programs

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

Published Case Study 4: Ager, A. A., et al. (2021). Balancing ecological and economic objectives in restoration of fire frequent forests – Case study from the Four Forest Restoration Initiative. Gen. Tech. Rep. RMRS-GTR-424. Fort Collins, CO, USDA Forest Service, Rocky Mountain Research Station: 30. <https://www.fs.usda.gov/research/treesearch/62640>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Spatial optimization; multiple objectives

Scale: National forest (970,000 ha)

Key Findings:

- Forest restoration to increase fire resiliency poses significant financial challenges, but scenario planning can identify treatment locations that project revenue from harvested wood ultimately improving the likelihood that projects will be implemented

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.

Published Case Study 5: Ager, A. A., et al. (2021) Planning for future fire: scenario analysis of an accelerated fuel reduction plan for the western United States. Landscape and Urban Planning 215, 104212 DOI: 10.1016/j.landurbplan.2021.104212 <https://www.fs.usda.gov/research/treesearch/63129>

Science and Management Application: Target the Source of Wildfire Transmission to Communities; Assessing Planning Risk

Spatial Algorithm: Predefined planning areas; ForSys with Fire

Scale: Sub-national (59 million ha)

Key Findings:

- Scheduling of an accelerated forest and fuel management scenario that targeted the source of wildfire exposure to developed areas
- Incorporated uncertainty into scenario planning to understand how the plan might be impacted by wildfires and treatment

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

Published Case Study 6: Ager, A. A., et al. (2019). Tradeoffs between US national forest harvest targets and fuel management to reduce wildfire transmission to the wildland urban interface. Forest Ecology and Management 434: 99-109. <https://www.fs.usda.gov/research/treesearch/57897>

Science and Management Application: Target the Source of Wildfire Transmission to Communities

Spatial Algorithm: Predefined planning areas; Multiple objectives

Scale: Sub-national (59 million ha)

Key Findings:

- Quantified production frontiers to measure how the efficiency of meeting harvest volume targets is affected by prioritizing treatments to areas that transmit fire to the communities
- First large-scale assessment of the strong tradeoffs and scale effects on production frontiers, and more importantly substantial variation among planning areas and national forests

Abstract: US public land management agencies are faced with multiple, often conflicting objectives to meet management targets and produce a wide range of ecosystem services expected from public lands. One example is managing the growing wildfire risk to human and ecological values while meeting programmatic harvest targets for economic outputs mandated in agency budgets. Studies examining strategic management tradeoffs on federal lands and program efficiencies are rare. In this study we used the 79 western US national forests to examine tradeoffs between forest management scenarios targeting wildfire risk to the wildland urban interface (WUI) and those meeting agency convertible volume production targets. We quantified production frontiers to measure how the efficiency of meeting harvest volume targets is affected by prioritizing treatments to areas that transmit fire to the WUI. The results showed strong tradeoffs and scale effects on production frontiers, and more importantly substantial variation among planning areas and national forests. Prioritizing treatments to reduce fire transmission to the WUI resulted in an average harvest volume reduction of about 248 m³ per ha treated. The analysis also identified opportunities where both management objectives can be achieved. This work represents the first large-scale tradeoff analysis for key management goals in forest and fuel management programs on national forests.

Published Case Study 7: Ager, A. A., et al. (2012). Overview and example application of the Landscape Treatment Designer. Gen. Tech. Rep. PNW-GTR-859. Portland, OR, USDA Forest Service, Pacific Northwest Research Station: 11. <https://www.fs.usda.gov/research/treesearch/40115>

Science and Management Application: n/a

Spatial Algorithm: n/a

Scale: n/a

Key Findings: n/a

Abstract: The Landscape Treatment Designer (LTD) is a multicriteria spatial prioritization and optimization system to help design and explore landscape fuel treatment scenarios. The program fills a gap between fire model programs such as FlamMap, and planning systems such as ArcFuels, in the fuel treatment planning process. The LTD uses inputs on spatial treatment objectives, activity constraints, and treatment thresholds, and then identifies optimal fuel treatment locations with respect to the input parameters. The input data represent polygons that are attributed with information about expected fire behavior and the polygon's overall contribution to one or more landscape management objectives. The program can be used in a number of different ways to explore treatment priority and decision rules that manifest themselves on large (1 million ha) landscapes as spatially explicit treatment strategies. This report describes the LTD program and an example application on the Ochoco National Forest. Further information including program download and a tutorial can be found at <https://www.fs.usda.gov/wwetac/tools/ltd/index.php>.

Published Case Study 8: Ager, A. A., et al. (2013) Restoration of fire in managed forests: a model to prioritize landscapes and analyze tradeoffs. *Ecosphere* 4, 29 DOI: 10.1890/ES13-00007.1 <https://www.fs.usda.gov/research/treesearch/48615>

Science and Management Application: Restoration Treatments to Reintroduce Resource Objective Wildfire

Spatial Algorithm: Spatial optimization

Scale: Ranger district (14,000 ha)

Key Findings:

- Exploring the effect of changing treatment threshold on meeting objectives
- Increasing treatment intensity reduced the potential loss of old growth to wildfire within projects, but it also reduced the size of the restored area, thus prolonging the time to restore the larger landscape and increasing the chance for wildfire losses outside of the project

Abstract: Ongoing forest restoration on public lands in the western US is a concerted effort to counter the growing incidence of uncharacteristic wildfire in fire-adapted ecosystems. Restoration projects cover 725,000 ha annually, and include thinning and underburning to remove ladder and surface fuel, and seeding of fire-adapted native grasses and shrubs. The backlog of areas in need of restoration combined with limited budgets requires that projects are implemented according to a prioritization system. The current system uses a stand-scale metric that measures ecological departure from pre-settlement conditions. Although conceptually appealing, the approach does not consider important spatial factors that influence both the efficiency and feasibility of managing future fire in the post-treatment landscape. To address this gap, we developed a spatial model that can be used to explore different landscape treatment configurations and identify optimal project parameters that maximize restoration goals. We tested the model on a 245,000 ha forest and analyzed tradeoffs among treatment strategies as defined by fire behavior thresholds, total area treated, and the proportion of the project area treated. We assumed the primary goal as the protection and conservation of old growth ponderosa pine trees from potential wildfire loss. The model located optimal project areas for restoration and identified treatment areas within them, although the location was dependent on assumptions about acceptable fire intensity within restored landscapes, and the total treated area per project. When a high percentage of stands was treated (e.g., >80%), the resulting project area was relatively small, leaving the surrounding landscape at risk for fire. Conversely, treating only a few stands with extreme fire behavior (<20%) created larger projects, but substantial old growth forests remained susceptible to wildfire mortality within the project area. Intermediate treatment densities (35%) were optimal in terms of the overall reduction in the potential wildfire mortality of old growth. The current work expands the application in spatial optimization to the problem of dry forest restoration, and demonstrates a decision support protocol to prioritize landscapes and specific areas to treat within them. The concepts and model can be applied to similar problems in spatial ecology.

Published Case Study 9: Ager, A. A., et al. (2017). Economic opportunities and trade-offs in collaborative forest landscape restoration. *Ecological Economics* 136: 226-239. <https://www.fs.usda.gov/research/treesearch/54922>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Predefined planning areas; Multiple objectives

Scale: Regional (four national forests; 2.5 million ha)

Key Findings:

- Detailed economic analysis of potential restoration treatments including costs and revenue at the stand-scale
- Scarce economic opportunities for restoration, but economic viability highly dependent on the prioritization scheme used
- Trade-offs are scale-dependent and exist both within planning areas in terms of specific stands to treat, as well among planning areas

Abstract: We modeled forest restoration scenarios to examine socioeconomic and ecological trade-offs associated with alternative prioritization scenarios. The study examined four US national forests designated as priorities for investments to restore fire resiliency and generate economic opportunities to support local industry. We were particularly interested in economic trade-offs that would result from prioritization of management activities to address forest departure and wildfire risk to the adjacent urban interface. The results showed strong trade-offs and scale effects on production possibility frontiers, and substantial variation among planning areas and national forests. The results pointed to spatially explicit priorities and opportunities to achieve restoration goals within the study area. However, optimizing revenue to help finance restoration projects led to a sharp reduction in the attainment of other socioecological objectives, especially reducing forest departure from historical conditions. The analytical framework and results can inform ongoing collaborative restoration planning to help stakeholders understand the opportunity cost of specific restoration objectives. This work represents one of the first spatially explicit, economic trade-off analyses of national forest restoration programs, and reveals the relative cost of different restoration strategies, as well scale-related changes in production frontiers associated with restoration investments.

Published Case Study 10: Alcasena, F. J., et al. (2022) Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk. *Journal of Environmental Management* 114650 DOI: 10.1016/j.jenvman.2022.114650 <https://www.fs.usda.gov/research/treesearch/65114>

Science and Management Application: Target the Source of Wildfire Transmission to Communities

Spatial Algorithm: Predefined planning areas

Scale: Regional (1.3 million ha)

Key Findings:

- Comparison of scenarios that targeted exposure and loss from alternative treatment strategies at different scales
- Home ignition zone treatments were more cost-effective, but efficiency varied among planning areas
- Variability among planning areas in terms of the treatment efficiency, as measured by both financial and per area leverage, reinforces the idea that mitigation strategies are site specific

Abstract: We examined the financial efficiency and effectiveness of landscape versus community protection fuel treatments to reduce structure exposure and loss to wildfire on a large fire-prone area of central Idaho (USA). The study area contained 63,707 structures distributed in 20 rural communities and resorts, encompassing 13,804 km². We used simulation modeling to estimate expected structure loss based on burn probability and characteristics of the home ignition zone. We then designed three fuel management strategies that targeted treatments to: 1) the surrounding areas predicted to be the source of exposure to communities from large fires, 2) the home ignition zone, and 3) a combination of the landscape and home ignition zone. We evaluated each treatment scenario in terms of exposure and expected structure loss compared to a no-treatment scenario. The potential revenue from wood products was estimated for each scenario to assess the cost-efficiency. We found that the combined landscape and home ignition zone treatment scenario which treated 5.7% of the study area resulted in the highest overall reduction in predicted exposure (47.5%, 100 structures yr⁻¹) and predicted loss (69.1%, 57 structures yr⁻¹). Home ignition zone treatments provided the best predicted economic and per area treated performance where exposure and loss were reduced by one structure by treating 89 and 111 ha per year, respectively, with an annual cost of \$33,645 and \$73,672. Revenue from thinning was the highest for landscape fuel treatments and covered 16% of the required investment. This work highlighted economic and risk tradeoffs associated with alternative fuel treatment strategies to protect developed areas from large wildland fires.

Published Case Study 11: Alcasena, F. J., et al. (2018). Optimizing prescribed fire allocation for managing fire risk in central Catalonia. *Science of The Total Environment* 4(621): 872-885. <https://www.fs.usda.gov/research/treesearch/57191>

Science and Management Application: Prioritizing Prescribed Fire Blocks

Spatial Algorithm: Predefined planning areas

Scale: County (130,000 ha)

Key Findings:

- Prioritize areas for prescribed fire
- Strong trade-offs among different fire exposure metrics, showed treatment mosaics that optimize the allocation of prescribed fire, and identified specific opportunities to achieve multiple objectives.

Abstract: We used spatial optimization to allocate and prioritize prescribed fire treatments in the fire-prone Bages County, central Catalonia (northeastern Spain). The goal of this study was to identify suitable strategic locations on forest lands for fuel treatments in order to: 1) disrupt major fire movements, 2) reduce ember emissions, and 3) reduce the likelihood of large fires burning into residential communities. We first modeled fire spread, hazard and exposure metrics under historical extreme fire weather conditions, including node influence grid for surface fire pathways, crown fraction burned and fire transmission to residential structures. Then, we performed an optimization analysis on individual planning areas to identify production possibility frontiers for addressing fire exposure and explore alternative prescribed fire treatment configurations. The results revealed strong trade-offs among different fire exposure metrics, showed treatment mosaics that optimize the allocation of prescribed fire, and identified specific opportunities to achieve multiple objectives. Our methods can contribute to improving the efficiency of prescribed fire treatment investments and wildfire management programs aimed at creating fire resilient ecosystems, facilitating safe and efficient fire suppression, and safeguarding rural communities from catastrophic wildfires. The analysis framework can be used to optimally allocate prescribed fire in other fire-prone areas within the Mediterranean region and elsewhere.

Published Case Study 12: Ariza, A. M., et al. (2015). Trends in wildfire risk at time-scale: Optimizing fuel treatments configurations in eucalyptus plantations in Portugal. Padua, Italy, University of Padua. https://www.medfor.eu/sites/default/files/editor/martinari-za2015_thesis_medforfinal.pdf

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Unknown

Scale: Not summarized

Key Findings: Not summarized

Abstract: The increase of forest threats in a global change context encourage fire prevention activities for the role in maintaining diversity and land sustainability as a multiuse system as well as for ensuring the welfare of the Mediterranean people. Silviculture prevention management is a complex, dynamic instrument implying many variables, needing knowledge about the strategic localization of fuel treatments. Optimization is driven by the need of accomplishing an objective (or multi-objective) with a limited number of resources, namely money, time, machinery or human resources. Where to treat? How much? Shape and size? The current framework was driven taking into account the Landscape Treatment Designer (LTD), a decision support tool to spatially explore optimal levels of fuel landscape treatment planning regarding: i) objectives as timber value and carbon storage; ii) treatment thresholds as fire hazard metrics (e.g. rate of spread, ROS and flame length, FL), iii) and constraints selected (annual budget restrictions to represent the total treatment allowance - area/ha). The research considered a property (extent $\approx$ 1500 ha) from the Grupo Portucel Soporcel (gPS), located in Serra do Socorro (Torres Vedras, Portugal), where eucalypt (*E. globulus*) is predominant. The central objective is to minimize the losses from wildfire to strategically allocating and scheduling fuel treatments into a spatial-temporal analysis without encroaching budget constraints, and further creates opportunities for the suppression, taking into account over time, wood supply for the pulp industry and meeting demands of carbon values. While the primary objective is to change stand conditions. The ultimate goal of the fuel treatments allocation is to increase landscape resistance to the severe effects of wildfire at different scales, following certain constraints. Explicitly: i) identifying understory fuel composition and stand conditions at temporal stage (t_0, t_1, t_2, t_3 corresponding to 2015, 2018, 2021 and 2024 respectively); ii) characterizing temporal fire behavior (t_0, t_1, t_2, t_3) using FlamMap 5. simulator for two weather scenarios (10% and 7% fuel moisture content for average and critical conditions, respectively), crossed with wind speed of 32 km/h; iii) examining optimal treatment locations for each temporal stage; iv) perform sensitivity analyzes (area treated - two treatment intensities of 70 ha and 100 ha), and v) improve spatialtemporal fire resistance at landscape level. The effect of each scenario was changed by a set percentage of optimal parameters to address the identification of thresholds for radical change in fire behavior, and further insight to support hazard-reduction fuel practices. The accuracy of the results provided an overview of effective management strategies for fuel modifications on improving fire resiliency and selecting priority intervention areas in the gPS eucalyptus plantation.

Published Case Study 13: Belavenutti, P., et al. (2022). Designing forest restoration projects to optimize the application of broadcast burning. *Ecological Economics* 201: 107558. <https://www.fs.usda.gov/research/treesearch/65117>

Science and Management Application: Prioritizing Prescribed Fire Blocks

Spatial Algorithm: Spatial optimization (Patchmax); multiple objectives

Scale: National forest (520,000 ha)

Key Findings: (1) Not reported

Abstract: Active forest restoration programs on western US national forests face multiple challenges to meet their broad ecological goals while designing projects that generate sufficient revenue to build and maintain private forest management capacity needed to expand the scale and scope of treatments. We explored ways to design projects where admixing of treatments along gradients of dry and moist mixed conifer forest types could maximize financial viability while including substantial area where broadcast burning could be applied in conjunction with other treatments. In general, we found that restoration treatments in dry forests that included density reduction thinning and broadcast burning resulted in a net projected cost ranging from \$110 to \$8000 per ha. By contrast, density reduction thinning in moist mixed conifer forests on more productive microsites generated significant commercial timber volume and projected revenue that ranged from \$4000 to \$20,000 per ha. We used spatial optimization methods to identify potential project areas that maximized revenue while meeting constraints to treat a minimum proportion of each project with broadcast burning. Multiple project area sizes were also explored to understand the effect of restoration scale on financial outcomes. We found that optimal projects in terms of generating revenue to subsidize density reduction and broadcast burning were 810 ha and contained >50% dry forest area. Larger projects and those with a higher percentage of dry forest area resulted in lower revenue, eliminating revenue when projects reached 2700 ha. Forest restoration programs can use these methods to plan and design restoration projects that are financially viable while addressing the broadcast burn backlog in dry forests that require relatively expensive fuel reduction treatments prior to re-introducing fire.

Published Case Study 14: Belavenutti, P., et al. Multi-objective scheduling of fuel treatments to implement a linear fuel break network. *Fire* 2023, 6(1): 1. <https://www.fs.usda.gov/research/treesearch/66816>

Science and Management Application: Prioritizing Fuel Break Networks

Spatial Algorithm: Spatial optimization (Patchmax); multiple objectives

Scale: National forest (520,000 ha)

Key Findings: Not reported

Abstract: We developed and applied a spatial optimization algorithm to prioritize forest and fuel management treatments within a proposed linear fuel break network on a 0.5 million ha Western US national forest. The large fuel break network, combined with the logistics of conducting forest and fuel management, requires that treatments be partitioned into a sequence of discrete projects, individually implemented over the next 10-20 years. The original plan for the network did not consider how linear segments would be packaged into projects and how projects would be prioritized for treatments over time, as the network is constructed. Using our optimization algorithm, we analyzed 13 implementation scenarios where size-constrained projects were prioritized based on predicted wildfire hazard, treatment costs, and harvest revenues. We found that among the scenarios, the predicted net revenue ranged from USD 3495 to USD 6642 ha⁻¹, and that prioritizing the wildfire encounter rate reduced the net revenue and harvested timber. We demonstrate how the tradeoffs could be minimized using a multi-objective optimization approach. We found that the most efficient implementation scale was a sequence of relatively small projects that treated 300 ha +/- 10% versus larger projects with a larger treated area. Our study demonstrates a decision support model for multi-objective optimization to implement large fuel break networks such as those being proposed or implemented in many fire-prone regions around the globe.

Published Case Study 15: Belavenutti, P., et al. (2021). The economic reality of the forest and fuel management deficit on a fire prone western US national forest. Journal of Environmental Management 293: 112825. <https://www.fs.usda.gov/research/treesearch/63130>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Predefined planning areas

Scale: National forest (520,000 ha)

Key Findings:

- Identified a blueprint and financial plan for addressing treatment needs on a large fire prone landscape including a mix of restoration treatments and associated costs
- Financial dynamics of projects relative to increasing restoration area examined for break-even points
- Extent to which the project shape, size and treatment portfolio can be optimized to maximize area treated and minimize reliance on external financial subsidies at the landscape scale

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.

Published Case Study 16: Botequim, B. R., et al. (2014). Addressing trade-offs among fuel management scenarios through a dynamic and spatial integrated approach for enhanced decision-making in eucalyptus forest. Advances in Forest Fire Research. D. X. Viegas. Coimbra, Portugal, Coimbra University Press.

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Unknown

Scale: Unknown

Key Findings: n/a

Abstract: None

Published Case Study 17: Chiono, L. A., et al. (2017) Landscape-scale fuel treatment and wildfire impacts on carbon stocks and fire hazard in California spotted owl habitat. *Ecosphere* 8, e01648 DOI: 10.1002/ecs2.1648 <https://www.fs.usda.gov/research/treesearch/53514>

Science and Management Application: Other Applications

Spatial Algorithm: Not reported

Scale: Landscape (55,398 ha)

Key Findings:

- Landscape fuel treatments can alter fire hazard both within and outside of treated stands
- Simulated treatments within protected areas significantly reduced potential fire intensity relative to both the no-treatment landscape and a treatment scenario that did not permit treatment within protected areas

Abstract: Forest managers are challenged with meeting numerous demands that often include wildlife habitat and carbon (C) sequestration. We used a probabilistic framework of wildfire occurrence to (1) estimate the potential for fuel treatments to reduce fire risk and hazard across the landscape and within protected California spotted owl (*Strix occidentalis occidentalis*) habitat and (2) evaluate the consequences of treatments with respect to terrestrial C stocks and burning emissions. Silvicultural and prescribed fire treatments were simulated on 20% of a northern Sierra Nevada landscape in three treatment scenarios that varied in the land area eligible for treatment. Treatment prescriptions varied with topography, vegetation characteristics, and ownership. We then simulated many wildfires in the treated and untreated landscapes. Additional simulations allowed us to consider the influence of wildfire size on estimated emissions. Treatments constrained to the land area outside of spotted owl activity centers reduced the probability of burning and potential fire intensity within owl habitat and across the landscape relative to no-treatment scenarios. Allowing treatment of the activity centers achieved even greater fire hazard reductions within the activity centers. Treatments also reduced estimated wildfire emissions of C by 45–61%. However, emissions from prescribed burning exceeded simulated reductions in wildfire emissions. Consequently, all treatment scenarios resulted in higher C emissions than the no-treatment scenarios. Further, for wildfires of moderate size (714–2133 ha), the treatment scenarios reduced the C contained in live tree biomass following simulated wildfire. When large wildfires (8070–10,757 ha) were simulated, however, the treatment scenario retained more live tree C than the no-treatment scenario. Our approach, which estimated terrestrial C immediately following wildfire, did not account for long-term C dynamics, such as emissions associated with post-wildfire decay, C sequestration by future forest growth, or longer-term C sequestration in structural wood products. While simulated landscape fuel treatments in the present study reduced the risk of uncharacteristically severe wildfire across the landscape and within protected habitat, the C costs of treatment generally exceeded the C benefits.

Published Case Study 18: Day, M. A., et al. (2021). An assessment of forest and woodland restoration priorities to address wildfire risk in New Mexico. *Gen. Tech. Rep. RMRS-GTR-423*. Fort Collins, CO, USDA Forest Service, Rocky Mountain Research Station. <https://www.fs.usda.gov/research/treesearch/62639>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Predefined planning areas; Multiple objectives

Scale: State (24 million ha)

Key Findings:

- Among planning areas the potential to treat two restoration priorities was often correlated, meaning that if you pick a planning area that is high risk for one it will also be high risk to another
- But within a planning area there was a tradeoff between locating treatments to address one restoration versus another (which stands to select within a planning area)
- Risk was concentrated on particular ownerships within planning areas rather than spread out across multiple jurisdictions in terms of the areas identified for treatment

Abstract: The New Mexico Shared Stewardship Agreement created a framework to allow for the State of New Mexico and the USDA Forest Service to collaboratively identify mutual restoration goals to respond to the increasing suite of challenges facing the communities, landscapes, and natural and cultural resources of New Mexico. We used scenario planning to evaluate where forest management could achieve multiple shared restoration objectives, in particular, to reduce wildfire risk to water supply and quality; communities and infrastructure; and biodiversity. The results showed clusters of planning areas that were sources of substantial wildfire risk that span ownerships and forest types. Within a planning area there was a tradeoff between locating treatments to address wildfire risk to communities versus locating them in areas that will best reduce wildfire risk to water quality/supply. However, among planning areas the potential to treat two restoration priorities was often correlated, meaning that if you pick a planning area that is high risk for water quality/supply it will also be high risk to communities. The results also showed that risk was concentrated on particular ownerships within planning areas rather than spread out across multiple jurisdictions in terms of the areas identified for treatment in the modeling. Thus, planning areas are not necessarily compromised by not being cross-boundary. This report was intended as a decision support framework to prioritize planning areas, identify cross-boundary opportunities, and provide a wide array of maps and graphic outputs upon which to further develop active forest management programs.

Published Case Study 19: Kreitler, J., et al. (2019). Cost-effective fuel treatment planning: a theoretical justification and case study. *International Journal of Wildland Fire* 29(1): 42-56. <https://doi.org/10.1071/WF18187>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Spatial optimization; No spatial constraint

Scale: Ranger district (160,930ha)

Key Findings:

- Using cost-effectiveness increases the expected averted losses from fuel treatments, but also allows a larger area to be treated for the same cost, by incorporating costs and cost-effectiveness into the prioritization routine

Abstract: Modelling the spatial prioritisation of fuel treatments and their net effect on values at risk is an important area for applied work as economic damages from wildfire continue to grow. We model and demonstrate a cost-effective fuel treatment planning algorithm using two ecosystem services as benefits for which fuel treatments are prioritised. We create a surface of expected fuel treatment costs to incorporate the heterogeneity in factors affecting the revenue and costs of fuel treatments, and then prioritise treatments based on a cost-effectiveness ratio to maximise the averted loss of ecosystem services from fire. We compare treatment scenarios that employ cost-effectiveness with those that do not, and use common tools and models in a case study of the Sisters Ranger District on the Deschutes National Forest in central Oregon, USA. Using cost-effectiveness not only increases the expected averted losses from fuel treatments, but it also allows a larger area to be treated for the same cost, simply by incorporating costs and cost-effectiveness into the prioritisation routine. These results have considerable implications for policymakers and land managers trying to minimise risk. Incorporating costs into the spatial planning of treatments could allow more effective outcomes without increasing fuel treatment budgets.

Published Case Study 20: Martín, A., et al. (2016) Temporal optimization of fuel treatment design in blue gum (*Eucalyptus globulus*) plantations. *Forest Systems* 25(2), eRC09-eRC09 <https://www.fs.usda.gov/research/treesearch/54962>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Spatial optimization; No spatial constraint

Scale: Project (1,449 ha)

Key Findings:

- Potential to accomplish multiple objectives such as augmenting profits and sustaining ecological assets while reducing wildfire risk at landscape scale
- Scenarios without optimization simulate forest owner treatment within predefined treatment thresholds and constraints

Abstract: Aim of study: This study was conducted to support fire and forest management planning in eucalypt plantations based on economic, ecological and fire prevention criteria, with a focus on strategic prioritisation of fuel treatments over time. The central objective was to strategically locate fuel treatments to minimise losses from wildfire while meeting budget constraints and demands for wood supply for the pulp industry and conserving carbon.

Area of study: The study area was located in Serra do Socorro (Torres Vedras, Portugal, covering ~1449 ha) of predominantly *Eucalyptus globulus* Labill forests managed/cultivated for pulpwood by The Navigator Company.

Material and methods: At each of four temporal stages (2015-2018-2021-2024) we simulated: (1) surface and canopy fuels, timber volume ($\text{m}^3 \text{ha}^{-1}$) and carbon storage (Mg ha^{-1}); (2) fire behaviour characteristics, i.e. rate of spread (m min^{-1}), and flame length (m), with FlamMap fire modelling software; (3) optimal treatment locations as determined by the Landscape Treatment Designer (LTD).

Main results: The higher pressure of fire behaviour in the earlier stages of the study period triggered most of the spatial fuel treatments within eucalypt plantations in a juvenile stage. At later stages fuel treatments also included shrublands areas. The results were consistent with observations and simulation results that show high fire hazard in juvenile eucalypt stands. **Research highlights:** Forest management planning in commercial eucalypt plantations can potentially accomplish multiple objectives such as augmenting profits and sustaining ecological assets while reducing wildfire risk at landscape scale. However, limitations of simulation models including FlamMap and LTD are important to recognise in studies of long term wildfire management strategies.

Published Case Study 21: Palaiologou, P., et al. (2021) Spatial optimization and tradeoffs of alternative forest management scenarios in Macedonia, Greece. *Forests* 12, 697 DOI: 10.3390/f12060697 <https://www.fs.usda.gov/research/treesearch/62755>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Spatial optimization

Scale: National (3.4 million ha)

Key Findings:

- Attainment of ecosystem services and forest production were correlated, suggesting that the same projects have high values for both priorities; however, sharp project tradeoffs between forest production and suppression difficulty
- Prioritization was critical; decreasing efficiency of treatment after a certain threshold at which attainment ceases to increase substantially

Abstract: Managing forests has been demonstrated to be an efficient strategy for fragmenting fuels and for reducing fire spread rates and severity. However, large-scale analyses to examine operational aspects of implementing different forest management scenarios to meet fire governance objectives are nonexistent for many Mediterranean countries. In this study we described an optimization framework to build forest management scenarios that leverages fire simulation, forest management, and tradeoff analyses for forest areas in Macedonia, Greece. We demonstrated the framework to evaluate five forest management priorities aimed at (1) protection of developed areas, (2) optimized commercial timber harvests, (3) protection of ecosystem services, (4) fire resilience, and (5) reducing suppression difficulty. Results revealed that by managing approximately 33,000 ha across all lands in different allocations of 100 projects, the area that accounted for 16% of the wildfire exposure to developed areas was treated while harvesting 2.5% of total wood volume. The treatments also reduced fuels on the area that are responsible for 3% of the potential fire impacts to sites with important ecosystem services, while suppression difficulty and wildfire transmission to protected areas attainment was 4.5% and 16%, respectively. We also tested the performance of multiple forest district management priorities when applying a proposed four-year fuel treatment plan that targeted achieving high levels of attainment by treating less area but strategically selected lands. Sharp management tradeoffs were observed among all management priorities, especially for harvest production compared with suppression difficulty, the protection of developed areas, and wildfire exposure to protected areas.

Published Case Study 22: Salis, M., et al. (2019). Coupling wildfire spread and erosion models to quantify post-fire erosion before and after fuel treatments. *International Journal of Wildland Fire* 28(9): 687-703. <https://www.fs.usda.gov/research/treesearch/58627>

Science and Management Application: Other Applications

Spatial Algorithm: Spatial optimization

Scale: Landscape (68,000 ha)

Key Findings:

- Treatment strategies effective at reducing post-fire sediment delivery at both the landscape scale and in treated areas
- The local effect of fuel treatments on simulated sediment delivery was substantial and supports the need to optimize fuel treatment location to maximize effects on burn severity mitigation and post-fire soil erosion reduction at the landscape scale

Abstract: Wildfires are known to change post-fire watershed conditions such that hillslopes can become prone to increased erosion and sediment delivery. In this work, we coupled wildfire spread and erosion prediction modelling to assess the benefits of fuel reduction treatments in preventing soil runoff. The study was conducted in a 68 000-ha forest area located in Sardinia, Italy. We compared no-treatment conditions v. alternative strategic fuel treatments performed in 15% of the area. Fire behaviour before and after treatments was estimated by simulating 25 000 wildfires for each condition using the minimum travel time fire-spread algorithm. The fire simulations replicated historic conditions associated with severe wildfires in the study area. Sediment delivery was then estimated using the Erosion Risk Management Tool (ERMiT). Our results showed how post-fire sediment delivery varied among and within fuel treatment scenarios. The most efficient treatment alternative was that implemented near the road network. We also evaluated other factors such as exceedance probability, time since fire, slope, fire severity and vegetation type on post-fire sediment delivery. This work provides a quantitative assessment approach to inform and optimise proactive risk management activities intended to reduce post-fire erosion.

Published Case Study 23: Salis, M., et al. (2016). Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area. *Forest Ecology and Management* 368: 207-221. <https://www.fs.usda.gov/research/treearch/52997>

Science and Management Application: Target the Source of Wildfire Transmission to Communities; Other Applications

Spatial Algorithm: Spatial optimization

Scale: Landscape (68,000 ha)

Key Findings:

- Application of fire spread modeling methods to quantify tradeoffs from alternative landscape fuel treatment strategies
- When a small percentage of the study area is treated, the effects are localized and not effective at the landscape scale; although the extent varied by strategy
- Selection of treatment priority for reducing fire exposure to specific values of interest affected overall landscape protection

Abstract: The goal of this work is to evaluate by a modeling approach the effectiveness of alternative fuel treatment strategies to reduce potential losses from wildfires in Mediterranean areas. We compared strategic fuel treatments located near specific human values vs random locations, and treated 3, 9 and 15% of a 68,000 ha study area located in Sardinia, Italy. The effectiveness of each fuel treatment was assessed by simulating 25,000 wildfires using the MTT fire spread algorithm. The simulations replicated severe wildfires observed around the study area, using historic weather and fuel moisture conditions (97th percentile). Wildfire exposure profiles for the study area as a whole and for locations with specific values of interest were analyzed. Results indicated significant variations in wildfire exposure among and within the fuel management strategies and treatment intensities. The simulated mitigation strategies substantially decreased the average wildfire exposure with respect to the untreated condition, and this effect was unequivocal for all strategies. Increasing the percentage of land treated improved the effectiveness of all fuel treatment strategies. The strategy based on road protection provided the highest performances for several wildfire exposure indicators. The methodology presented in this work can be applied to facilitate the design of fuel management programs and support policy decisions to address growing wildfire risk in the region. This work is one of the first applications of fire simulation modeling to evaluate fuel management effectiveness on wildfire risk mitigation in the Mediterranean areas.

Published Case Study 24: Thompson, M. P., et al. (2022). Comparing risk-based fuel treatment prioritization with alternative strategies for enhancing protection and resource management objectives. *Fire Ecology* 18: 26. <https://www.fs.usda.gov/research/treearch/66231>

Science and Management Application: Target the Source of Wildfire Transmission to Communities; Other Applications

Spatial Algorithm: Not reported

Scale: Regional (8.5 million ha)

Key Findings: Not reported

Abstract: Background: Advances in fire modeling help quantify and map various components and characterizations of wildfire risk and furthermore help evaluate the ability of fuel treatments to mitigate risk. However, a need remains for guidance in designing landscape-scale fuel treatments with protection objectives, resource management objectives, and wildfire response in mind. It is also important to consider how human factors related to risk tolerance may affect opportunities to manage fire. We build on these themes to illustrate an approach for examining whether, and how, fuel management can simultaneously minimize housing exposure while maximizing area suitable for expansion of beneficial wildfire. We generate multiple hypothetical post-treatment conditions according to distinct treatment prioritization schemes (Housing Protection, Federal Transmission, Random) and variable treatment extents and compare performance across strategies for a 8.5 million ha case study landscape in north-central New Mexico, USA.

Results: In general, we find that treating near housing units can provide the greatest level of protection relative to treating more remote wildlands to reduce transmission potential. Treating on federal lands to reduce federal transmission was highly effective at reducing exposure from federal fires and at expanding opportunities for beneficial fire but contributed comparatively little to reducing housing exposure from all fires. We find that treatment extents as low as 2.5–5% can yield significant benefits with spatially optimized strategies, whereas the random strategy did not perform comparably until reaching a much larger treatment extent. Increasing risk tolerance for housing exposure expanded the area suitable for managed fire, while decreasing risk tolerance for beneficial fire opportunity and flame length probability shrunk the area suitable for managed fire.

Conclusions: This work provides a contribution in terms of explicitly framing risk analysis and fuel treatment design around federal land and resource management objectives and adds to the knowledge base for designing effective landscape fuel treatment strategies that can protect communities and expand beneficial wildfire on a fire-prone landscape. Successful integration of these themes requires embracing all pillars of the National Cohesive Wildland Fire Management Strategy, including coordinated management of fuels on various ownerships, home ignition zone mitigation, and cross-boundary fire response planning that can guide fire operations in reducing transmission and expand response options.

Published Case Study 25: US Forest Service, Stanislaus National Forest. (2021) Appendix E. Using landscape condition metrics and ForSys for the Social and Ecological Resilience Across the Landscape Project. Social and Ecological Resilience Across the Landscape (56500) Draft Environmental Impact Statement Stanislaus National Forest. Sonora, CA.

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Predefined planning areas

Scale: Project (100,000 ha)

Key Findings: Not reported

Abstract: n/a

Published Case Study 26: Vogler, K. C., et al. (2015). Prioritization of forest restoration projects: tradeoffs between wildfire protection, ecological restoration and economic objectives. *Forests* 6: 4403–4420. <https://www.fs.usda.gov/research/treesearch/52992>

Science and Management Application: Ecological and Economic Tradeoffs and Forest Restoration

Spatial Algorithm: Predefined planning areas; Multiple objectives

Scale: National forest (915,000 ha)

Key Findings:

- Limited opportunities to achieve multiple management objectives at the stand scale thus creating steep tradeoffs within planning areas
- Some restoration objectives had greater utility at the planning area scale thus indicating that objectives must be carefully selected to match the spatial distribution of forest stressors

Abstract: The implementation of US federal forest restoration programs on national forests is a complex process that requires balancing diverse socioecological goals with project economics. Despite both the large geographic scope and substantial investments in restoration projects, a quantitative decision support framework to locate optimal project areas and examine tradeoffs among alternative restoration strategies

is lacking. We developed and demonstrated a new prioritization approach for restoration projects using optimization and the framework of production possibility frontiers. The study area was a 914,657 ha national forest in eastern Oregon, US that was identified as a national priority for restoration with the goal of increasing fire resiliency and sustaining ecosystem services. The results illustrated sharp tradeoffs among the various restoration goals due to weak spatial correlation of forest stressors and provisional ecosystem services. The sharpest tradeoffs were found in simulated projects that addressed either wildfire risk to the urban interface or wildfire hazard, highlighting the challenges associated with meeting both economic and fire protection goals. Understanding the nature of tradeoffs between restoration objectives and communicating them to forest stakeholders will allow forest managers to more effectively design and implement economically feasible restoration projects.

Published Case Study 27: Washington State Department of Natural Resources (2015) “Forest Health Assessment and Treatment Framework 2020 RCW 76.06.200. Office of the Commissioner of Public Lands, Hilary Franz Forest Health and Resiliency Division – Planning, Science, and Monitoring Section

Science and Management Application: Prioritizing Fuel Break Networks

Spatial Algorithm: Spatial optimization

Scale: Landscape

Key Findings: Not reported

Abstract: n/a

Table A2. Decomposition of planning areas into treatment need, costs and revenues for the Umatilla National Forest for two example planning areas show in figure 13. Data outputs were taken from Belavenutti et al. (2021).

Treatment need	Planning Area A			Planning Area B		
	Treatable area (%)	Cost (%)	Revenue (%)	Treatable area (%)	Cost (%)	Revenue (%)
a. Commercial thin only	0.0	0.0	0.0	0.0	0.0	0.0
b. Commercial thin and broadcast burn	9.1	29.3	91.0	6.5	21.1	42.8
c. Commercial thin and pile and burn	0.2	1.0	2.5	7.2	27.1	46.0
d. Stewardship contract only	0.0	0.0	0.0	0.0	0.0	0.0
e. Stewardship contract and broadcast burn	0.7	3.3	6.3	0.8	3.8	3.6
f. Stewardship contract and pile and burn	0.0	0.2	0.2	1.5	9.9	7.6
g. Non-commercial thinning only	0.3	0.3	0.0	0.7	0.5	0.0
h. Non-commercial thinning and broadcast burn	56.6	62.7	0.0	12.7	10.7	0.0
i. Non-commercial thinning and pile and burn	1.4	2.5	0.0	12.5	16.7	0.0
j. Broadcast burn	9.1	0.7	0.0	18.0	1.0	0.0
k. Pile and burn	0.2	0.2	0.0	16.8	9.2	0.0
l. No treatment	22.3	0.0	0.0	23.4	0.0	0.0

Table A3. Ownership composition in treated areas among the top 25 watersheds in the State of New Mexico when prioritizing only the reduction in risk to water supplies. Data accompanies the stacked bar chart in figure 14.

Top projects	BLM	DoD	Other Federal	Private	State	Tribal	USFS
1	0	0	0	0.07	0.95	0	0
2	0	0	0	0.04	0.00	0.00	0.94
3	0	0	0	0.88	0.02	0.00	0.03
4	0	0	0	0	0.00	0.92	0
5	0	0	0	0.06	0	0.00	0.83
6	0	0	0	0.04	0.00	0.79	0.04
7	0	0	0	0	0.00	0.00	0.84
8	0	0	0	0.00	0	0	0.84
9	0	0	0	0.09	0	0.00	0.75
10	0	0	0	0.07	0	0.00	0.74
11	0	0	0	0.06	0	0	0.73
12	0	0	0	0	0	0	0.78
13	0	0	0	0.05	0	0	0.73
14	0	0	0	0.03	0	0	0.74
15	0	0	0.03	0.01	0.00	0	0.69
16	0	0	0.00	0.05	0.00	0.00	0.68
17	0	0	0	0.45	0.19	0.00	0.08
18	0	0	0	0	0.00	0	0.71
19	0	0	0	0.63	0	0	0.04
20	0	0	0	0.00	0	0.65	0
21	0	0	0	0.65	0	0.00	0
22	0	0	0	0.00	0	0	0.64
23	0	0	0	0.02	0	0	0.62
24	0	0	0	0.53	0	0	0.09
25	0	0	0	0.02	0	0	0.59

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotope, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at http://www.ascr.usda.gov/complaint_filing_cust.html and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.



To learn more about RMRS publications or search our online titles:

www.fs.usda.gov/research/rmrs/products/publications

www.fs.usda.gov/research/treesearch